European Commission

SCIENCE *for* Disaster Risk Management 2020

Acting Today, Protecting Tomorrow

Disaster
Risk
Management
Knowledge
Centre

EUR 30183 EN

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JRC114026
EUR 30183 EN

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Print	ISBN 978-92-76-18182-8	ISSN 1018-5593	doi:10.2760/571085
PDF	ISBN 978-92-76-18181-1	ISSN 1831-9424	doi:10.2760/438998

Luxembourg: Publications Office of the European Union, 2021

How to cite this report:
Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), 'Science for Disaster Risk Management 2020: acting today, protecting tomorrow', EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

Designed by Pierre Francois Dausse

Chapter 1

Introduction

Online Version

1 Introduction

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1 Introduction

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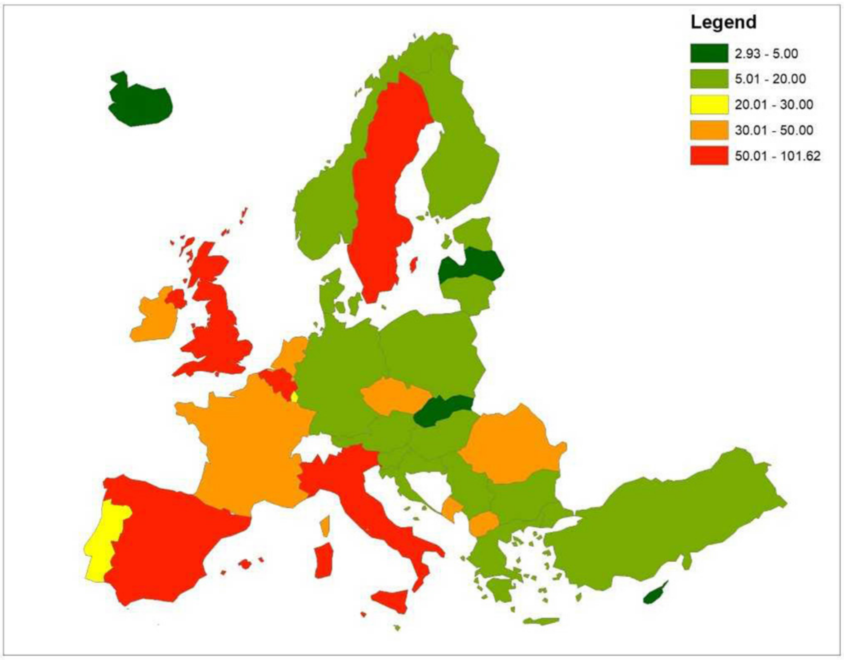
1 Introduction

In a globalised world, we experience the impacts of events happening far from our communities. The coronavirus disease 2019 (COVID-19) emergency that we are living through shows us what systemic risk means in practice. Whereas in January and February 2020 most cases of COVID-19 were reported in China, Europe became the centre of the pandemic in March, and it spread through other parts of the world in the following months.

The pandemic has disrupted our daily lives and affects several socioeconomic and cultural aspects of our societies. In early November 2020, the number of cases globally is over 48 million, with more than one million deaths (ECDC, 2020a). In Europe, the number of deaths is over 25 000 in various countries, although the rates are highly variable (Figure 1).

Figure 1. *Number of deaths reported by countries on the 1st November 2020 per 100.000 inhabitants.*
Source: *Authors, based on data from ECML-COVID (European Commission, 2020a) and the Eurostat, 2019.*
Note: *the countries selected are part of the Union Civil Protection Mechanism (UCPM).*



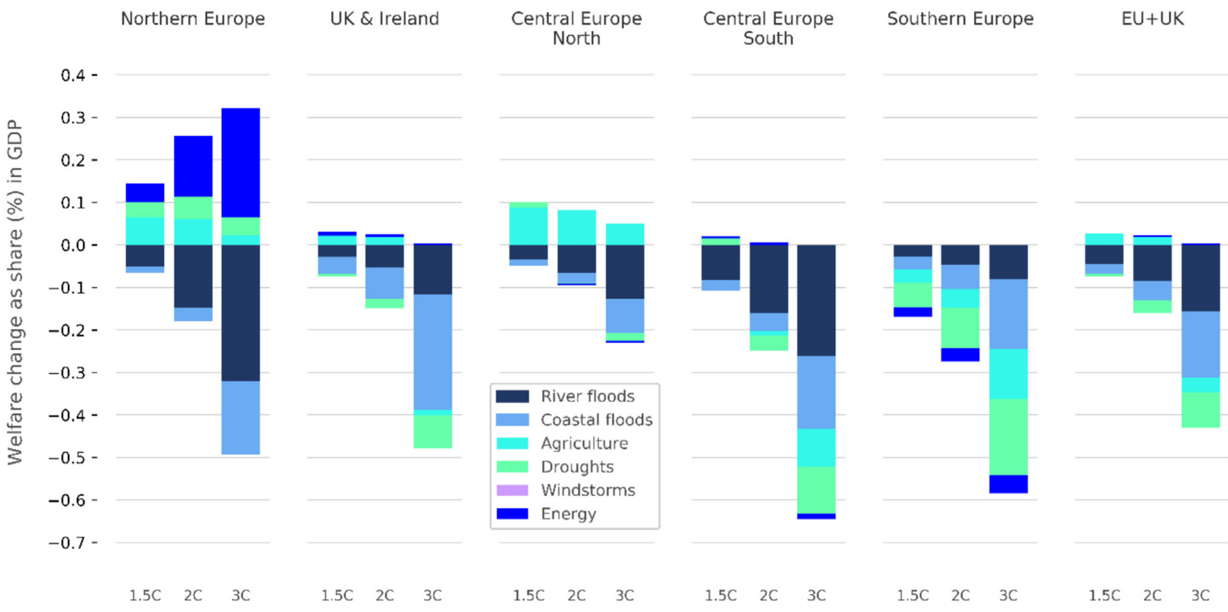
A deep recession is expected in the EU in the years to come. The EU's gross domestic product (GDP) contracted by 3.3 % in the first months of 2020 and by 11.9 % in the second quarter of the year, showing the effects of the containment measures taken by Member States because of the pandemic, with sharp reductions in employment (Eurostat, 2020a). The second wave of infections in autumn would hinder a fast economic recovery.

The industrial sector contracted by more than 18 % between February and May 2020 (Eurostat, 2020b) and the loss in the service sector has been around 22 %, with the downturn particularly affecting hotels and restaurants. In early June 2020, the automotive sector, one of the sectors most affected by the lockdown measures, declared having produced 2 million vehicles fewer than expected in the EU-27 and the United Kingdom during the crisis; the average shutdown duration in the EU-27 and the United Kingdom was 30 days (ACEA, 2020). A full overview of the first estimates of the economic impacts of COVID-19 in the EU can be found in the Commission staff working document 'Identifying Europe's recovery needs' (European Commission, 2020b).

We already knew that risks do not respect borders. The floods of 2005, 2010 and 2016, which affected several countries in central and eastern Europe; the fire in an agrochemical storehouse in Sandoz, Switzerland, that contaminated the surrounding area and affected the water and fauna of the Rhine River kilometres away; the floods in Thailand in 2011 that disrupted the production lines of Toyota in countries such as Canada, Malaysia and Vietnam (Toyota, 2011) – all these provided evidence of this fact. Both direct and indirect impacts can be suffered far away in time and space. It is no longer necessary to emphasise that the level of globalisation we have reached means that everything is connected to everything else. Besides cascading effects, disasters happening in a relatively short time span can result in greater losses than the sum of the independent events. A second lockdown was imposed on account of the sharp rise in COVID-19 cases in Lebanon after the explosions in the port of Beirut in August 2020 (Aljazeera, 2020). The event increased the vulnerability of Beirut's inhabitants, as more than 300 000 people were left homeless and around half of the city's health facilities were reported to be non-functional (BBC, 2020).

Mass displacement is indirectly related to disasters, albeit not straightforwardly (Berlemann and Steinhardt, 2017). Disasters, together with conflict, violence, environmental degradation and other underlying drivers, seem to push people to look for new opportunities far from home (Naude, 2008; Drabo and Mbaye, 2011; IOM, 2019).

Figure 2. *Welfare loss (% of GDP) from climate impacts considered for three warming levels for the EU and the United Kingdom, and for macro-regions. The results represent the change in welfare if warming levels act upon the current economy, compared with the current economy in the present climate..* ***Source****: Feyen et al., 2020.*



Anomalies in temperature and precipitation are related to individuals migrating to richer countries (Backhaus et al., 2015; Coniglio and Pesce, 2015); human mobility can form part of a strategy for adapting to climatic changes. In the European context, the study Peseta IV (Feyen et al, 2020) evaluated the benefits of reducing greenhouse gas emissions and potential adaptation measures for some sectors in response to extreme events such as floods, forest fires and droughts (Figure 2). It concluded that taking no mitigation or adaptation measures would have significant consequences for our welfare.

The characteristics of the assets exposed to risk play a vital role in explaining why some groups of individuals or sectors are more affected than others one a hazard materializes. Socioeconomic, cultural and physical factors have an influence on the consequences of an event. Older age, which is related to issues of mobility, communication and chronic diseases, increases the susceptibility of people to disasters. Figures from recent disasters support this concept: of the nearly 1 000 people who died in Louisiana as a result of Hurricane Katrina in 2008, almost half were 75 or older (NBC, 2008), and the average age of victims of the wildfires in 2017 and 2018 in California was over 70 (Los Angeles Times, 2017, 2018). Europe has one of the highest numbers of old people in the world, and the population continues to grow older: by 2070 there are expected to be 20 % more people in Europe aged 65 or older compared with the number today (UN, 2019; European Commission, 2020c). This is another example of vulnerability. Besides the vulnerability dimension of the assets exposed, the nature of the hazard and the decisions taken post event explain the long-term consequences (Noy and du Pont IV, 2016).

Culture shapes our understanding of the significance and role of disasters, influencing how we perceive risk (Alexander, 2012). Other factors, such as past experiences and trust in authorities and scientific advisory groups, have an effect on risk perception and how people prepare for risk (Wachinger et al, 2013). Loewenstein et al. (2001) point out that emotional reactions play a significant role in the moment of decision-making. The differences in response between countries and regions in the first weeks of the COVID-19 emergency are an example of this: different restrictions to ensure social distancing were applied in Europe at different times from February 2020, even within certain countries (ECDC, 2020b). Governments made decisions in the middle of the crisis, with limited knowledge and few data available to analyse, which resulted in a sense of a lack of coordination and distrust of citizens (Krastev and Leonard, 2020). Misinformation also fuelled rumours, conspiracy theories and stigma around the world (Islam et al., 2020). It became obvious that we are still striving to find the right process to inject science into policy in a timely manner.

Data are essential in developing efficient responses to many of the crises that the EU is currently facing. Through data, policymakers are able to understand which measures to take and projects to fund to enhance the social and economic recovery, but the benefit of data goes beyond this. Databases of historical events and their related effects allow us to track the events and the loss trends over time, to assess the measures implemented before the event to prevent it or mitigate its effects and to study the roots of disasters. Identifying and analysing the causes and drivers of hazards, exposure and vulnerability, and the capacities of people and assets, would allow us to better predict future events and more effectively plan measures to reduce risk, which will enhance resilience. The collection and sharing of data after a disaster should be reinforced to enable actions to be taken to prevent hazards materialising.

Unity and solidarity have been key in the EU in the face of the COVID-19 pandemic, showing that our interdependencies require us to work together, more than ever, to be stronger. Amid the difficult times in which we are living, we should take advantage of the post-disaster period to increase our resilience, by working towards a greener, more digital and inclusive society. The response to and recovery from the pandemic are of course a priority, but should not distract us from reaching imperative societal goals. Learning from our past experiences and investing in research and innovation will help us to better direct our efforts. Could this crisis become an opportunity to launch a reinforced evidence-based and coordinated risk management governance?

2 Towards a more preventive approach

The Union Civil Protection Mechanism (UCPM) and the Sendai framework have pushed the disaster risk management (DRM) community to anticipate losses and damages before these materialise

The cooperative effort to manage disaster risk at EU level began in 2001 with the aim of improving the response of EU countries to disasters (EU, 2001). Taking into account the increasing costs of disaster losses, the Union Civil Protection Mechanism (UCPM) (EU, 2013) went beyond response towards a more preventive approach to disaster risk. This mechanism aims to provide a better understanding of the risk landscape and the potential capacities and to ensure a quick mobilisation of these before and during an event. The UCPM has allowed the exchange of experts and lessons learned and the realisation of exercises. It has received more than 100 requests for internal assistance and monitored hundreds of events, inside and outside the EU (Directorate-General for European Civil Protection and Humanitarian Aid Operations, 2018). In 2019, the mechanism was reinforced to increase the EU's overall capacity to directly confront events (Decision (EU) 2019/420; EU, 2019a) and, as a result of the COVID-19 emergency, the European Commission has proposed further enhancements (see Section 4 below).

Risk anticipation and management are fundamental to the major closely related international agreements and frameworks that have been in place since 2015 – the Sendai framework, Agenda 2030, the Paris Agreement and the 2016 Urban Agenda. Notably, in adopting the Sendai framework the international community agreed a fundamental shift in the approach to disaster risk reduction, moving from managing disasters to a proactive and systemic risk management approach, promoting the mainstreaming of DRM in countries' sustainable development and poverty reduction approaches, and the building of resilience in and by communities.

Furthermore, the Sendai framework focuses on the importance of building a solid data and evidence base, investing in risk reduction and strengthening disaster risk governance, as well as continuing to strengthen preparedness. In addition, the Sendai framework expanded the original Hyogo framework remit of DRM beyond natural hazards to include 'man-made hazards, as well as related environmental, technological and biological hazards and risks' (UNDRR, 2015, p.5). To monitor the progress of countries in achieving this goal, seven targets were set on the impacts of disasters on populations, critical infrastructures and livelihoods.

These international frameworks have also presented significant opportunities to build coherence across different policy areas. For example, there is clear recognition of the links between the Sendai framework and the Agenda 2030 Sustainable Development Goals in terms of reporting, monitoring and thematic overlap. In addition, there are clear synergies between the science and technology objectives of the Sendai framework and the Paris agreement through national and regional projects and improved coordination of existing networks and scientific research institutions.

There is no doubt that local action is needed to implement global international frameworks and agreements that are relevant for DRM, and more broadly to achieve sustainable development. Cities and municipalities are the testing ground for innovative solutions on how to prepare for, deal with and recover from disasters. Local action can bring significant and immediate benefits, harness local public opinion and facilitate cooperation across sectors. This facilitates an integrated approach to the implementation of global frameworks for disaster risk reduction, climate change and sustainable development.

3 Science for policy planning and implementation

Science plays an important role in societal debates and allows policies to be based on the most up-to-date knowledge. Science can help policymakers visualise the complexity of the problems at hand, better define the issues and put alternative policies on the table.

The push for a more preventive approach to anticipate risk requires collaboration between different disciplines, but also stakeholders engaged in different sectors. *Science for disaster risk management 2017* (Poljansek et al., 2017) highlighted the need to reinforce transdisciplinarity to work across sectors and levels to manage risk. This type of approach helps to create knowledge for complex problems through the collaboration, and the integration of knowledge, of different stakeholders and disciplines, which leads to approaches and solutions that are easier to implement in practice (Gall et al., 2015; Ismail-Zahed et al., 2017). Despite the differences between and challenges facing the science–policy interface for disaster risk reduction in the EU (Albris and Cedervall Lauta, 2020), solid alliances and research strategies have been created in the last few years to reinforce collaboration between these actors. The European Commission used the Sendai framework as an opportunity to develop a disaster risk-informed approach for all policies (European Commission, 2016), engaging the research community to address the gaps in knowledge through different frameworks, such as the EU research and innovation programme Horizon 2020. At the same time, significant progress has been made under the joint coordination by the policy departments of European Commission (Directorate-Generals (DGs)), establishing close ties between projects under Horizon 2020 and their potential users (such as DG HOME through the Community of Users on Secure, Safe and Resilient Societies ([1])).

The forthcoming Horizon Europe research initiative (2021–2027) will be implemented by the Commissioner for Innovation, Research, Culture, Education and Youth, together with Member States, the research community and civil society. With the aim of delivering solutions to the greatest challenges the world is facing, the programme will be structured in missions, grouped into different areas. One of these areas, ‘Adaptation to climate change, including societal transformation’, will support citizens to connect with science and policymakers in the process of climate change adaptation. Lastly, it will reinforce the culture of evidence-based policymaking and create and make full use of the knowledge, information and research within the Commission in the development of policies.

3.1 Assessing potential consequences

Disaster risk management needs to be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment – Sendai framework for disaster risk reduction 2015–2030.

([1]) *https://www.securityresearch-cou.eu/home*

The foundation for effective DRM is to first identify and assess the risk of a natural or man-made hazard; hence, understanding of risk is the first Sendai priority (UNDRR, 2015). By quantifying disaster risk and communicating the potential impacts, governments, communities and individuals can make informed decisions to manage their risk.

Disaster risk assessments enable decision makers to obtain quantitative information to understand the potential impacts and risks of natural hazards. The fundamental elements of risk – hazard, exposure and vulnerability – are integrated through modelling to determine the likely deaths, damages and losses that will result from a hazard event, before the disaster strikes. The scientific community should be engaged in the risk assessment exercise, and particularly in the analysis of risk, its interpretation and communication, and the design of recommendations for action (see section 3.2).

The ability to model disaster loss is a powerful tool for DRM. Risk assessments can serve multiple purposes depending on the stakeholder – these can range from undertaking urban risk assessments for disaster preparedness, to multi-country financial risk assessments to support the design of financial transfer mechanisms. They can also be used to understand the cost–benefit ratios of investing in measures to reduce risk. Risk assessments are also increasingly used to calculate risk under current and future climate and socioeconomic scenarios, providing decision makers with an additional impetus to act immediately on the underlying drivers of risk.

In recent years, the numbers of national-, regional- and city-level risk assessments have rapidly increased, with

BOX 1 a)

Anticipating risks at the local level

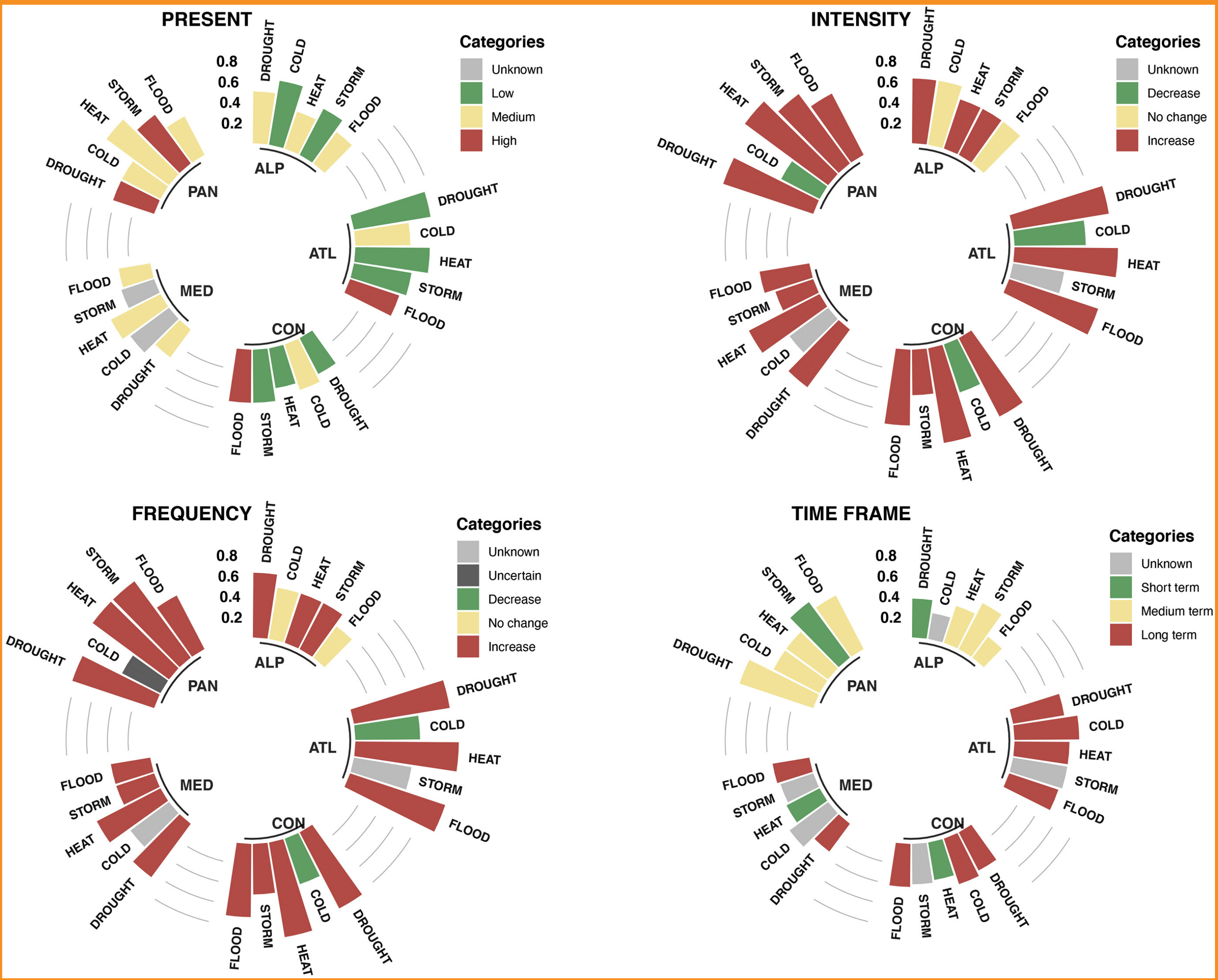
Several cities and regions already make extensive use of short- and long-term projections for adaptive strategies. For instance, the Austrian Environment Agency uses the Copernicus Services to measure surface imperviousness for the whole country, enabling local discussions on flood risks (Copernicus, 2019). Early warning systems for heatwaves are in place in several cities and regions of Europe, bringing together information on weather projections, health services and the vulnerability of the population to better target health service interventions (see, for instance, Lowe et al., 2011).

Under the Covenant of Mayors for Climate and Energy, local authorities combine DRM with climate risk assessment and vulnerability and adaptation measures, thus integrating future climate change-related disasters into planning. By September 2020, almost 2 800 cities in the EU had committed to develop local climate adaptation strategies (Covenant of Mayors for Climate and Energy, 2020). From the risk and vulnerability assessments developed by the signatories, many hazards have been identified (Figure 3), many of which are expected to increase in frequency.

BOX 1 b)

Anticipating risks at the local level

Figure 3. *Current hazard level, expected changes in future intensity, frequency, and time frame reported by the municipalities of the Covenant community.* ***Source****: Hernandez et al., 2020*



city-scale risk assessments driving short- and long-term city resilience planning (Box 1 a,b) and national risk assessments providing access to investment funds for risk reduction, such as in EU Member States. Sector-level risk assessments are also increasingly common in the transport, education, agriculture, health and water sectors – evidence that disaster risk reduction is increasingly moving into the mainstream.

Risk identification provides the basis for any assessment and therefore all DRM actions: whether to reduce risk by putting policies and plans in place that will help avoid the creation of new risk or by addressing existing risk either physically or financially, or to inform improved resilient reconstruction design. Emergent risks are typically obvious in retrospect – they are the result of a series of events that cross human-imposed boundaries, whether institutional, geographic, disciplinary, conceptual or administrative. Scientists should support the stage of risk identification, using data from previous events studied, from foresight exercises, from hazard monitoring and from research in general, to frame the problem at hand.

In some cases risks are not actually new, but are emerging systemic risks that require new methods of assessment, management and governance. To fully understand systemic risks, it is necessary to understand the gap between global, regional and local risks and integrate risk perception and prevention and mitigation strategies to evaluate the potential impacts of financial market regulations and possible innovative financial tools on several sectors such as food security and the environment.

3.2 Tackling the risk drivers

Addressing disaster risk delivers both immediate and longer term development gains. While investing in disaster resilience often requires higher start-up costs, it is cost-effective in the long term. Studies have indicated that investing in preventive measures pays off: a report from the US National Institute of Building Sciences found that, for every dollar spent on grants aimed at improving disaster resilience, society saves six dollars (Multihazard Mitigation Council, 2017).

Since we cannot prevent some hazards from occurring, the main opportunity for reducing risk lies in tackling vulnerability and exposure (Box 2). Reducing these two components of risk requires the underlying drivers of risk to be identified and reduced. These are particularly related to poor economic and urban development choices and practices, degradation of the environment, poverty and inequality and climate change. Addressing these underlying risk drivers will reduce the consequences of disaster impacts and, consequently, maintain the sustainability of development.

The Intergovernmental Panel on Climate Change (IPCC) had already recognised in 2012 that climate change poses new challenges to disaster managers (Lavell et al., 2012) (Box 3). Both the disaster risk reduction and the climate change adaptation communities have made efforts to integrate their work to exploit synergies and avoid any overlaps in meeting the common objectives of decreasing vulnerabilities and enhancing resilience. Hemmers et al. (2020) stressed the need to work together on data collection and risk assessment methodologies as areas of common interest.

BOX 2

Examples of holistic solutions

Land use planning

Between 1970 and 2010, the total urban surface area exposed to flooding more than doubled, from 18 000 km2 to 44 000 km2 (Jongman et al., 2012). At least 1 000 million urban dwellers are highly exposed to flood risk in the world (Ehrlich et al., 2018; Gu, 2019). The expansion of impermeable surfaces decreases infiltration and increases run-off during precipitation events. Deforestation also contributes to increased surface run-off not only by reducing the amount of moisture that trees absorb from the soil but also by removing the tree canopy; without the canopy, more rainwater reaches the ground, and reaches it more quickly. Poor planning at city level can create a vicious cycle, exacerbating risks and exposure. For instance, the covering of soil for housing and roads increases the absorption of energy from the sun and leads to higher urban temperatures, which is also known as the 'urban heat island effect'.

Land-use-planning policies that incorporate risk are important for controlling increases in disaster risk, primarily by providing a mechanism to prevent new development or detrimental changes of use in hazard-prone areas. For example, land-use-planning policies can help to ensure that vulnerable or high-value assets and heavily occupied buildings (business and residential) are not located on hazard-prone land and can seek to reduce risk exposure by placing low-density-usage activities (agriculture, parks and recreational land) in those areas.

Nature-based solutions

With more extreme weather events, and increasing development along rivers and coastlines, impacts from climate-related disasters are on the rise. Governments are turning to nature to help manage these disasters. Nature-based solutions can conserve or restore nature, while supporting conventionally built infrastructure systems, or 'grey infrastructure'.

The use of green infrastructure such as forests, parks, wetlands, green walls and green roofs has been effective in reducing the risk of disasters at local level. Such approaches also lead to significant co-benefits such as better air quality and enhanced quality of life, as well as opportunities for employment (Pridmore et al., 2017; McVittie et al., 2018).

In 2016, Bratislava, Slovakia, implemented measures to enhance the urban resilience of the city, planting trees and establishing green roofs and rainwater retention facilities to mitigate the impact of intense rainfall and heat. Similarly, the city of Malmö, Sweden, has integrated green infrastructure and storm water management measures as part of its Western Harbour development (Climate-ADAPT, 2020).

BOX 3

Building resilient infrastructures

According to Hallegatte (2009), one problem in adapting to climate change is the rate at which conditions are changing: infrastructure and investments being implemented now must be robust enough to cope with a wider range of climate conditions in the future. This need incurs additional costs for designing that infrastructure. Hallegatte (2009) cites five methods to promote effective adaptation in an uncertain future climate:

- 'No-regret' strategies, which provide benefits regardless of whether the disaster risk evolves because of a changing climate. These strategies include improved building insulation to provide immediate energy-saving benefits, and land use planning to reduce losses under current and future climate conditions.

- Reversible and flexible options. These options can be halted or adjusted at short notice, with little or no sunk cost. They include climate-proofing new buildings and erecting flood defences that can easily be made higher and stronger at little cost.

- Safety margins in investments. The design of infrastructure systems and structures should account for worst-case scenarios, rather than relying on later modifications. For example, drainage systems should be designed with sufficient capacity to cope with anticipated run-off.

- Appropriate adaptation strategies. These include 'soft' adaptation strategies, such as early warning systems, evacuation plans and insurance schemes, and long-term planning horizons with shorter term revisions of plans.

- Shorter lifetime of investments. This approach reduces the uncertainty about climate change in decision-making. Cost–benefit assessment of investments should account for future losses and costs as well as current costs; this approach is particularly important for long-term investments.

A new framework for understanding infrastructure resilience was recently proposed, highlighting the ability of infrastructure systems to function and meet the needs of populations during and after natural hazards (Hallegatte et al., 2019).

Climate change projections call for action and scientific groups are already working to encourage the adaption of European standards to a changing climate. Athanasopoulou et al. (2020) have prepared the basis for further work on the thermal design of structures and Sousa et al. (2020) presented the expected implications of corrosion due to climate change.

3.3 Information technology

In recent years, data-driven approaches have emerged in response to disasters through the smart use of data. One of the targets established to monitor the progress of the Sendai framework calls for multi-hazard early warning systems and risk information to be made available and accessible in the future. Warnings are issued based on predictions, that is, on the systematic monitoring of precursors of hazards, which are analysed together with the assets exposed and the vulnerability and capacities of the system. This constant assessment of potential events requires sound scientific knowledge.

The scientific community has made huge progress in improving warning systems by adopting the most advanced combination of technologies (including artificial intelligence and space data) to capture any kind of anomalous signal and reactively analysing such signals using a combination of technologies and expert advice, such as the Epidemic Intelligence from Open Sources (EIOS) ([2]), the Global Disaster Alert and Coordination System (GDACS) ([3]), the European Forest Fire Information System (EFFIS) ([4]), the European Flood Awareness System (EFAS) ([5]), the European Drought Observatory (EDO) ([6]) and the future European observatory of Climate Change and Health. In the last few years, social media has been revealed as a useful tool to collect and analyse data, both before and during an emergency, and for issuing a response (Box 4). Bee and Budimir (2019) outline some examples of tools that exploit the opportunities provided by social media.

BOX 4.

Projects exploiting social media data: FIUME and SMDRM

FIUME (Flood risk and Impact in Urban areas using social Media) is an exploratory research activity focused on identifying the impacts of floods in urban areas on populations, infrastructures and services by building hyper-local geocoders and a machine learning model.

FIUME will be integrated in the medium term in SMDRM (social media for disaster risk management), which aims to use social media to improve situational awareness during any kind of disaster, and especially to fill the gap during the first hours of response before satellite maps are available. The SMDRM project has several work packages, which were developed at the Joint Research Centre (JRC) together with external collaborators:

- a multilingual machine learning classifier for identifying relevant text;
- a machine learning image classifier for detecting the impacts of a disaster;
- a geocoder at the global scale for aggregating the information extracted;
- a filter for selecting the most relevant information and presenting it to crisis managers.

The system packages for flood classification will be released into the Global Flood Awareness System (GloFAS) (Lorini et al., 2019).

([2]) *https://www.who.int/eios*
([3]) *http://dev.gdacs.org/*
([4]) *https://effis.jrc.ec.europa.eu/*
([4]) *https://www.efas.eu/*
([5]) *edo.jrc.ec.europa.eu*

4 Building a more resilient EU post COVID-19 – challenges for disaster risk management

'In the next five years, we have to work together to allay fears and create opportunities' – Ursula von der Leyen.

In July 2020, the European Council agreed an ambitious COVID-19 recovery plan, also known as 'Next Generation EU'. The plan, with a total budget of EUR 750 billion, was agreed alongside the EU's Multiannual financial framework (MFF) for 2021–2027; together they will contribute to the implementation of the new European Green Deal presented in December 2019 (European Commission, 2019). These key policies are mutually reinforcing and are based on sound science and strengthened risk management principles, bringing new challenges and increased demands for research in DRM. Overall, all EU policies are placing increased emphasis on the integration of climate and disaster risks in policy actions and operations, including by earmarking 30 % of the funding in the MFF and Next Generation EU for climate change.

Both the Next generation EU and the European Green Deal have been widely documented ([7]) ([8]); in this section the key elements of DRM are presented, including suggestions for research and data priorities.

4.1 Next generation EU

RescEU will be enhanced so that Europe is able to act more quickly and be more flexible once a serious cross-border threat, such as COVID-19, emerges.

The recovery plan addresses economic and social investment in the Member States and also includes the enhancement of crisis and health preparedness and response at the EU level. The reforms and investments will help the EU to recover by allowing Member States to move towards a greener, more digital and socially resilient future.

Among the lessons learnt from the COVID-19 crisis has been the need for enhanced coordination and an improved crisis preparedness response at the European level to help address future scenarios. To improve crisis preparedness and management, the Commission will reinforce the European Medicines Agency and give a stronger role to the European Centre for Disease Control (ECDC) in coordinating medical responses in crises. The Commission has also proposed a standalone EU4Health programme to support Member States and the EU to build capacity and preparedness for future health crises. It will help deliver a long-term vision for well-performing and resilient public health systems, notably by investing in disease prevention and surveillance, and improving access to healthcare, diagnosis and treatment.

In addition, the Commission has proposed strengthening rescEU to build permanent capacity to handle all types of emergencies. This will enhance its capacity to invest in emergency response infrastructure, transport capacity and emergency support teams. It will create EU-level reserves of essential supplies and equipment to be mobilised in response to major emergencies.

([7]) See *https://ec.europa.eu/info/live-work-travel-eu/health/coronavirus-response/recovery-plan-europe_en*
([8]) See *https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en*

In addition, European standards provide a means to roll out security technologies. European standardisation organisations can contribute to overcoming fragmentation in this field by increasing the interoperability and compatibility of systems and products related to security, crisis management, risk, resilience and business continuity. Another lesson is the need for a fast, flexible and coordinated EU response to crises. In this regard, the Commission is proposing to strengthen its emergency tools and make them more flexible so that resources can be deployed quickly and at scale when needed. This includes the European Solidarity Fund and the European Globalisation Adjustment Fund. The Solidarity and Emergency Aid Reserve will also be significantly strengthened to enable a rapid response to crises both within and outside the EU.

Furthermore, with the aim of strengthening civil protection, the Commission has proposed reinforcing a cross-sectoral and societal preparedness and preventative approach to transboundary DRM, including establishing a baseline and planning elements at the European level, taking into account how climate change affects disaster risk.

As part of the Next Generation EU investment and recovery plan, the European Commission has announced recently the “New European Bauhaus”. It would be a space of co-creation where architects, engineers, artists and designers would work to transform the EU to reach its environmental, economic and culture goals. The initiative aims primarly to bring the European Green Deal to life by rethinking the way we relate with environment and to tackle climate change (European Commission, 2020e).

4.2 The European Green Deal – key elements for disaster risk management

COVID-19 recovery actions are an opportunity to deal with the root causes of the disaster and to accelerate our transition towards a more sustainable society.

The Commission will adopt a new, more ambitious EU strategy on adaptation to climate change. This is essential, as climate change will continue to create significant stress in Europe in spite of the mitigation efforts. Strengthening the efforts on climate-proofing, resilience building, prevention and preparedness is crucial. Work on climate adaptation should continue to influence public and private investments, including in nature-based solutions. It will be important to ensure that, across the EU, investors, insurers, businesses, cities and citizens are able to access data and develop instruments to integrate climate change into their risk management practices.

The Sustainable Europe Investment Plan is the investment pillar of the European Green Deal and will mobilise through the EU budget and the associated instruments at least EUR 1 trillion of private and public sustainable investments over the coming decade. It will form an integrated European approach to reinforce risk management, recognising the importance of green investments in any recovery strategy to be applied to the pandemic.In late 2019, before the COVID-19 pandemic, more than 75 % of European citizens felt that climate change is a serious problem in the EU and 98 % believed that it has a direct effect on their personal life ([9]). In the middle of the COVID-19 crisis, EU citizens still believe that part of the budget should be dedicated to climate change and environmental protection, together with public health and economic recovery (European Parliament, 2020).

Accessible and interoperable data are crucial to the Green Deal. Data, combined with digital infrastructure (e.g. supercomputers, the cloud, ultra-fast networks) and artificial intelligence solutions, facilitate evidence-based decisions and expand the capacity to understand and tackle risk management challenges.

([9]) https://ec.europa.eu/commfrontoffice/publicopinion/index.cfm/survey/getSurveydetail/instruments/special/surveyky/2257

A specific urgent priority is to boost the EU's ability to predict and manage environmental disasters, bringing together European scientific and industrial excellence to develop a very high-precision digital model of the Earth. Biodiversity is one of the pillars of the Green Deal. The EU Biodiversity strategy 2030 (European Commission, 2020e) aims to ensure that ecosystems function for our health and security, indicating that they protect us from disasters and other drivers of risk. The Commission is currently preparing an impact assessment setting out options for EU nature restoration targets in 2021 (including making them legally binding) to restore degraded ecosystems, in particular those with the most potential to capture and store carbon and to prevent and reduce the impact of disasters.

Linking biodiversity, resilience and sustainable economic recovery, a new EU Forest strategy will also be put forward by the Commission in early 2021, as part of the Green Deal. Likewise, the Strategy Farm to Fork (European Commission, 2020f) has been drafted to ensure food security in face of several recurring threats, such as biodiversity loss, forest fires, pests and droughts.

Investing in research, innovation and knowledge exchange will be key to gathering the best data and developing the best nature-based solutions. Research and innovation can test and develop how to prioritise 'green' over 'grey' solutions and help the EU to support investments in nature-based solutions, such as in old industrialised, low-income and disaster-hit areas (European Commission, 2020e).

EU space policy aims to tackle some of the most pressing challenges today, including fighting climate change and disasters. Under Copernicus, the EU's Earth observation programme, immediate information has been provided when disasters strike, such as earthquakes, forest fires or floods, enabling better coordination between emergency and rescue teams. In addition, the satellites supporting this observation system help countries to assess the risks of such disasters. The EU has two other flagship space programmes: Galileo, Europe's global satellite navigation system, and EGNOS, the European Geostationary Navigation Overlay Service. These provide 'safety of life' navigation services to aviation, maritime and land-based users over most of Europe. Under the new Green Deal, additional resources for the three services are planned, as well as reinforcement of their efforts to address climate risks and crisis management.

4.3 Digitalisation and inclusiveness

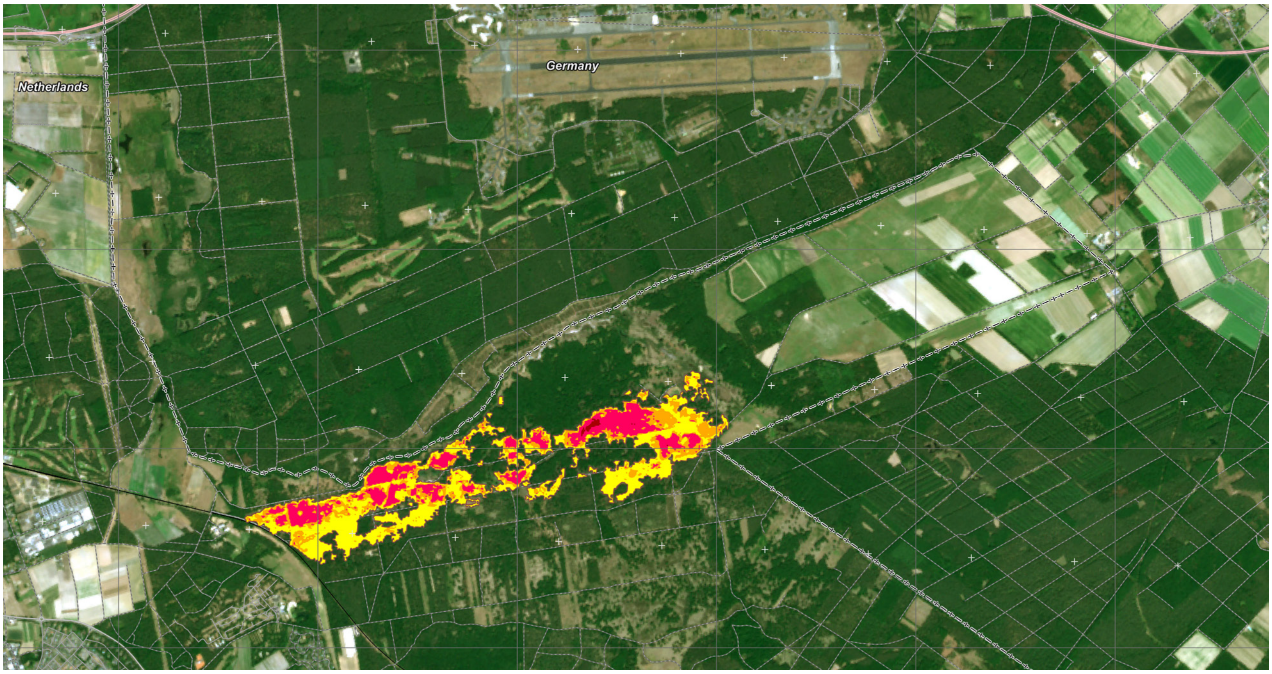
Closing borders and spaces to mitigate the spread of COVID-19 put technology at the centre of our lives, ensuring business continuity and access to services and facilitating people's interactions in general. The added value of digitalisation and data analytics in DRM is vast: data from satellite imagery and sensors can be used for developing vulnerability maps to plan how to prevent certain hazards or to predict damages; it is necessary to count with data and assess the capacities in place to monitor risks, as part of early warning systems; and machine learning can help to classify information from social media for use while responding to an event. Digitalisation allows DRM to optimise processes and to obtain new results. In remote situations or when the reality does not allow face-to-face meeting, information and communication technology infrastructure provides an opportunity for raising awareness and capacity building, such as through the use of training and courses.

The Copernicus Emergency Management Service (EMS) on-demand mapping provides geospatial information on the request of EU Member States to support emergency activities. The service has been activated more than 400 times since 2012, analysing the immediate damages from floods, forest fires, cyclones and industrial accidents, among others([10]).

([10]) https://emergency.copernicus.eu/mapping/list-of-activations-rapid

Likewise, Copernicus can provide geospatial information in support of disaster management activities not related to the immediate response, such as information on damage assessment after the earthquake that hit Zagreb in March 2020 or after the wildfire in Meinweg National Park (the Netherlands) in May of the same year. The analysis of the vegetation before and after the events served to determine the burned area in Meinweg National Park, which was almost 150 ha (Figure 4).

Figure 4. *Overview map of the damage assessment analyses of the affected area in Meinweg National Park.*
Source*: e-GEOS, SIRS, 2020. © European Union, 2020.*
Note*: Yellow, negligible damage; orange, moderate damage; red, high level of damage; dark red, destroyed area.*



Both the infrastructure and regulations should be in place to keep the EU safe and active. Following the EU Cybersecurity Act (Regulation (EU) 2019/881; EU, 2019b) and the Directive (EU) 2019/1024 on open data and the re-use of public sector information (EU, 2019c), a set of actions has been planned to enable data and artificial intelligence to drive the future of the EU.

Security threats related to information and communication technologies will probably increase over the next few years. Social media and media platforms can provide a window to access information to facilitate social interactions, strengthening transparency and accountability and social innovations. In contrast, disinformation in times of disasters is particularly dangerous. For example, during Hurricane Irma in 2017, fake news circulated in the United States before and after the event. The US National Weather Service publicly denied one fake weather forecast but the information had already been shared on social media more than 36 000 times (Concha, 2017).

Digitalisation supports the implementation of other European Commission priorities, facilitating citizens to fulfil their rights and boosting the EU market. During the first weeks of the pandemic, the number of countries providing information related to the emergency through their portals, apps or social media increased considerably (United Nations, 2020). Furthermore, digitalisation directly benefits some groups of society, such as people with disabilities, with regard to entering the labour market (Kilhoffer et al., 2019).

New technologies create a space for citizens to participate in research, opening channels for new audiences and citizens in general to contribute in research, by collecting, analysing and visualising data, although it is important to consider affordability and access (Mazumdar et al., 2018).

The COVID-19 emergency has also made evident the differences in digitalisation between and within countries. While 79 % of people in Denmark participated in social media in 2017, this share was below 50 % in France, Italy and Slovenia (Eurostat, 2019). Similarly, the use of social media drops considerably among people aged over 65 (Khoros, n.d). In addition, in spite of having access to internet, low broadband speeds and high costs have a direct effect on small and medium-sized enterprises and low-income families. Finally, before the pandemic crisis, 23 % of EU citizens had a low level of digital skills and 21.4 % had no digital skills at all (Dewar et al., 2017).

Disaster risk reduction must consider the diversity in needs and capacities of different social groups and minorities (related to age, gender, origin, sexual orientation, educational level, etc.), both before and after an event. Vulnerable groups that tend to be left outside the decision-making process suffer the most once a disaster strikes. Transgender people experience difficulties when registering for shelter and using facilities after a disaster as gender binary norms are assumed (Dominey-Howes et al., 2018).

At the same time, efforts should be made to ensure that digitalisation is ready for the ambitious green goals, supports the common European Health Data Space and supports the new requirements posed by the COVID-19 pandemic, such as telework and e-learning.

5 The Science for Disaster Risk Management 2020 report

The data and information collected after a disaster should be exploited, not only to guide recovery, but also to reinforce the prevention and mitigation of future events.

As shown in the previous sections, we are working to break down silos and encourage collaboration among governance levels and stakeholders to reach a comprehensive understanding of risk, which will help us to reduce disaster risk in a more effective way. The report *Science for Disaster Risk Management 2020: acting today, protecting tomorrow* follows that idea and aims to provide evidence for use by society. As evidence can come from a varied set of actors, the report has engaged experts from academia and research institutions and gathered experiences of civil protection organisations, international organisations, national institutions and civil society organisations in that task. The outcome of the collective effort of more than 300 experts, from different background and disciplines, ensures that the report is comprehensive and relevant, as well as being robust and up-to-date.

As with the previous report, *Science for Disaster Risk Management 2017: Knowing more and losing less*, the current report aims to increase knowledge on disaster risk in Europe by collecting and merging the scientific results from and experiences of several actors. In this report, disaster risk is studied through the analysis of the consequences of an event on various assets of interest: population, economic sector, critical infrastructures, environment and cultural heritage. Chapter 3 is fully dedicated to these assets. Focusing on the impacts, we aim to link different sectors and cover different types of hazardous events, including disasters of natural, technological and malicious origin. We believe that the asset approach followed allows us to have a more systemic view of risk, and to pay attention to vulnerability, one of the risk factors that could be better tackled at the asset level.

A good analysis of impacts, in time and space, is an interesting source of knowledge to exploit to reduce disaster risk. Our resilience depends on our ability to anticipate events and to recover from them. By studying the consequences of a disaster, it is possible to test the actions put in place before it, while it can also be an opportunity to develop the methods and tools used in the risk assessment. At the same time, an assessment of the impacts post event facilitates the building of more sustainable systems as part of the recovery phase, which favour the prevention and mitigation of future losses and damages.

The study of impacts helps us to connect different governance levels, from the international level to the local level. The impacts of a disaster are intensively felt at the local level, although these impacts can expand to other areas while resources from other levels can be used to respond to the disaster. At the same time, the decisions and investments made at international and national levels strongly guide the efforts made at community and local levels. This report is full of examples of past disasters, which have been analysed to find lessons and gaps, with an attempt to extract most of the information from the post-disaster period. The idea is to move from identifying need to proposing solutions, and although a disaster and its consequences are unique, the approaches followed and actions implemented can provide opportunities for other groups and sectors.

The current report *Science for Disaster Risk Management 2020* provides recommendations to four groups of society that can contribute to reducing disaster risk: policymakers, practitioners (including here civil protection groups), scientists and citizens. The context and its audience are primarily European, although lessons and cases from outside our borders have been included, considering their potential to be applied in a European context.

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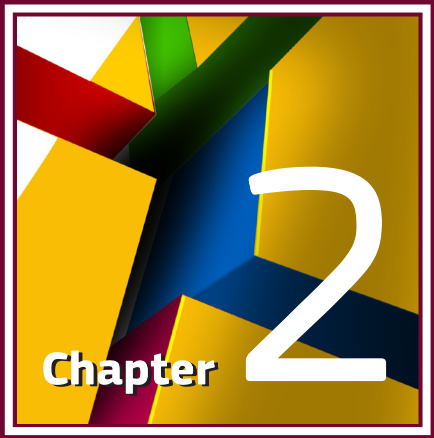

Integrating the risk management cycle

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Online Version

Tagarev, T., Papadopoulos, G. A., Hagenlocher, M., Sliuzas, R., Ishiwatari, M., Gallego, E., 'Integrating the risk management cycle', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

2 Integrating the risk management cycle

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Introduction

Science provides valuable support to the definition of disaster risk management (DRM) norms, procedures, organisation, objectives and requirements, identification of measures and development of capabilities, i.e. the formulation and implementation of DRM policies. The understanding of disaster risk is fundamental for effective policy-making (Clark et al., 2017) and needs to be shared by all key stakeholders. Furthermore, it needs to be comprehensive in terms of policy scope, the types of hazards and intensity of disasters, and the risk management process.

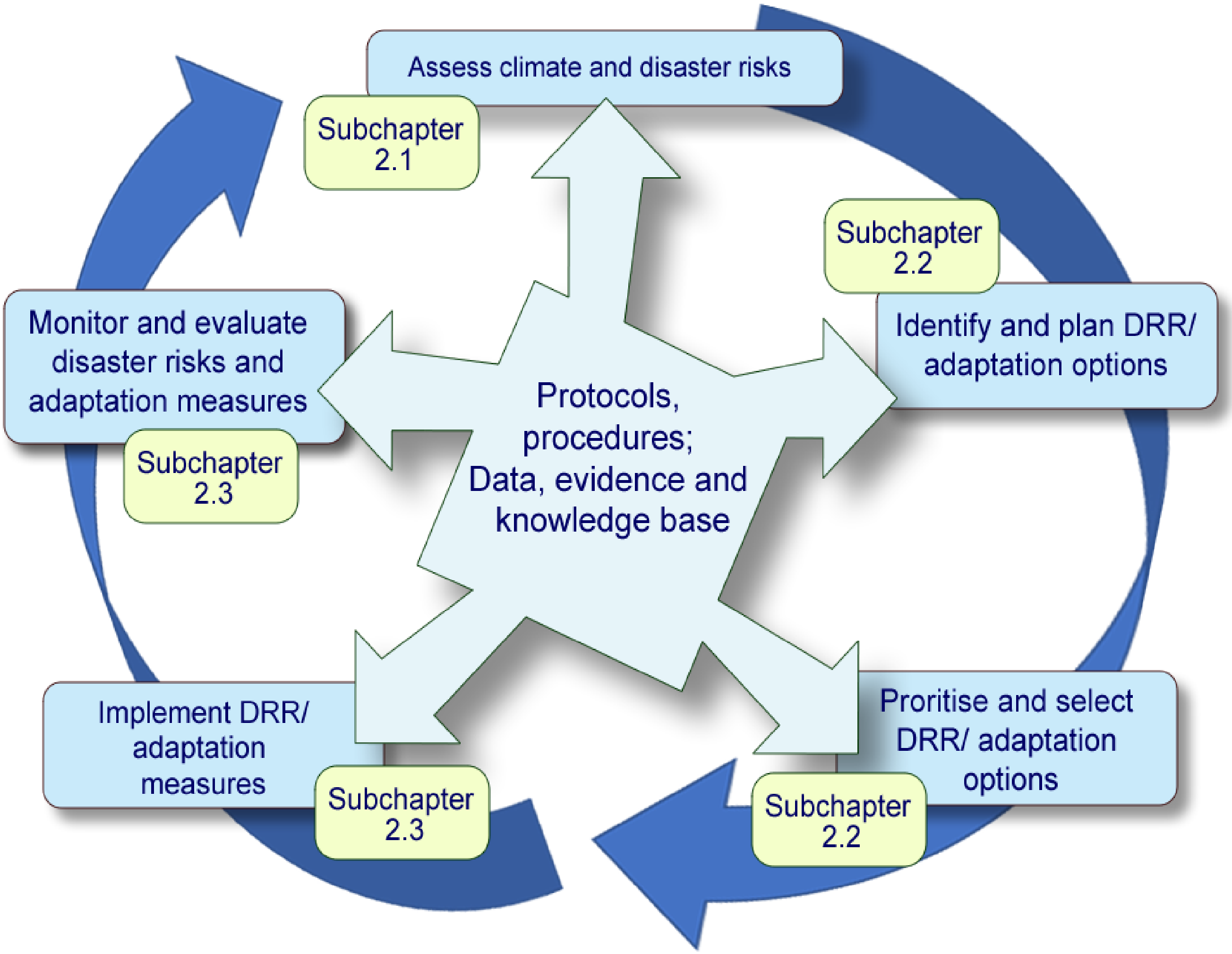
First, the understanding and assessment of risk should cover three components: natural and human-induced hazards; exposure of humans, infrastructure and ecosystems; and systems' vulnerability. Correspondingly, the definition of DRM policy addresses prevention, mitigation (including for example spatial planning), and protection strategies and measures, as well as adaptation to longer-term natural and socioeconomic processes such as climate change and the development of capabilities for response and recovery.

The functional approach allows policymakers to address the activities most appropriate to the context (Thorvaldsdóttir and Sigbjörnsson, 2014). A recently developed comprehensive taxonomy of crisis management functions provides a common framework for consideration of all respective measures and capabilities (Tagarev and Ratchev, 2020).

Second, an all-hazards approach to risk governance is fundamental to enhancing resilience, prevention, emergency preparedness and response (OECD, 2018) and needs to cover emergencies of various intensities, from an incident, through a disaster, to a crisis.

Third, it is not sufficient to assess risk periodically. Risk management is a continuous activity that includes assessment of climate and disaster risks; identification, prioritisation and selection of disaster risk reduction and adaptation measures, preferably in a consistent DRM policy; implementation of the selected measures; and monitoring and evaluation of risk reduction and adaptation measures. Figure 1 presents this activity as a cycle.

Figure 1. *Integrating the risk management cycle.* ***Source****: Authors*



2.1
Risk assessment

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1 Introduction

Disaster risk management and adaptation policies, strategies and plans should be based on a common understanding, assessment and monitoring of the risks associated with natural and human-induced hazards based on a multi-hazard risk approach..

Causing damage to human well-being, ecosystems, infrastructure and disrupting entire economies, disasters continue to undermine sustainable development. Reducing the impacts of natural hazards and identifying pathways towards resilient societies hence remains a global priority. Understanding and assessing the drivers, patterns and dynamics of risk associated with single or multiple hazards is a necessary precondition for the identification, planning and implementation of targeted disaster risk reduction (DRR), risk transfer and climate change adaptation (CCA) policies, strategies and solutions. This realisation is reflected in key international agreements of the post-2015 agenda (e.g. the Sendai Framework for Disaster Risk Reduction 2015–2030, the 2030 Agenda for Sustainable Development, and the Paris Agreement) as well as the European Union's Civil Protection Mechanism and the European Agenda on Security – all of which include an explicit or implicit call for risk assessments. This subchapter provides an overview of current risk assessment concepts (Section 2), highlights the relevance of a transdisciplinary perspective when assessing risk (Section 3) and presents approaches to tackle the complex nature of risk (Section 4). Furthermore, it emphasises the need to analyse and communicate uncertainties as part of the risk assessment process as well as the essential role of risk communication to support disaster risk management.

2 Understanding risk: key elements and conceptual foundations

Risk is the potential for adverse consequences or impacts due to the interaction between one or more natural or human-induced hazards, exposure of humans, infrastructure and ecosystems, and systems' vulnerabilities.

Over the past few decades, conceptual approaches to understanding risk have undergone considerable paradigm shifts. Early conceptualisations drew on environmentally deterministic approaches, which focused primarily on understanding and assessing key characteristics of the hazard (e.g. floods, droughts, storms), such as their frequency, intensity, duration or extent (White, 1973). The choice and frequent use of the term 'natural disasters' reflects the thinking of that time that disasters are to be understood as being random, exceptional events, or purely natural phenomena (Hewitt, 1983; Burton, 2005). Criticising this hazard-driven view, a number of scholars in the early 1970s and 1980s started to call for the consideration of vulnerability as a key driver of risk (O'Keefe et al., 1976; Hewitt, 1983; Blaikie et al., 1994; Lewis, 1999; Wisner et al., 2004) emphasising the role of agency (i.e. the action people take to reduce their vulnerability) and structure (i.e. the social, economic or political structures that place people in vulnerable conditions). Building on these developments, more holistic risk concepts have been put forward that integrate environmental, social, economic, political, infrastructural and governance-related drivers of disaster risk (Turner et al., 2003; Birkmann et al., 2013; IPCC, 2014; UNDRR, 2019). As a result, a multitude of conceptual foundations and frameworks on how to define disaster risk coexist (see Box 1). While vulnerability and risk were conceptualised differently by the DRR and CCA communities for a long period of time, recent developments, such as the Special Report on Extreme Events (SREX) (IPCC, 2012) or the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014), have made a significant contribution to reconciling contrasting definitions (Giupponi and Biscaro, 2015). Although a commonly accepted definition of risk is still lacking, it is widely acknowledged today that risk (i.e. the potential for adverse consequences) is more than just the likelihood and severity of hazardous events and potential impacts. Rather, it results from the interaction of hazardous events with exposure of humans, infrastructure and ecosystems, and systems' vulnerabilities (IPCC, 2014, 2019; UNDRR, 2015, 2019). Evidence has shown that the impacts of hazards are not equally distributed within society (UNDRR, 2018), but largely linked to the question of how vulnerable an individual, community, infrastructure, society, asset or (eco)system is to such events (Schneiderbauer et al., 2017). Consequently, the following components should be considered when assessing risk.

Hazard, i.e. the process, phenomenon or human activity that carries the potential to cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. Hazards can be natural (e.g. earthquakes, droughts, floods) or anthropogenic (e.g. oil spills, terrorist attacks) in origin and can be characterised by their location, likelihood of occurrence, intensity or magnitude, duration, and extent. Hazards can be sudden onset events (e.g. flash floods, storms, mudflows, landslides, earthquakes) or creeping processes (e.g. droughts, salinisation) (IPCC, 2014; UNDRR, 2016).

Exposure, i.e. the presence of people, infrastructure, housing, production capacities, species or ecosystems, and other tangible human assets in places and settings that could be adversely affected by one or multiple hazards (IPCC, 2014; UNDRR, 2016). Exposure may vary in space and time, for example, as people commute between their work place and their home.

BOX 1

Current risk assessment frameworks: similarities and differences

Several risk assessment frameworks have been formulated to capture the multi-dimensional, dynamic nature of risk. Such frameworks can serve as (1) a heuristic for characterising risk (e.g. how to frame and link its key drivers and components), (2) 'thinking tools' for the assessment of risk, as well as (3) policy guidance (e.g. providing entry points for risk management and adaptation). Here, similarities and differences of relevant risk assessment frameworks are presented:

- Risk as a result of the interaction of hazard(s), exposure and vulnerability (e.g. IPCC AR5 (IPCC, 2014), ISO 14091, or the Global Risk Assessment Framework (GRAF, UNDRR, 2019)). Although the AR5 and ISO 14091 illustrate risk related to climate impacts, these frameworks may be applied to other non-climatic hazards. The GRAF emphasises the systemic nature of risk across sectors and scales and promotes a multi-hazard and multi-risk approach.

- Risk is expressed in terms of risk sources, potential events, their consequences and their likelihood (e.g. ISO 31000: 2009). ISO 31000: 2018 builds on the same concept and proposes a three-step approach of risk identification, risk analysis, and risk evaluation. The risk framework of the World Economic Forum (WEF) follows the same logic.

Vulnerability, i.e. the propensity or predisposition of an individual, a community, infrastructure, assets or systems (incl. ecosystems) to be adversely affected (UNDRR, 2016). Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (Birkmann et al., 2013; IPCC, 2014).

Hence risk is different from impacts, which can be seen as the manifestation of risk in the form of materialised effects on human and natural systems (IPCC, 2019, 2014)

3 The need for a transdisciplinary perspective

The integration of experts from natural and social sciences, as well as relevant stakeholders (including state and non-state actors), is needed to tackle the complexity of risk and facilitate the mainstreaming of risk information into policy and practice.

Given its complex multidimensional nature, risk cannot be adequately characterised or assessed by a single discipline (e.g. geosciences) alone. Instead, it requires the involvement of experts from both natural and social sciences (multi- or interdisciplinary perspective), and ideally should go one step further and involve relevant stakeholders (taking a transdisciplinary perspective). The interaction between scientists, policy- and decision-makers, practitioners, the private sector and citizens is critical to ensure knowledge is co-created, to increase trust in the outcomes of risk assessments, and to mainstream co-produced risk information into evidence-based policy- and decision-making for DRR and CCA (Ismail-Zadeh et al., 2017; Brown et al., 2018).

While this might sound like an easy task, a number of challenges persist that make it difficult to move from traditional multidisciplinary (i.e. working within disciplinary silos) or interdisciplinary approaches (i.e. working across disciplinary silos but using disciplinary methods) of risk assessment to integrated transdisciplinary approaches (Donovan, 2019). Examples include a lack of common understanding of what constitutes risk, limited awareness of the potential methodological contributions different disciplines can make to risk assessments, the willingness and capacity of stakeholders to engage with opposing views, power relations or simply the choice of the ‘right’ stakeholders (Ismail-Zadeh et al., 2017). However, such approaches have significant potential to address some of the communication challenges around risk assessments, as well as ensuring that all relevant knowledge is incorporated (Donovan and Oppenheimer, 2015).

4 Risk assessment: approaches, opportunities and challenges

Research is increasingly engaged in monitoring, assessing, and understanding risk by developing concepts, methods and approaches. However, several challenges persist when it comes to unravelling the complexity and dynamics of risk in assessments.

Over recent decades, there has been a major increase in the number of risk assessments, drawing on a multitude of conceptual foundations and methodological approaches (Preston et al., 2011; de Sherbinin et al., 2019; Hagenlocher et al., 2019). As a result, a bewildering variety of risk assessment methods and approaches exists. Independent of the approach that is chosen, common steps in risk assessment include (1) scoping (i.e. understanding the context, scope, objectives and expected outcomes of the risk assessment) and definition of the methodological approach, (2) identification of the root causes/drivers[1] of risk through expert and/or community consultation and literature reviews, (3) data acquisition, (4) integrated analysis and evaluation of hazard, exposure and vulnerability, (5) validation and (6) visualisation and communication of the results (Zebisch et al., 2018). For semi-quantitative or purely quantitative approaches, the evaluation of uncertainties and confidence levels represents another key step that should be part of the validation process (Zebisch et al., 2018). Furthermore, the entire risk assessment should undergo a verification process to identify if it was developed in a sound and correct way. As risk assessment should not be an end in itself, every risk assessment should ideally include the identification and evaluation of possible risk reduction, risk transfer (e.g. through insurance mechanisms) or adaptation options (Hagenlocher et al., 2018a).

Despite major advances in terms of understanding risk and developing methods for its assessment, several challenges persist. These include issues such as how to best (1) integrate local knowledge and intangible factors (e.g. risk perception, behaviour, values, norms and beliefs) into risk assessments (UNDRR, 2015, Hagenlocher et al., 2018b) or (2) capture and represent dynamics (including future scenarios) of risk (Jurgilevich et al., 2017), non-linearities, human–environmental and cross-scale interactions, and compound or cascading effects (EC, 2017; Ford et al., 2018; Adger et al., 2018; UNDRR, 2019). The following sections reflect on these challenges by outlining the current state of the science, existing solutions and good practices as well as potential ways forward.

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4.1 Integrating qualitatitative and quantitative approaches to tackle complexity

Risk assessments have to deal with an increasing diversity of possible adverse events and increasing complexity and interdependency of the drivers of risk (see Box 2). To address these challenges, a number of qualitative, semi-quantitative and quantitative methodologies have been developed. The selection of the most appropriate approach depends on the scope of the assessment, the level of quantification and spatial differentiation demanded within the context of each assessment, and its defined objectives. These demands may vary among the three main assessment phases: (1) risk identification, (2) risk analysis and (3) risk evaluation (ISO 31000:2009).

[1] For indicator-based approaches (see Section 4.1), this step may also include the identification of valid, reliable, understandable, comparable and measurable indicators.

In many circumstances a combination of methods is necessary to tackle the complexity and systemic nature of risk. To support the identification of risks it is useful to start with an investigation of past events and associated impacts. Such information can be either found in appropriate inventories at national, regional or global level (e.g. the EU Risk Data Hub(2), the Emergency Events Database (EM-DAT)(3) or the Sendai Monitor(4) or drawn from traditional and/or expert knowledge. Records of past events need to be augmented by a comprehensive list of additional potential hazards and risks that should be compiled based on the knowledge and experience of relevant experts. The output of the risk identification process is in most cases conceptual and qualitative. Within the context of global warming it is of crucial importance to consider the modification of past risks not yet reflected in event databases as well as the emergence of new risks due to changing environmental (including climatic) and societal conditions.

The objective of risk analysis is to understand possible risks and their drivers, patterns, dynamics and potential consequences. Techniques used for this task differ depending on context and the complexity of the types of risks in question. In the case of risks related to accidents in technical production processes, relevant analytical steps can rigidly follow potential failure causal chains, as applied, for example, in failure mode and effect analysis or event tree analysis (US Department of Health and Human Services Food and Drug Administration, 2006). The identification of risks associated with natural hazards or climate-related extreme events requires a more flexible approach that allows for systemic perspectives that explicitly scrutinise exposure and vulnerability factors in addition to the hazardous events themselves, for example when developing impact chains (Hagenlocher et al., 2018b; Schneiderbauer et al., 2013) or influence diagrams (McDaniels et al., 2012).

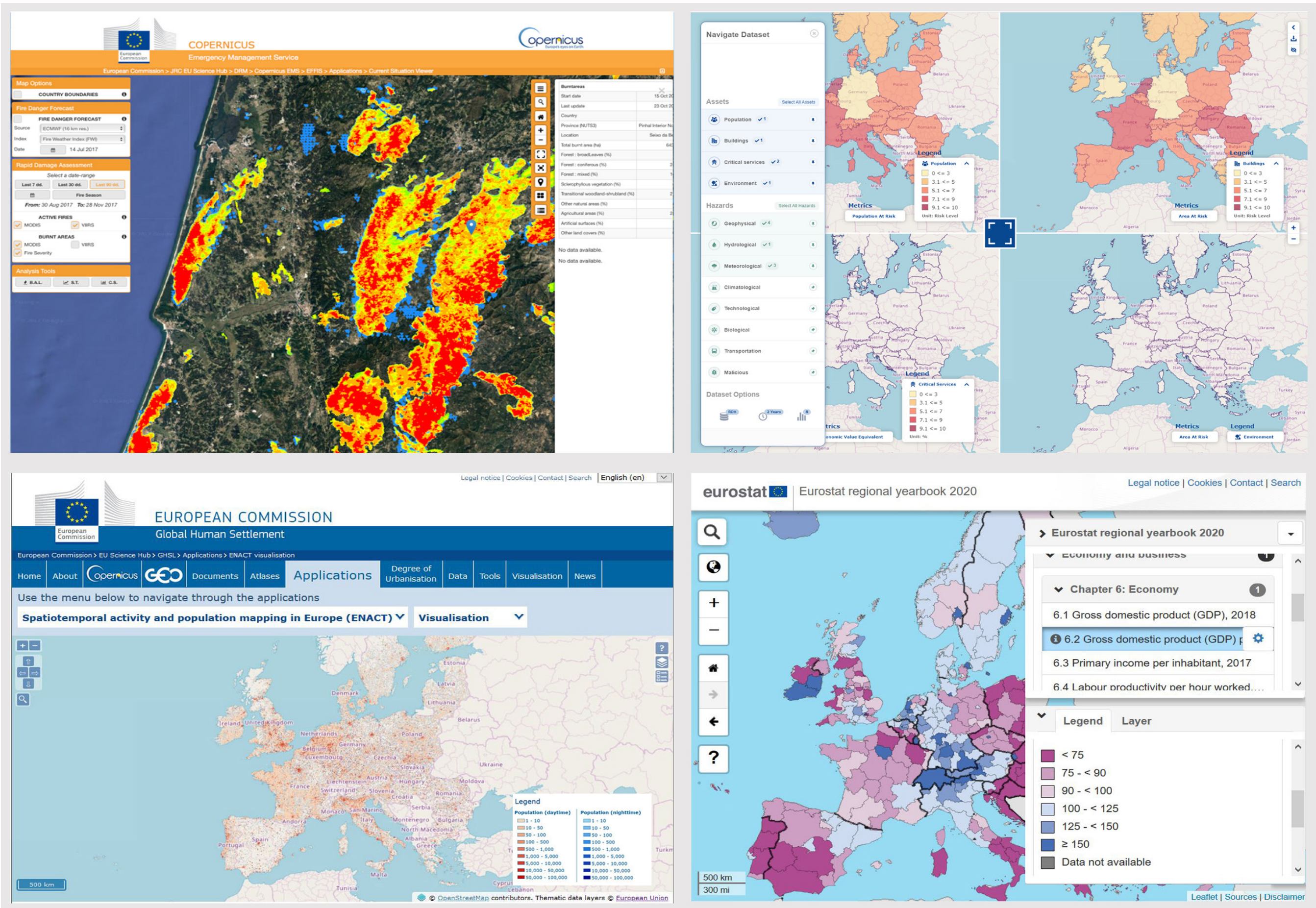
To get a full picture of the risk situation, and to understand related drivers as well as possible consequences, qualitative information embedded in storylines and narratives is crucially important (Jasanoff, 1999). Many aspects relevant to understanding complex risks – particularly those of an intangible nature – cannot be found in databases, statistics or the outputs of equations and models. These are often linked to issues such as governance (e.g. the role of traditional or informal governance systems that exist in parallel to official administrative structures) and culture (e.g. the role of religion/beliefs in shaping risk perception and behaviour). Nonetheless, quantification is vital when risk analyses aim to determine frequencies and probabilities of consequences, particularly when a comparison in time or space is requested. There are many available methods and tools for this assessment step, such as stochastic modelling/Monte Carlo simulations (e.g. Musson, 2000), system dynamics modelling (e.g. Simonovic, 2011), sensitivity analysis (e.g. Glas et al., 2016), event tree analysis (e.g. Tang et al., 2018) or composite indicators (e.g. De Groeve et al., 2016). A specific challenge concerns risk analysis questions that require spatially explicit investigations, such as assessments that aim to inform the spatial planning of DRR and adaptation options, or the allocation of funds to high-risk regions. Such spatial analysis also requires quantitative assessment approaches. In this case, data paucity and time required for data collection and data processing can be restricting factors. However, the ever-increasing availability and resolution of remote sensing data as well as citizen-generated data also provide new opportunities. Figure 1 illustrates a number of existing platforms that provide access to risk data of EU relevance. Consistent population (e.g. Global Human Settlement project[5]), land use (e.g. the Copernicus Land Monitoring Service(6) or socioeconomic data (e.g. Eurostat(7), as well as spatial information on hazards (e.g. Copernicus Emergency Management Service(8), exposure and impacts (e.g. Risk Data Hub(2), are available for EU countries.

Furthermore, depending on the scale of the analysis, participatory mapping or primary data collection (e.g. through household surveys) may also enhance data availability. Semi-quantitative risk analyses represent a structured

(2) https://drmkc.jrc.ec.europa.eu/risk-data-hub/
(3) https://www.emdat.be
(4) https://sendaimonitor.unisdr.org
(5) https://ghsl.jrc.ec.europa.eu/
(6) https://www.copernicus.eu/en/services/land
(7) https://ec.europa.eu/eurostat
(8) https://emergency.copernicus.eu/

way to rank risks by applying comparative scores. This procedure often applies participatory indicator-based approaches (e.g. Simmons et al., 2017; Aguirre-Ayerbe et al., 2018). When data and resources are limited, qualitative methods (e.g. interviews, focus group discussions) allow an estimation of risk levels in a descriptive manner. Risk evaluation is the final assessment step with a direct link to supporting decision-making. In this step, the risk analysis results are verified regarding context-specific criteria, which strongly depend on actors' risk perception and awareness. The methods of risk evaluation mainly comprise techniques for the acquisition of expert knowledge and the engagement of relevant actors

Figure 1*. Illustrative examples of risk data platforms for Europe: the COPERNICUS EMS Fire Danger Forecast (top left), the EU Risk Data Hub (top right), the Global Human Settlement platform (bottom left), and EUROSTAT (bottom right).* ***Source****: Authors.*



4.2 Single hazard risk, multi-hazard risk, and multi-risk

Quantitative risk assessments are commonly performed hazard by hazard as single-hazard risk assessments. However, to make informed decisions on priorities in risk management, spatial planning or risk communication, it is necessary to consider all hazards and know all risks relevant to the area under investigation (Durham, 2003). Multi-hazard assessments have not been standardised up to now and are thus distinguished by the level of interaction and interdependencies between different risk components. If no interaction between hazard processes is considered in the hazard models or in the vulnerability models, Zschau (2017) refers to this type of assessment as multi-layer single-risk assessment, for which Kappes et al. (2012) distinguish three basic approaches: indices, matrices and curves. Any of them can address single components of the risk equation or the total risk (see, for example, Kappes et al., 2012; Zschau, 2017). One example of an index-based approach is the Index for Risk Management (INFORM) Global Risk Index (IASC and EC, 2019), which assesses risk at the global level. Early examples of a matrix approach are the Switzerland-wide all-hazard risk assessment Katastrophen und Notlagen in der Schweiz (KATANOS and its successor KataRisk (BABS, 2003; BZS, 1995). Grünthal et al. (2006) presented one of the first examples of risk curves using the City of Cologne in Germany as a case study to compare earthquakes, storms and floods. One key challenge with risk curves is to use a comparable and consistent methodology across different hazards.

To assess risk more realistically, it is necessary to account for interactions between hazards and vulnerabilities. Three types of hazard interactions can be distinguished: compound, interacting and cascading events (Pescaroli and Alexander, 2018). Compound events are described as (1) simultaneous or successively occurring events, such as a heatwave that is accompanied by dry conditions leading to wildfires that cause – among other things – heavy air pollution (Zscheischler et al., 2018), (2) events combined with background conditions that augment their impacts, e.g. sea level rise and coastal storms, and (3) a combination of (several) average values that result in an extreme event (IPCC, 2012; Pescaroli and Alexander, 2018). For example, the power outage caused by heavy snowfall in Münsterland, Germany, in November 2005 could be traced back to a combination of heavy wet snowfall, a temperature range around 0 °C, moderate to strong wind and the type of steel used in the constructions (Klinger et al., 2011). Importantly, this last type of compound events calls for new, bottom-up modelling approaches that start with a forensic analysis of damaging events to identify the root causes of damage and failure (Zscheischler et al., 2018). The European Cooperation in Science and Technology (COST) action DAMOCLES (Understanding and modelling compound climate and weather events) focuses on understanding and modelling compound events.

In contrast to compound events, interacting events are predominantly addressed by earth scientists investigating 'how physical dynamics develop through the existence of a widespread network of causes and effects' (Pescaroli and Alexander, 2018, p. 2248). In this regard, mechanisms and combinations of hazards in their temporal and spatial domains are often the focus. Gill and Malamud (2014) systematically analysed the interaction of 21 hazards, revealing that geophysical (e.g. landslides and avalanches) and hydrological hazards are most often triggered by other hazards (i.e. they are secondary events), and atmospheric and geophysical hazards (in particular earthquakes and eruptions) are the most common triggers (i.e. primary events). Understanding and modelling these interactions is of great importance for improving forecasting, early warning and emergency management (Pescaroli and Alexander, 2018), but is still hampered by the complexity of the processes (Komendantova et al., 2014).

If there is a clear link between the primary and secondary hazards, this chain is also often referred to as a cascading event. Pescaroli and Alexander (2018), however, argue that cascading events are associated with uncontrolled chain losses involving critical infrastructures. In their view, cascading events can also be the result of cumulative vulnerabilities, not necessarily a chain of different hazards (Pescaroli and Alexander, 2016). If interactions between vulnerabilities are included in the risk analysis, Zschau (2017) calls them multi-risk assessments.

Currently, there is no systematic application of multi-risk assessments in Europe, owing to different methodological approaches and databases and ambiguous terminology (Tilloy et al., 2019; Zschau, 2017). Insufficient cooperation and long-term partnerships between institutions, lack of funding, data or an overarching communication strategy are further challenges (Zschau, 2017). However, recently progress has been achieved regarding the mapping of relevant terminologies (e.g. by the EU project Platform for Climate Adaptation and Risk Reduction, PLACARD), clarifying modelling approaches for different hazard interrelations (Tilloy et al., 2019), the development and assessment of multi-sector/stakeholder partnerships (Aerts and Mysiak, 2016) and the development of guidelines for enhanced (multi-hazard) risk management (Lauta et al., 2018).

BOX 1

Interdependencies and cascading effects: operationalisation in risk assessments for policy guidance

When considering multiple hazards and their interactions it is possible that the total risk estimated can be greater than the sum of their individual parts. This is mainly because risk can emerge from the interconnections that occur at the hazard level where an initial hazard may trigger other events, such as a tsunami triggered by an earthquake, or when several events occur simultaneously such as a bushfire starting during a heatwave. Risk can also emerge from the interactions that occur at the vulnerability level (i.e. a system's vulnerability), where the first hazard event can make the affected system or community more prone to the negative consequences of a second hazard event. Moreover, slow-onset phenomena, such as climate change, act as 'threat multipliers' by exacerbating other hazards (e.g. temperature increase leading to more wildfires), but may also lead to exceeding the adaptive (coping) capacities of a population or system. Therefore, the emergence of complexities and unprecedented threats needs sound principles, innovative thinking, advanced databases, models, methods and simulations to capture the cascading effects of hazards and the interdependencies between drivers of vulnerability. In addition, infrastructure systems are also interdependent, as they use each other's output and operate together to provide joint services to communities (Fu et al., 2014; Hasan et al., 2015). A single hazard event can trigger a cascading failure in these systems (Pescaroli and Alexander, 2016) with cascading impacts on people and societies. Therefore, management strategies for one infrastructure network (e.g. telecommunications, water, gas, electricity or transportation) often rely on the functionality of other networks, so all components should be considered part of an overall 'system of systems' (Helbing, 2013).

An all-hazards and multi-risk approach requires that risk assessments take account of these cascading effects and interdependencies across risk components, sectors, scales and borders (EC, 2017). Modelling approaches for understanding interdependencies, cascading effects and the systemic nature of risk include empirical approaches that use historical failure data and expert judgement (Luiijf et al., 2008), agent-based simulation (Rome et al., 2009), system dynamics (Stergiopoulos et al., 2016) or network-based approaches (Ulieru, 2007). All of these modelling approaches can also be supplemented by expert judgement (EFSA, 2014).

4.3 Space-time dynamics and future risk scenarios

Risk is not static, but rather dynamic in both space and time. Dynamics are a key property of all three components of risk: hazard, exposure and vulnerability.

For example, flooding in a downstream area of a catchment might not only result from heavy rainfall in the catchment area, but can also be exacerbated by deforestation and erosion processes upstream. Capturing these dynamics in hazard models is common practice (e.g. Metin et al., 2018; Merz et al., 2014). Similarly, exposure to hazards can be highly dynamic (Birkmann et al., 2013; Jurgilevich et al., 2017) as people move through space in time or as a result of seasonal hazard variability. While exposure assessments still tend to be quite static in their nature, technological advances in remote sensing and the ever-increasing availability and accessibility of geolocated data (e.g. mobile phone data, Twitter) have led to advances in spatiotemporal exposure assessments from local to pan-European scales. For example, Renner et al. (2017) analysed the changes in population distribution and associated exposure to river floods during a work day and night in the city of Bolzano, Italy, for different months of the year. The ENACT (Spatiotemporal activity and population mapping in Europe) project produced population density grids for Europe considering daily and seasonal variations, and Batista e Silva et al. (2018) also analysed space–time patterns of tourism in the EU at high resolution.

Vulnerability also exhibits a dynamic and non-linear nature (Wisner et al., 2004; Birkmann et al., 2013; IPCC, 2014; Jurgilevich et al., 2017; Ford et al., 2018), for example driven by changes in social, economic, physical or natural capital, and/or as a result of human–environmental interaction. Particularly in rural, natural-resource-dependent settings, where livelihoods rely on ecosystems and their services, a social-ecological systems perspective that also considers the vulnerability of ecosystems and their interlinkages with the vulnerability of the communities depending on them is necessary (Sebesvari et al., 2016; IPCC, 2019). Recent reviews of vulnerability and risk assessments, however, have revealed that, although the number of studies that include dynamics is growing, the focus is still mostly placed on assessing biophysical dynamics linked to hazard and exposure patterns, rather than dynamics in vulnerability (Tonmoy et al., 2014; Jurgilevich et al., 2017; Ford et al., 2018; Hagenlocher et al., 2019; de Sherbinin et al., 2019).

Furthermore, the dynamics of risk are also directly linked to global environmental change (e.g. land use and climate change), development trends and societal transformation (Peduzzi, 2019). This calls for assessments that capture potential changes in risk over time. Future risk scenarios are useful tools to (1) illustrate different potential development pathways and associated risk trends, and (2) help to identify policies and measures to prepare for a range of possible futures (Birkmann et al., 2015). The representative concentration pathways (RCPs) (Moss et al., 2010) and the shared socioeconomic pathways (SSPs) (Kriegler et al., 2012; O'Neill et al., 2014) provide substantial guidance for the assessment of future risks and options for their management (van Ruijven et al., 2013). However, existing future-oriented risk assessments still tend to focus on future hazard and exposure scenarios (e.g. combining urban growth simulations with future hazard trends; Güneralp et al., 2015; Hallegatte et al., 2013; Jongman et al., 2012; Neumann et al., 2015), while scenarios of vulnerability remain an underdeveloped field (Birkmann et al., 2015; Jurgilevich et al., 2017). To date, only a few studies have simulated future vulnerability (e.g. Rohat et al., 2018) and risk scenarios (e.g. Rohat et al., 2019) in Europe based on RCPs and SSPs.

4.4 Uncertainty

Sound decision-making should be based on up-to-date and reliable information on current and possible future risks, including associated probabilities and uncertainties as well as the full range of possible consequences. Information on extreme events and associated uncertainties about their occurrence is especially important when assessing the risk associated with low-probability but potentially high-impact events. In the context of risk assessments, uncertainties can arise from the given variability of the physical environment (random or aleatory uncertainty), as well as from limited knowledge, measurement or modelling capabilities (epistemic uncertainty) (Swart et al., 2009). Uncertainty is inherent in all steps of the risk assessment, from the conceptualisation of risk (conceptual model uncertainty), through the acquisition of data (uncertainty in data), to the actual analysis of risk (expert bias, uncertainty in risk perception, model uncertainty) (Sword-Daniels et al., 2018; Donovan, 2019). Uncertainties should therefore be explicitly considered at each step of the assessment and, together with their impacts on the results, documented and communicated in a transparent manner (Manning et al., 2004). The analysis and expression of uncertainty may be qualitative (e.g. expert-based) or quantitative (i.e. based on statistical models). While assessing and communicating uncertainties associated with hazardous events has become standard practice (e.g. Merz and Thieken, 2009), the analysis of inherent uncertainties in the assessment of vulnerability and risk (e.g. Feizizadeh and Kienberger, 2017) is still an emerging field.

5 Communicating risk information to support disaster risk management

Risk communication is key to link risk perception to risk awareness and any subsequent decision making

Effective communication of knowledge and results generated by risk assessments is crucial for efficient disaster risk management (DRM). All steps of risk assessments should tackle the question of how the findings can be transferred from theory to practice and policy while ensuring that the science is useful, usable and used (Boaz and Hayden, 2002). The communication of risks should go far beyond a unidirectional flow of information. Particularly, it should represent a dialogue-oriented process as a precondition for developing compromises among actors with different values, norms and interests. It may follow different goals, which might focus on aspects such as information exchange, awareness building or legitimisation of decision-making (Renn, 1992; Höppner et al., 2010). Risk communication is strongly connected to risk awareness. Only if policy-makers perceive certain risks will they communicate them, which in turn has a direct influence on their perception among stakeholders and the population (Hagemeier-Klose and Wagner, 2009).

There are a variety of tools for communicating knowledge generated from risk assessments. Hazard, exposure, vulnerability and risk maps, in digital or analogue form, are a core instrument for informing policy-makers, relevant stakeholders and the general public about possible risks. However, map-based risk communication poses various challenges, since it is limited by the amount of information visualised and can being interpreted differently depending on a user's capacity to comprehend its meaning. Therefore, Meyer et al. (2012) recommend creating user-specific maps. In order to be useful in DRM, it is therefore necessary to integrate map-based instruments into a complementary communication strategy (Hagemeier-Klose and Wagner, 2009; Wenk et al., 2018). Such a strategy should, depending on the target group, translate knowledge from risk assessments into activities such as school campaigns, exhibitions, radio programmes, blogs, public consultations and hearings, opinion polls and much more (Höppner et al., 2018; see also Chapter 4 of this report).

6 Conclusions and key messages

Disaster risk management and adaptation to climate change are increasingly prioritised in policy debates. In response there has been a rapid rise in the number of risk assessments at different spatial and temporal scales aiming to inform the identification, prioritisation and (spatial) planning of risk reduction, risk transfer and adaptation options. Evidence shows that the impacts of hazards are not equally distributed within society, and that risk assessments need to consider relevant hazards, exposure and vulnerability as well as the interactions between them. Going beyond the assessment of current risks, future risk scenarios are useful to anticipate and prepare for future challenges. Since risk is accompanied by a degree of uncertainty, special care should be given to evaluating and communicating uncertainties.

Policymakers

Policies tackling issues of land use, settlement or infrastructure planning as well as sustainable development should be risk-informed to reduce future loss and damage. Risk assessments, co-designed with relevant stakeholders (including state and non-state actors), can provide baselines for preventative and adaptive decision-making.

Practitioners

A great variety of risk assessment approaches exists. The participation of a wide range of disciplines and actors, such as scientists from the social and natural sciences, policy-makers, practitioners, the private sector and citizens, is key for the acceptance of the outputs and outcomes. Risk assessments should include the identification and evaluation of possible risk reduction, risk transfer or adaptation options. Outcomes of risk assessments, as well as associated uncertainties, should be communicated in an understandable and actionable manner.

Citizens

Traditional and/or local knowledge is a vital source of information in the process of assessing risk. Participation of citizens in risk assessments, particularly at local level, raises the awareness of the public, and increases the acceptance of the outcomes of risk assessments and associated recommendations of how to reduce existing and prevent future risk.

Scientists

Further research is needed on how to better integrate local/traditional knowledge and intangible factors (e.g. risk perception, values, norms and beliefs) into risk assessments, and how to capture the dynamic and systemic nature of risk in assessments. The analysis of inherent uncertainties in the assessment of risk is an additional area that requires further research.

2.2 Risk management planning

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Sliuzas, R., Jackovics, P., Thorvaldsdóttir, S., Kalinowska, K., Tyrologou, P., Resch, C., Castellari, S., Greiving, S., 'Risk management planning', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Methodological foundations of risk management planning

Effective risk management requires multi-stakeholder, multi-level processes that are built upon continuous cycles of assessment, planning, implementation, evaluation and learning from both the theory and the practices of risk reduction.

This subchapter extends the previous discussion of risk assessment and examines other disaster-related functions and processes, many of which are focused on translating the outcomes of risk assessments into actions that reduce risk and increase resilience. Broadly speaking, we can refer to these actions as disaster risk management planning (DRMP).

1.1 Goals, problems and objectives of risk management planning

DRMP refers to the application of processes developed and adopted by institutions to prepare for, and implement measures to reduce the risk of the impact of, disasters of various kinds. The goal of DRMP is to ensure that societies and their communities are able to enhance their levels of resilience in relation to disasters with which they can reasonably expect to be confronted, within a specified time frame. DRMP aims to develop clear procedures, protocols and capabilities to significantly reduce or eliminate risks through systematic, well-coordinated actions from public, private and civic groups and individuals. However, these aims may not be fully realised in practice.

Problems and objectives can be viewed from a substantive or a procedural perspective, though these are clearly interrelated. Substantive issues revolve around the nature of potential hazardous events that confront a country or region and its population (see for example European Commission, 2017) and the various measures that can be undertaken in response to these hazards. For example, all EU countries have been tasked to prepare national adaptation plans in relation to climate change, including associated hazards (European Commission, 2018).

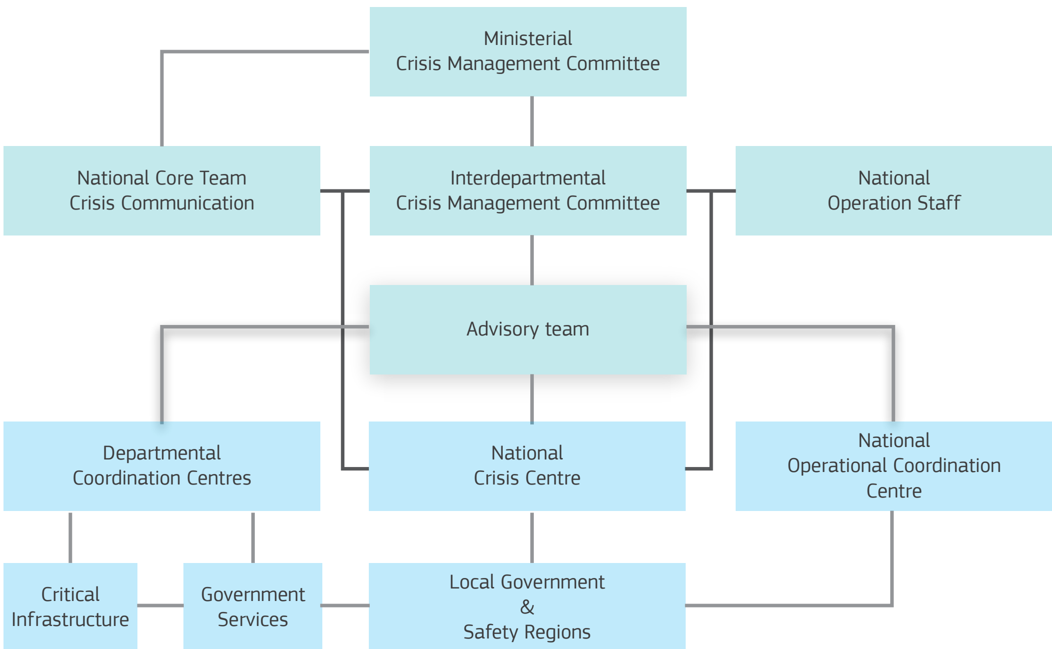
Procedural issues are related to the legal and institutional frameworks that underlie all disaster risk management (DRM) activities: issues such as institutional structure, quality of national vulnerability assessments, knowledge creation (local and national observation systems in relevant sectors and climate modelling), development and implementation of various kinds of action plans, scale and accessibility of funding mechanisms, level of DRM mainstreaming into sectoral policies such as spatial planning and environmental impact assessment, risk insurance policy and mechanisms, quality of transboundary cooperation, various types of monitoring mechanisms in different sectors and governance levels. The availability of reliable and up-to-date risk assessments, together with assessments of risk management capacities, is therefore of paramount importance in DRMP in order to support and protect five vital safety and security interests: territorial, physical, economic, ecological, and social and political stability (Netherlands, Ministry of Security and Justice, 2014).

1.2 Vertical and horizontal integration in disaster risk management planning

The risks confronting European states and communities are highly diverse in nature, intensity, scale and extent. Therefore, DRMP necessarily involves the integration of risk management activities both vertically (i.e. between multiple actors from local to European and even through to global level via various international initiatives, e.g. UN agreements and frameworks) and horizontally (i.e. between actors working at similar levels). These activities are established under the European Civil Protection Mechanism (EU, 2013) and other related legislation (e.g. Directive 2007/60/EC on the assessment and management of flood risks and Directive 2012/18/EU on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC) but also through legislation and agreements at national or subnational levels. DRM activities are especially important at local level, the level where most disaster impacts occur. Moreover, disasters of all sizes will always require a local response of some kind, either independently or in collaboration with higher levels.

Vertical and horizontal integration are key components of policy mainstreaming, which is built upon three main components: comprehensiveness, aggregation and consistency (Rauken et al., 2015). They argue that all local decision-making has a vertical component, as local authority is derived or delegated responsibility from a higher authority. Similarly, much national-level decision-making is related to EU-level directives and policies and therefore needs to be vertically aligned. However, for successful integration it is important to agree from the outset on results that are to be achieved and to recognise that 'collaboration' should not necessarily be the ideal level of integration (Keast et al., 2007).

***Figure 1**. The Netherlands Civil Security System. **Source**: National Coordinator for Security and Counterterrorism, 2013*



Member states have specific structures of organisations engaged in Crisis Management and DRM. The Netherlands civil security system (Figure 1) shows how vertical and horizontal integration in safety and security issues is supported by various public and other bodies (Kuipers and Boin, 2014).

There are specific roles for municipalities and other local-level bodies, 25 safety regions (groups of neighbouring municipalities) and several national bodies. Horizontal integration in DRMP is through departmental crisis coordination centres. DRMP occurs at various levels, and DRM is also integrated into plans in related policy fields. Several national committees and advisory bodies further coordinate DRM policy for coherence. Command, control and coordination are critical functions of this system.

1.3 Collaborative disaster risk management planning and governance

As risk is essentially socially constructed (Gordy, 2016), governance processes are vital to DRMP. Vertical and horizontal integration are required in day-to-day governance processes in non-crisis situations as well as in DRMP. Policies and measures taken by different sectors can contribute to (or hinder) disaster risk reduction (in the environment/water sectors, forestry and agriculture, spatial planning (see Box 1), energy, etc.).

Therefore, coordination between them across different governance levels allows a coherent approach to disaster risk reduction. Risk reduction measures also affect policy fields such as environment or spatial planning, sometimes negatively. Many risk reduction measures (e.g. flood protection levees, water retention basins, firebreaks) have a spatial footprint and/or social, environmental and economic impacts. Various impact assessments and decision support tools can be used to assess these impacts and decide between alternative options (see Section 2.3 below). Integration between policies is therefore crucial in DRMP, and some risk reduction measures may be excluded from consideration because of resistance from other policy fields.

Moreover, the formulation, design and realisation of DRM measures often require a transdisciplinary approach. Just as expert knowledge from many disciplines is required for all-hazards risk assessment, the identification of possible courses of action and decision-making requires many perspectives. Beyond scientists with expertise in specific hazards, and officials from public agencies at multiple levels, DRMP requires inputs from the private sector, non-governmental organisations and citizens. The rationale for such a transdisciplinary approach is twofold.

First, no single group has all of the expertise and resources needed for effective DRM; second, there is often no shared understanding of the risk level. Deliberation and collaboration for planning and management purposes are therefore required. All groups are engaged in DRMP in various ways: in addition to contributing knowledge, skills and resources for DRMP, many may play specific roles in the DRM activities and all are potentially exposed to one or more hazards and therefore potentially at risk.

In the Netherlands, for example, citizens are legally obliged to provide the government with technical safety- and security-related information, while the government will compensate citizens for disaster-induced damage under certain conditions (Kuipers and Boin, 2014). A transdisciplinary approach to DRMP both broadens and deepens the platform for effective DRMP and helps to establish a risk-informed society, though much depends on the levels of trust between stakeholders (see also Section 2.3).

BOX 2

Aligning DRM and spatial planning

Spatial planning takes decisions for society about if and how space is to be used now and in the future. Thus, it may influence hazards, vulnerability and exposure. Spatial planning is relevant to the prevention and preparedness phases of DRM by keeping vulnerable land uses away from endangered areas and/or protecting the building stock against hazard exposure. Hazard and risk maps provided by sectoral organizations (e.g. for water management or geological surveys) inform spatial planners of hazard and risk levels. Such information should be regularly revised, as hazards and risks are often highly dynamic. However, this strategy is not always fully applied and applicable (e.g. in countries where the law or 'rational'plans do not fit the urbanisation reality of population agglomeration and rapid development). Unfortunately, spatial planning may also contribute to risk, as hazard zones may attract low-income households to cheap, hazard-prone land. Consequently, retreat from hazard-prone areas and upgrading of specifically susceptible structures located in these areas become globally more and more important (Greiving et al., 2018).

The Sendai Framework's Priority 4 ('Build back better') underlines the importance of spatial planning in the recovery phase: 'to develop capacities that reduce disaster risk … including through the development of measures such as land-use planning..' (UNISDR 2015, pp21-22). In addition, the New Urban Agenda (United Nations, 2017, p21) advocates 'strengthening the resilience of cities and human settlements, including through the development of quality infrastructure and spatial planning …, especially in risk-prone areas of formal and informal settlements … including the rehabilitation and upgrading of slums and informal settlements'.

1.4 Adaptation and transformation

To reduce risk, business as usual will not suffice. Effective DRMP is based upon continual adaptation and transformation to current and foreseen risks. Through transdisciplinary research activities involving scientists, public and private bodies and citizens, the knowledge and understanding of dynamic risk landscapes has steadily improved. DRMP considers changes in all dimensions of risk: hazard, exposure, vulnerability and adaptive capacity; in particular, how human action can be directed to each of these through combinations of hard, green and soft measures. For greater effectiveness, these combine knowledge and practices of engineering with those of nature-based solutions and human behaviour. Adaptation measures must be based on what is technically, socially, environmentally and financially feasible if they are to be mainstreamed in policy and practice at various levels (Wamsler and Brink, 2014). One recent study in Malta (Appleby-Arnold et al., 2018) showed how personal characteristics and culture (e.g. life attitude, resourcefulness, family and cultural ties) are important in adaptation and transformation for DRM. Such studies are at the core of the Carsimand([1]) project (Culture and Risk Management in Man-Made and Natural Disasters) and provide important insights for a diverse continent such as Europe. Reckien et al. (2018) reviewed local climate plans of 885 cities of various sizes from across the EU-28. This study showed the diversity of activity in climate action planning across the EU, with central and northern EU cities being more advanced, smaller cities lagging behind larger cities, and mitigation planning more common than adaptation planning. Even so, the general picture is that local climate action has increased since 2014. Recently, ecosystem-based approaches for climate change adaptation (CCA) and DRR have been applied more often in order to reduce risk to hazards and to preserve ecosystems in urban contexts (see Subchapter 3.5). On the other hand, a hybrid approach (combining blue, green and grey approaches) is emerging as the most effective strategy at urban level (Kabisch et al., 2017).

([1]) *http://www.carismand.eu*

2 Generation and analysis of alternatives

As uncertainty is omnipresent in risk assessments, risk management planning must prepare for constellations of hazards and responses, using scenarios that support training and learning.

2.1 Key impact indicators

Different types of indicators are used in various functions of DRMP. When considering alternative scenarios and associated DRM measures, a standard set of key impact indicators is valuable. These can be for both direct and indirect impacts and be quantitative or qualitative in nature. The Netherlands national safety and security strategy (Minister of Security and Justice, 2014) is based on scenarios and a set of indicators for five vital interests (Table 1). Every scenario is evaluated in terms of two risk components: impact of consequences and likelihood of the event occurring (from highly unlikely to highly likely) within the next 5 years. An outcome score that ranges from limited to catastrophic is generated, along with assessments of uncertainty. This is used to identify gaps in capabilities (see Section 3.4) that need to be addressed through new investments or changes in procedures.

***Table 1.**. Examples of impact indicators for vital safety or security interests in the Netherlands*
***Source**: adapted from Ministry of Security and Justice of the Netherlands, 2014.*

	VITAL SAFETY OR SECURITY INTEREST	IMPACT CRITERIA AND INDICATOR
1	Territorial	Encroachment on the national territory
		Infringement of the international position of the nation
2	Physical	Fatalities
		Seriously injured and chronically ill
		Physical suffering (lack of basic life necessities)
		Loss and damage to buildings and infrastructures
3	Economic	Costs of impairment of the economy
4	Ecological	Long-term effects on the environment and nature, including flora and fauna
5	Social and political	Disruption of everyday life
		Damage to the democratic legal order
		Social psychological impact and social unrest

2.2 Risk levels as thresholds for development options

Risk assessment requires a broad understanding of the relevant losses and harms, and their consequences for interested or affected parties, and it must be targeted to determine the acceptability of a given risk to diverse groups or individuals within any society. Risk acceptability and tolerance depend on the existing social, economic, political, cultural, technical and environmental conditions present at societal and individual levels at a given time. Nevertheless, acceptable risk levels are usually defined, on the basis of a scientific risk assessment, by a normative judgement of governmental institutions or politicians that are democratically legitimised, rather than by the people affected (Peters-Guarin and Greiving, 2013). In this context, some countries define individual risk levels for different land use classes in accordance to their susceptibility and partly also their systemic criticality. This is particularly relevant for those infrastructures disruption of whose services may lead to cascading effects elsewhere, such as electricity and water supplies, transport and telecommunication (Greiving et al., 2016; European Commission, 2017).

2.3 Scenario-based planning, impact assessments and uncertainty

Scenario modelling is increasingly used to understand and manage possible future situations with relatively high levels of uncertainty, including disasters (Riddell et al., 2018). DRMP scenarios are combinations of possible future hazardous events with possible future development situations, both of which embody uncertainty. These are used to test and evaluate DRMP performance and the effectiveness of alternative policies and measures in terms of their contribution to risk reduction, all of which are deeply uncertain (Kwakkel, 2017). Scenarios are evidence based, but formulated by stakeholders to address situations that are considered to be significant from a policy perspective at any given time. In the Netherlands, for example, the network of analysts for national safety and security, composed of experts with diverse backgrounds, prepares and executes risk scenarios annually, considering issues such as the time horizon, the level of threat, its location and its geographical extent (Netherlands, Ministry of Security and Justice, 2014). The scenario outcomes are inputs for investment decisions to address capacity shortfalls. Scenario-based DRMP tools are developed and used in several EU projects (e.g. Crossing New Frontiers in Disaster Preparedness([2]), European Disasters in Urban Centers: a Culture Expert Network([3]), and the European Network of CBRN Training Centres([4])).

In addition, impact assessment frameworks and decision support tools are used in DRMP. A strategic environmental assessment (SEA) can be applied to general or sector-specific DRM plans or strategies to assess their effects. At the European level, the SEA Directive (2001/42/EC) requires the identification, description and evaluation of 'reasonable alternative' (Article 5(1)), but this is rarely done in planning practice. An environmental impact assessment (EIA) can be made for different projects or structural measures (e.g. flood protection levees) contained in the DRM plans, or developed independently.

A cost–benefit analysis (CBA) is an important tool used for decision-making (e.g. during planning), as it helps to understand the trade-off between different options over time (European Commission, 2014). However, CBA often only allows a monetary assessment. For DRM and CCA, cost-effectiveness analyses or multi-criteria analyses may be preferred, especially where different social and environmental values are to be protected but cannot be translated into monetary terms (e.g. the protection of life).

([2]) https://www.in-prep.eu
([3]) http://educenhandbook.eu/
([4]) https://www.h2020-enotice.eu/?redirect=0

The uncertainties about future climate change impacts require a parallel modelling approach (IPCC, 2014) combined with representative concentration pathways (van Vuuren et al., 2011). A similar approach stressing detailed land uses was used to assess local and regional climate impacts (van Ruijven et al., 2014; Greiving et al., 2015). Demographic and socioeconomic changes are projected in parallel to the changes of the climatic system in order to assess the future impact of climate change on future society. Rohat et al. (2019) combined climate and socioeconomic scenarios to assess future heat stress risk in Europe and concluded that changes in vulnerability play a major role in shaping this specific future risk. Parallel modelling is also relevant at the regional and local levels, to derive tailor-made adaptation strategies (van Ruijven et al., 2014; Birkmann and Mechler, 2015)

At the European level, the recent EIA Directive (2014/52/EU) addresses more areas such as resource efficiency, climate change and disaster prevention. It underlines the need for a parallel modelling approach by stating: 'Climate change will continue to cause damage to the environment and compromise economic development. In this regard, it is appropriate to assess the impact of projects on climate (for example greenhouse gas emissions) and their vulnerability to climate change' (EU, 2014, art. 13). Therefore, an evolving baseline trend for both climate and societal indicators has to be considered when assessing the environmental effects of a plan or project (European Commission, 2013c).

3. Policy instruments and products for disaster risk management planning

Adopting a risk-informed planning approach can assist nations and their communities to increase their disaster resilience by reducing risk and being better prepared for response and recovery processes should a disaster occur.

This section provides a non-exhaustive overview of several policy instruments and products in various DRMP functional areas (Tagarev, et al., 2017) as a means to illustrate some of the variety of approaches that are required. Capacity development functions are critical for all such instruments and products. Sound analysis of the necessary resources and capabilities to respond to current and expected risks is required (ISO, 2009).

Capacity development builds the additional capacities to mitigate or reduce the occurrence probability of risks. Activities are geared towards building the capacities and resources that should be further developed or expanded to reduce the risk or to work more effectively against the impacts of the risks (Jackovics, 2016). Important elements include, but are not limited to, elaborating the list of potentially developable capacities (European Commission, 2010); distinguishing between the capacities that specifically refer to a particular event type and those that are of general interest in a variety of event types (Netherlands, Ministry of Security and Justice, 2014); and selecting and ranking the capacities to be developed for multiple types of risk (European Commission, 2012, 2013a,b). EU Member States will be required to deliver capability assessment reports by the end of 2020. The examples below serve to briefly illustrate several specific measures for reducing risk and increasing resilience. More detailed descriptions of such instruments can also be found in the later chapters and cases studies in this report.

3.1 Early warning systems

An early warning system (EWS) is an instrumental system providing a warning about a forthcoming or ongoing hazardous event. For example, a meteorological agency may issue an extreme rainfall early warning. EWSs are also operational for volcanic activity, earthquakes and tsunamis, among other hazards. An EWS consists of upstream and downstream components: the former incorporates the system's tools and procedures for the creation of the early warning message by a monitoring or operational centre, while the latter is dedicated to the dissemination of the early warning message. Despite the advances in technology, communication and partnerships at international, national, regional and local levels are considered crucial for EWSs (Marchezini et al., 2018). Emergency plans and public education and training should be an integral part of the downstream component of EWSs.

An alternative categorisation of EWSs is based upon the approach used, i.e. a top-down 'last mile' approach that is hazard-centred and a bottom-up 'first mile' approach that is people-centred (Basher, 2006; Thomalla and Larsen, 2010; Garcia and Fearnley, 2012; Villagrán de Leon, 2012; Kelman and Glantz, 2014; Marchezini et al., 2018). A last-mile EWS has often proven insufficient. For example, Pakistan's national multi-hazard EWS plan distributed 90 % of its budget to monitoring and warning services, leaving little for the response by the vulnerable and exposed population (Mustafa et al., 2015). In practice, the problem lies with the capability to make EWSs effective at societal level.

At global scale there are four regional tsunami EWSs (one for the Pacific Ocean est. mid-1960s; and three created after the Indian Ocean tsunami of 2004 for the Indian Ocean, for the Caribbean Sea and the North-East Atlantic, and for the Mediterranean and connected seas), which are based on collaborating national monitoring centres operating under the coordination of intergovernmental bodies in the framework of Unesco. The distinction between far-field and near-field tsunamis is critical. In far-field conditions there is enough time for effective response, as the travel time of the tsunami is in the order of hours. However, in the Mediterranean Sea, tsunami travel times range from about 10 minutes to 2 hours (Papadopoulos, 2015). Thus, the time for effective warning, dissemination and response is extremely limited. This makes the North East Atlantic and Mediterranean Tsunami Warning System project very challenging. Forty Unesco Member States participate in this system, based in five national centres operating on a 24/7 basis. The upstream component functions with a warning time of around 10 minutes. The downstream component is still under preparation, as central and local civil protection authorities are investigating how to rapidly warn target groups.

Earthquake EWSs in Japan have been effective at local and national levels for several years (Japan Meteorological Agency, n.d.). Less advanced EWSs are found in other seismogenic countries such as Mexico (Allen et al., 2018) and Taiwan (Wu et al., 2015). In Europe, progress has been made in the regions of Irpinia, Italy, and Bucharest, Romania; however, here too, the downstream component is incomplete (Clinton et al., 2016).

Researchers recognise the need to co-produce knowledge through 'citizen science' programmes (Aitsi-Selmi, 2016) that engage the public in data collection, data analysis, information sharing and knowledge co-production (Teschenhausen, 2015). These include different forms of participation and models of cooperation, from contribution through collaboration to co-creation (Bonney et al., 2009). Near the Tungurahua volcano in Ecuador, a network of 35 community volunteers has assisted volcanologists in early warning, evacuation and community-based monitoring, directly contributing to risk reduction (Stone et al., 2014). Volunteers provide critical local knowledge to experts and have also initiated evacuations independently. The network's sustainability is built upon mutual trust. Regular periods of heightened volcanic activity serve to maintain community commitment.

Several European projects (ESPREssO([5]), beAWARE([6]), Reaching Out([7]), ResiStand([8])), contribute to the developing and testing of various types of EWSs. In addition, the World Meteorological Organization is collaborating with national meteorological organisations to provide the European Emergency Response Coordination Centre with accurate and authoritative information on natural hazards by designing a flexible multi-hazard scalable EWS for comprehensive 24/7 reporting of crisis information supported by an expert panel. Such efforts strengthen both top-down and bottom-up EWS capabilities (Aristotle-European Natural Hazard Scientific Partnership([9]).

3.2. Spatial plans

Spatial planning defines areas that are suitable for specific types of development. Spatial plans may keep hazard-prone areas free of further development or contain regulations on protecting the buildings, activities and populations against the impacts of hazards by defining minimum elevation heights or requirements on the groundwork of buildings, or other structural measures. Buffer zones are often used to mitigate hazardous effects (flood zones, protective forests, retention ponds, etc.). For some critical infrastructures, fast-track approval procedures may be applied. Even then, proposals that require a change of function or some sort of construction will require public scrutiny and debate. Ultimately, even DRR-related infrastructures could meet with high levels of resistance from some citizens or societal groups and lead to lengthy and costly legal procedures and consequent delays (Warner and van Buuren, 2011). Mainstreaming DRR concerns in spatial planning processes and vice versa provides a means to align the policies between these two fields for greater effect in DRR (Wamsler and Brink, 2014).

3.3 Civil Protection exercises and exchanges of experts

Joint exercises between countries are a useful tool to form and maintain partnerships in the area of disaster preparedness. The UCPM funds a number of civil protection exercises at the European level every year; involving several countries enhances cross-border cooperation in disaster preparedness. Events can be full-scale exercises, modules or field exercises for testing specific response capacities (EU MODEX([10])), or table-top exercises focused on in-depth training of key personnel. In October 2018, a flagship full-scale exercise took place in Romania, simulating a magnitude 7.5 earthquake hitting Bucharest and causing widespread damage to infrastructure, with a large number of wounded. The simulation mobilised over 1000 people, involved medical teams from Germany, Italy, Romania, Austria, Slovakia, Sweden, Norway and Israel, and experts from other states participating in the UCPM. In parallel, the UCPM facilitates an exchange of experts between countries ([11]) to foster sharing of knowledge and experience on all aspects of emergency management. A similar approach may also be adopted at national levels, such as in the United Kingdom (United Kingdom, Cabinet Office, 2014).

3.4 Dynamic adaptation policy pathways

Various decision support methods can help in making robust decisions under the uncertainty that climate change creates. Dynamic adaptive policy pathways (DAPP) have been used to manage uncertainties in large infrastructure projects for climate change adaptation, e.g. the Thames Barrier in London (United Kingdom, Environment Agency, 2020) and the Delta programme of the Netherlands ([12]) (Haasnoot et al., 2013). The Collaborative Risk Informed Decision Analysis (CRIDA) tool was developed based on DAPP to support robust decision-making for water resource management in particular (Mendoza et al., 2018). However, both DAPP and CRIDA have high costs in terms of

([5]) *www.espressoproject.eu*
([6]) *https://beaware-project.eu*
([7]) *https://reout.eu*
([8]) *www.resistand.eu*
([9]) *http://aristotle.ingv.it/tiki-index.php*
([10]) *www.eu-modex.eu/Red/*
([11]) *www.exchangeofexperts.eu/*
([12]) *https://english.deltacommissaris.nl/delta-programme*

knowledge, time and data-processing requirements. Carstens et al. (2019) provide a case study of a modified DAPP approach for smaller spatial planning projects at the municievel, where less financial and human resources are usually available, in the Swedish municipalities of Danderyds, Gävle and Söderhamn.

4. Engaging stakeholders in disaster risk management planning

Effective risk management planning requires a transdisciplinary approach.

The collaborative, transformative and transdisciplinary character of DRMP is crucial. Transformative adaptation, which complements coping and incremental adaptation, is a new challenge for governance, as it may imply fundamental shifts in power and representation of interests and values. For example, the IPCC (2014, p. 76) argues that 'adaptive responses to a changing climate require actions that range from incremental changes to more fundamental, transformational changes'. In some locations, such as coastal zones threatened by sea level rise and storm surges, river valleys prone to floods or mountain valleys affected by alpine hazards, 'responses could also require transformational changes such as managed retreat' (IPCC, 2014, p. 97), which could be financed by EU structural funds.

A particular need that must be met for adaptation at all spatial scales is the establishment of broad stakeholder involvement (Knieling and Leal Filho, 2013). Stakeholders are individuals, groups or organisations that may affect, be affected by or perceive themselves to be affected by a decision, activity or outcome of a project, programme or portfolio in which disaster risk is a core concern. Stakeholder engagement is indispensable for the acceptability, but also the applicability, of adaptation measures that are widely targeted to civil society (e.g. adaptation of buildings or agricultural activities). Moreover, political decisions based on uncertain knowledge need a broad mandate from all social groups (Greiving and Fleischhauer, 2012; Fleischhauer et al., 2012; Walker et al., 2014). Directly affected stakeholders should be involved throughout the DRMP process, including implementation of the adaptation measures. This is particularly important for adaptation measures that should be mainstreamed in regional and urban development (Kern and Bulkeley, 2009; EEA, 2013).

For example, regional and urban development agencies should play an important role in climate change adaptation because of its integrative, cross-sectoral character. As disasters occur in specific places and might cause conflicts with land use and regional development, there is a need to find territorially relevant answers to the challenges such conflicts entail. At the same time, spatial planning offers a variety of approaches to reduce the negative impacts of disasters (Greiving and Fleischhauer, 2012). DRM and CCA call for a cross-sectoral approach because of the variety of sectoral impacts and the interdependencies between impacts and response strategies. Mickwitz et al. (2009) also argued for a prominent role for comprehensive spatial planning in this regard. Non-adapted urban development with economic growth and urbanisation of landscapes that are exposed to climate hazards, such as floods or droughts, may increase risk for populations and infrastructures and reduce the resilience of natural systems.

CCA, DRM and sustainable development are all intertwined, as adaptive capacity building contributes to the well-being of both social and ecological systems globally. According to the IPCC (2014, p. 94), 'Effective implementation [of adaptation and mitigation options] depends on policies and cooperation at all scales and can be enhanced through integrated responses that link adaptation with other societal objectives'. Other socioeconomic trends (e.g. demographic or land use changes) are interrelated with climate change, and also determine adaptive capacity. That is why regional and urban development agencies are asked to base judgements on adaptation on a parallel modelling approach of climatic and socioeconomic trends, as explained in more detail in Section 1.6.

5 Conclusions and key messages

Effective DRMP requires well-conceived and coordinated strategies and actions between a diverse range of actors, including citizens, at multiple levels and integrating a large number of disciplines in order to ensure that adequate capacity and capability exists to execute major crisis management functions (Tagarev et al., 2017) in a competent and efficient manner.

Policymakers

Policymakers need to create enabling frameworks and institutions that support the development of effective DRMP, built upon well-conceived capabilities and functions that are supported by vertical and horizontal integration and coordination across all sectors as well as public, private and civic stakeholders. Their efforts can be guided by the taxonomy of DRM functions.

Practitioners

DRM practitioners are required in all sectors and levels of society and are crucial for effective DRM operations, and they act as focal points for the complex vertical and horizontal integration and coordination activities that are required for effective DRM.

Scientists

Multidisciplinary scientific research contributes to developing and strengthening all DRM functions throughout the entire DRM cycle. A diverse range of scientists enrich society's understanding of how risk is generated and strengthen risk management practices by driving methodological development and learning to inform DRM capability development.

Citizens

Effective DRM requires strong engagement with citizens. Citizens have various roles in DRM, from relatively passive to very active, depending upon their capabilities and capacities and the specific nature of a disaster. As they are the most numerous and diverse of all actors, there are many challenges to engaging them effectively in DRM. Clear communication and targeted capacity development can ensure an optimal contribution to DRM processes.

The investments that have been made through projects under Horizon 2020 and its predecessor programmes have substantially strengthened Europe's DRMP capabilities, enabling communities and Member States to build more effective adaptation and transformation processes in response to a dynamic risk landscape.

2.3 Implementing risk management measures

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Ishiwatari, M., Gallego, E., Wood, M., Cumiskey, L., Pulwarty, R.S., Meerpoel, M., Goretti, A., 'Implementing risk management measures', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Introduction

The application of methods, tools and evidence from science and technology is fundamental to successfully anticipating and managing risk. The Sendai Framework for Disaster Risk Reduction (SFDRR) (UNISDR, 2015) recognises the importance of science and technology in its priority actions of implementing risk management measures (Calkins, 2015; Aitsi-Selmi et al., 2016; Shaw et al., 2016; Trogrlić et al., 2017). The SFDRR, which the UN General Assembly endorsed, charted the global course over the next 15 years from 2015 until 2030. The European Commission (2016a) published Action Plan on the Sendai Framework for Disaster Risk Reduction 2015–2030: A disaster risk-informed approach for all EU policies in 2016. This 5-year action plan aims to guide the implementation of the SFDRR and to provide for a more systematic disaster-risk-informed approach in EU policymaking. The research community, engaging with the policy community, is expected to enhance the science–policy interface in policymaking. This subchapter describes how the role of science has evolved and scientists can support the implementation of risk management measures. Risk management mechanisms are evolving from top-down to networking approaches in Europe. Scientific knowledge can produce implementable solutions through engagement with stakeholders in addition to providing evidence-based information for decision-makers and government organisations (Scolobig et al., 2015). .

2 Governance - Sharing knowledge, risks and responsibility among stakeholders

Governance arrangements engaging relevant stakeholders need to be in place to efficiently implement risk management measures.

Risk governance is moving towards an approach by which stakeholders share responsibilities for decisions and for implementing risk management measures (UNDP, 2015). These stakeholders include governments at all levels, businesses, industries, communities and individuals, as well as civil society organisations. Governments have the primary role in reducing disaster risk, but government organisations alone cannot efficiently implement risk management measures (Tierney, 2012; Alexander et al., 2016, 2019; Rouillard and Spray, 2017; Tullos, 2018; Ishiwatari, 2019a). The SFDRR stresses the concept of disaster risk governance that requires all stakeholders to be engaged in the implementation of risk management strategies (UNISDR, 2015). Collaboration would be more effective if there were a systematic exchange of information and results from different disaster risk management processes. This needs to be triggered by regulation, standards and recommendations. Society in Europe has strengthened governance arrangements as shown in Figure 1. Local communities, civil society organisations, the private sector and volunteers have increasingly been engaged in managing disaster risks as well. Disaster risk governance has developed by focusing on natural and technological hazards, but arrangements can contribute to responding to public health emergencies, such as the COVID-19 pandemic (Djalante et al., 2020; UNDRR, 2020).

2.1 Government sector

a. Regional level

Improved collaboration is needed among actors across multiple sectors, to deliver integrated outcomes for risk management, strategically, operationally and in day-to-day actions. EU policy has made considerable progress in coordination of response to crises and has made initial steps towards fostering a multi-hazard approach across the risk management cycle. ARGUS, a rapid alert system, collects crisis information from various early warning systems within the Commission services to coordinate its response (Boin et al., 2014). The EU Civil Protection Mechanism pools responsecapacities from 34 participating states and can be deployed inside the EU and around the world. The Emergency Response Coordination Centre (ERCC) is the operational heart of this mechanism and it monitors and coordinates response to disasters. For example, the ERCC coordinated the deployment of firefighting aeroplanes, helicopters, ground vehicles and personnel from different countries at the big forest fires of 2017 in Portugal, and of 2018 in Greece and Sweden, the last one being the single biggest forest fire operation since the ERCC's creation. The EU upgraded the EU Civil Protection Mechanism in 2019. rescEU, which is a European reserve of capacities, expands in response to various threats such as medical emergencies or chemical, biological, radiological and nuclear (CBRN) incidents.

Figure 1. *Selected practices of governance arrangements.* ***Source****: Authors.*

World

- Sendai Framework for Disaster Risk Reduction

Regional

- **Directives.** Water Framework Directive, Flood Directive, Seveso Directive
- **Response.** ARGUS: rapid alert system, Civil Protection Mechanism, Emergency Response Coordination Centre, Copernicus Emergency Management Service
- **State cooperation.** Albufeira Convention between Spain and Portugal
- **Knowledge centres.** EU chemical, biological, radiological and nuclear centres of excellence, Disaster Risk Management Knowledge Centre
- **Action plan.** Action plan on SFDRR

State

- **Policy.** Room for River (Netherlands), strategic national framework on community resilience (UK)

Local

- Twinning arrangement (Italy)

Community

- Flood action groups, flood wardens (UK)

It is expected that initiatives such as the EU's Disaster Risk Management Knowledge Centre (DRMKC) will help the EU to move in future towards a multi-hazard approach across all stages of the risk management cycle. The DRMKC aims to serve as a central network of scientists, policymakers and practitioners where innovation, new knowledge and good practice can be exchanged. Its aim is to provide a rich forum where experts in these domains, associated with management of one or more types of natural or technological disasters, can learn from each other's work and experience.

The cooperation in southern Europe provides a good practice of collaborative drought management. The region has been historically highly vulnerable to droughts largely because of semi-arid climatic characteristics and intensifying water use, and is projected to be one of the regions in Europe most affected by climate change. While Portugal and Spain share five major rivers, more than three quarters of the total existing storage capacity of the shared river basins is located in Spain. The EU Water Framework Directive (WFD) (EU, 2000) set a new perspective for European water policy and management, advocating a river-basin-level approach, including the development of drought plans and river basin management plans to protect water bodies (Maia, 2008). The Convention on Cooperation for Portuguese–Spanish River Basins Protection and Sustainable Use, usually referred to as the Albufeira Convention, was framed under the WFD principles and was the first to address all the shared rivers, at river basin scales. Both countries are implementing drought management of the shared basins as follows (Pulwarty and Maia, 2015; Maia and Serranos, 2017):

- drought monitoring and early warning systems to predict drought occurrence,
- promotion of standard and common approaches in drought management,
- development of a sound common indicators system across drought types.

b. State and local levels

Each state has developed risk management systems according to its national context and historical experiences. Administrative responsibilities, legal frameworks and operational practices of civil protection differ by country. For example, federal countries take decentralised and local bottom-up approaches, while former communist countries tend to take more a centralised approach (Kuipers et al., 2015). Most countries have created the leading agencies responsible for crisis management at the national level, but agencies' roles vary per country. These roles include coordinator, supervisor, platform and service provider (Ishiwatari, 2013).

Some countries have developed new policies and strategies of risk management that aim to engage various stakeholders in implementing risk management measures. Germany revised flood risk management following serious floods in 2002 to cover (1) retention of floodwater, (2) adapted use of flood-prone areas and (3) response and recovery (Thieken et al., 2015). The United Kingdom is promoting the strategic national framework on community resilience and the Making Space for Water programme. The Netherlands is taking the approach of 'Room for River' to adapt to climate change. Furthermore, the EU Flood Directive (2007/60/EC; EU, 2007) aims for the active involvement of interested parties in the setting up of flood risk management plans.
Working in partnership is needed to effectively implement specific risk management measures, e.g. flood defences or early warning systems.

Figure 2. *Enschede fireworks disaster.* ***Source****: Bartflikweert, 2000.*

It is even more important for the effective implementation of cross-cutting measures and resilient housing development that can offer synergies and manage conflicts across multiple interests such as transport, environment, housing, economic growth (Hori et al., 2017; Cumiskey et al., 2019). It is also important that a wider range of sectors and ministries manage the risks specific to their systems and engage with each other to reach a mutual understanding of the risks and measures needed to address them with their recognised interdependencies. Reaching this level of collaboration in practice comes with its own set of challenges (Ishiwatari, 2016). Mechanisms that enable stronger communication and knowledge exchange between actors are needed, such as individual coordinators or 'boundary spanners' (Williams, 2002), and multi-stakeholder partnerships (Djalante, 2012). Funding cycles, timelines and bidding processes can vary from one government sector to another such that innovative funding mechanisms are needed that encourage and enable alignment and joint investment between different public-sector agencies.

At the local level, a twinning arrangement between local governments can function to provide expert support of recovery and emergency work. The twinning arrangement can avoid an overlap of support by clarifying responsibilities, achieve speed and continuity of support, and enhance accountability (Ranghieri and Ishiwatari, 2014). For example, following the 2002 Molise-Puglia earthquake in Italy, each region throughout the country was assigned to support one of the affected municipalities. Experts coming from outside the area assisted the local governments in conducting response and recovery activities, such as the provision of emergency shelters and building inspections (Goretti and Di Pasquale, 2009). This twinning approach was also applied to recovery programmes following the east Japan earthquake and tsunami of 2011 and the Wenchuan earthquake in China, 2008.

c. Knowledge management

Knowledge, expertise and good practice should be shared across government authorities nationally as well as regionally. Technological risk has led to the use of multidisciplinary public–private partnerships for managing the associated risk because understanding and managing the impacts of a technological disaster can involve diverse expertise, from engineering and economics through health and the environment to safety and security. EU competent authorities overseeing nuclear and chemical risks have exchanged knowledge and experience at the EU level for up to 30 years through joint research and working groups to improve risk management policy and implementation (European Commission, 2014; Wood, 2017).

Management of these risks requires a bottom-up approach, as decisions need to be sensitive to the cultural, social and economic perspectives of local communities. To illustrate, exchanges at the EU-level working group of Seveso inspectors provide information directly from the field on emerging risks that often trigger research and development of new tools and standards of practice. The substantial work on identification and management of risks associated with ageing hazardous sites (e.g. Wood et al., 2013; OECD, 2017) is one of many examples of how bottom-up approaches stimulate innovation.

In this spirit, the EU's CBRN centres of excellence support strengthening institutional capacity to manage these complex risks through regional networks of expertise (Goulart et al., 2018). Current security threats have a global, multidimensional and cross-border nature; therefore, CBRN risks cannot be dealt with by a single country operating in isolation. Areas of concern for the EU and its partner countries include disease surveillance, waste management, emergency planning, early warning, civil protection, export controls on dual-use goods and the cross-border trafficking of CBRN materials.

Participating countries work bottom-up to identify risks, assess gaps and needs, draw up national CBRN action plans and collectively agree on activities or projects to be taken forward at regional level. The projects often focus on building awareness and capacity in relation to preparedness, mitigation and response, and on identifying future needs in regard to strengthening legal frameworks and prevention. For example, the MediLabSecure project (Gaayeb et al., 2016) encompasses 55 virology and entomology laboratories in 22 non-EU countries and aims to enhance the preparedness for and response to the threat of emerging viral diseases in the Mediterranean and Black Sea regions.

BOX 1

Risk assessment and land-use planning of EU Seveso sites

The EU Seveso Directive (2012/18/EU; EU, 2012) requires that the Member States take account of chemical accident risk in their land-use-planning policies, with particular attention to siting of new hazardous facilities and building extensions of existing sites, as well as development of communities and community infrastructure around hazardous sites. Given the numerous possible inputs and the diversity of risk assessment and land use protocols, the outcome of the land-use-planning process for the same type of site can differ considerably from one country to the next. Much of this variation is difficult to avoid. It has long been acknowledged that risk methods and land-use-planning processes are embedded in local culture and pre-existing legal systems. However, technical aspects associated with the consequence analysis, in particular the selection of scenarios and scenario attributes, are not subject to this constraint and yet they can be distinctly different from country to country.

Governments and industry recognised an opportunity to work together to develop common accepted practices for determining which scenarios should be taken into account in the land-use-planning process. For several years a group of industry and competent authority experts organised by the European Commission Joint Research Centre's Major Accident Hazard Bureau worked together to build consensus around a selection of common reference scenarios, published in 2017 as the Handbook of scenarios for assessing major chemical accident risks (Gyenes et al., 2017). This reference handbook enables all authorities to consider the full range of possible outcomes when assessing risks associated with a major hazard site. Although it does not in any way ensure that authorities will arrive at similar risk figures or planning decisions, it gives a common framework in which the rules of science and logic can be applied. The use of common reference scenarios can, in particular, give citizens more confidence that authorities are ensuring that all necessary measures are being taken to reduce the impacts from serious chemical accidents.

2.2 Private sector

At national level, risk management for environmental risk is often a shared responsibility between government and industry. In most western countries, a substantial part of the environmental risk is directly or indirectly controlled by private hands. A good example is the Spanish protocol for radiological surveillance of metal recycling (Cadierno et al., 2006), which is effectively contributing to reducing the radiological risk in the metal recycling industry and to mitigating the consequences of possible incidents in this industrial sector. The frontline responsibility for control of a major chemical hazard lies with the owners and operators of the production or services that are involved in the processing and handling of dangerous substances. The EU Seveso Directive allocates responsibilities for controlling chemical hazard risks to both industry and government, fostering regular exchange between the two parties on risk reduction (see Box 1).

Experience also shows the importance of achieving an appropriate balance of responsibility and control between public- and private-sector actors. There are many disasters for which governments were faulted for failure to provide adequate oversight of risk management in the private sector, such as the West Fertilizer explosion and fire, USA, 2013 (US Chemical Safety Board, 2013) and the Enschede fireworks disaster, Netherlands, 2000 (Figure

2; French Sustainable Development Ministry, 2009). Some experts also argue that an overabundance of prescriptive regulations can be an obstacle to risk management in the private sector, as noted by Hale et al. (2015) in relation to occupational safety. Industry has also contributed to disasters when risk management is subordinate to other priorities, a failure attributed to BP in several disasters occurring between 2005 and 2010 (Bratspies, 2011).

2.3 Civil society organisations, community

Local communities are an important component of any DRR strategy when empowered with knowledge to understand the hazard and the risk on their doorsteps and with the ability to act to defend community interests. Community participation allows those most affected by the risk to explore and share their vulnerabilities and priorities, enabling risks to be better defined and appropriate interventions to be designed and implemented (Twigg et al., 2015; Das et al., 2020). Many sources recommend that such community involvement begin at the very start of the risk management cycle, that is, involving communities with hazard identification and risk assessment, continuing on to prevention and preparedness, and finally response and recovery (Ishiwatari, 2012).

Community insights can provide important input to DRR strategies. By extension, civil organisations and charities, as well as groups that advocate and give voice to communities (e.g. women leaders, impoverished communities, homeless populations, the elderly, people with disabilities), are also valuable stakeholders and have a perspective on the risks as well as a role to play in managing them (Tanaka et al., 2018). Moreover, as noted by United Nations Development Programme (UNDP, 2004), locally specific data can also help to refine policy at regional and national levels. To participate effectively, communities also need expert advice on understanding the risks and what can be done about them (see Subchapter 2.1). Risk communication contributes to strengthening capacities at the levels of individuals, communities and organisations concerned (see Chapter 4). Since communication serves multiple purposes and functions throughout the risk management cycle, the style of communication should match the needs of stakeholders (Höppner et al., 2012).

A remarkable case is the implementation of flood risk management, in which citizens are increasingly participating. Local communities fight against disasters on the front line by preparing equipment, helping neighbours escape, enhancing structures, rescuing other community members, operating emergency shelters, etc. In Poland, volunteer organisations, such as the Scouts, Caritas and the Red Cross, support flood emergency response. In England, flood action groups conduct various activities at the community level, including formulation of community flood action plans (Mees et al., 2016). In addition, volunteer flood wardens from communities are engaged in communicating official warning messages to local inhabitants (Lanfranchi et al., 2014).

3 Incorporating science in policy decision making and implementation

Science is vital for efficiently implementing strategies for mitigating the most serious consequences of hazards before they become disasters, by identifying the potential range and severity of exposures, patterns of causality and the bases for action.

Experiences of some governments in 2020 show that they may lose the people’s trust and have difficulty in de-

BOX 2

Incorporating science in recovery policymaking of tsunami disaster in Japan

The Japanese government incorporated the best available science and technology into the recovery policy after the great east Japan earthquake and tsunami (GEJE) in 2011. Japan revised the national disaster management plan and enacted the new law 'Building tsunami-resilient community' in accordance with scientists' recommendation in December 2011, 9 months after the tsunami disaster.

The government had established institutional mechanisms for scientists and researchers to participate in policymaking processes for risk management even before GEJE. The Central Disaster Management Council, which the Prime Minister chairs, has the mandates of formulating the national disaster management plan and providing advice on the overall policy, coordination and emergency measures for disaster management. The council can establish technical investigation committees. After GEJE, the council established a technical investigation committee in April 2011, consisting of scientists and researchers, to examine measures against tsunami disasters. This committee recommended preparing for the largest possible tsunami by taking both structural and non-structural measures. The recommended policy covers (1) strengthening evacuation systems; (2) building resilient communities by developing multiple defence lines, protecting crucial facilities and formulating urban plans considering disaster risks; (3) conducting DRR education programmes (Ishiwatari, 2019b).

ciding new policies and measures against pandemics if they do not release scientific data, models and assumptions (Nature, 2020). Thus, the scientific community has an important role to play in the implementation of risk management policies and measures (Box 2; Aitsi-Selmi et al., 2015; GFDRR, 2016).

3.1 Science in policymaking

The engagement of the scientific community needs to be twofold: firstly, the public institutions need to be more open to using scientific evidence, but at the same time the scientists and researchers need to adjust their research for more practical implications. Scientific institutions have more scope to conduct research on the effectiveness and impact of using new approaches to risk management such as nature-based solutions or property-level and community resilience, unlike more traditional engineering measures (e.g. embankments and flood walls against flood risks). Practitioners and policymakers need access to more of this scientific evidence to justify decisions to use these more innovative approaches with multiple benefits. However, the challenge arises when policymakers demand simplified information on short timelines, whereas scientists are more inclined to work on specific detailed information on longer timelines. The co-design, co-development and co-evaluation of knowledge, data and other information are crucial for success.

Science–policy partnerships can help to merge these two sides. For example, the Environment Agency in the United Kingdom runs a joint flood and coastal erosion risk management research and development programme, including a technical advisory group with members of the scientific community advising on their research, and supports uptake of the research in practice (Environment Agency, 2015). The Natural Hazards Partnership in the United Kingdom is another example of joint working to enable a coordinated voice between the academic and practitioner communities on natural hazards. This partnership is leading to a shift from hazard-based to impact-based research to better understand and forecast potential impacts, and is developing cutting-edge hazard impact models and framework (Hemingway and Gunawan, 2018).

BOX 3

Innovative and integrated flood risk management solutions: Leeds Flood Alleviation Scheme, United Kingdom

Following severe flooding in 2015 (Figure 3), Leeds City Council embraced an adaptive approach to tackling flood risk with multiple benefits for the city and surrounding communities. The scheme was successful in unlocking funding from a diverse range of public sector funds nationally, regionally and locally, which aligned the scheme with multiple beneficiaries: economic development, employment, infrastructure, ecological diversity and public space amenity (Alexander et al., 2016; Leeds City Council, 2018).

The first phase of the scheme, completed in 2017, provides a one-in-75-years level of protection, and the second phase started in 2019 to increase the protection level to one in 200 years (Leeds City Council, 2019a). The first phase, costing GBP 50 million, increased protection to more than 3 000 homes, 500 businesses and 300 acres of development land (Leeds City Council, 2019b). The scheme included the pioneering application of movable weirs that keep the river navigable, along with increasing the flow capacity by removing an island, and installing flood walls and a fish pass. The second phase, costing GBP 112 million, takes an integrated catchment approach, which includes a combination of natural flood management (NFM) and engineered measures (Leeds City Council, 2019a). The NFM measures include piloting the creation of a new woodland area, installing debris dams and restoring floodplains, with the aim of complementing additional engineering measures. The scheme works closely with multiple research projects.

For example, Yorkshire Integrated Catchment Solutions Programme supports the development of cost estimates and justifies additional budget (iCASP, 2019). Lessons from the Working with Natural Processes Evidence Directory (including 65 NFM case studies) supported the selection of NFM approaches (Environment Agency, 2018). The scheme also explored multi-stakeholder governance arrangements. Relationships between the key actors, including Leeds City Council, the Environment Agency, water companies, academia and non-governmental organisations, grew by ensuring multi-stakeholder project boards, catchment partnerships and encouraging individual leadership (Alexander et al., 2016). The scheme works closely with multiple research projects.

Figure 3. *2015 Flooding in Leeds.*
Source: *West Yorkshire Combined Authority 2016.*

For example, iCASP (Yorkshire Integrated Catchment Solutions Programme) supports the development of cost estimates and justify additional budget (iCASP, 2019). Lessons from the Working with Natural Processes Evidence Directory supported the selection of NFM approaches (Environment Agency, 2018). Also, the scheme explored multi-stakeholder governance arrangements. Relationships between the key actors, including the Leeds City Council, Environment Agency, water companies, academia and NGOs, grew by ensuring multi-stakeholder project boards, catchment partnerships and encouraging individual leadership (Alexander et al., 2016).

Cutting-edge science and engineering knowledge can contribute to promoting innovative measures for risk management and climate change adaptation (Box 3). Regional flood and coastal committees in England are statutory committees that ensure there are coherent plans, programmes of investment and collaboration between actors for flood and coastal erosion risk management regionally, and they often coordinate with academia (United Kingdom, Government, 2011; O'Connell and O'Donnell, 2014).

Conferences that engage scientists, practitioners and policymakers can also act as a good mechanism to bridge science and practice, e.g. the Flood and Coast Conference in the United Kingdom. Local scientists can form part of project implementation advisory groups, e.g. large flood alleviation schemes, to ensure connections to university students and research. At the regional level, the Driver+ project and the European Commission launched policy–research dialogue round tables to ensure comparability and improve the uptake of results stemming from EU-funded research and innovation projects. The outcomes of EU projects are expected to contribute to developing the capability of practitioner organisations in DRR and crisis management (Tagarev et al., 2017; Tagarev and Ratchev, 2020).

3.2 Application of scientific knowledge in implementation

Scientific knowledge requires mechanisms and interlocutors to translate it into action. In particular, effective risk management demands an integrated approach to ensure continuity of attention to causes and consequences across the risk management cycle. One such approach applied to chemical accidents is layer of protection analysis, in which elements of the cycle, starting with reduction of the hazard itself, and working outwards to accident prevention and lessons learned, are managed as individual but integrated layers of protection throughout the process life cycle (design to decommissioning) (Sharratt and Choong, 2002).

The starting point for effective control of reporting major chemical hazards is a systematic assessment of risk associated with the hazardous activities that guides the selection of prevention and mitigation measures, with proportionate attention to risks based on potential consequences (Villa et al., 2016). Prevention is considered the first line of defence, since it is considered that causes are controllable to a large extent and can even be eliminated. In reality, sufficient reduction of accident risks is a challenge. Thus, preparation is the second line of defence to limit risks by identifying and managing risks through safety measures and land use planning. Emergency response is the third line of defence to limit impacts, by adapting and testing emergency plans and communication of safety measures to the public. Managing risks requires improving continuously the cycle of these elements by learning lessons from accident reporting and data analysis.

Scientific knowledge and technology are used in the Copernicus programme, which aims to provide disaster information based on satellite Earth observation to mitigate the loss of lives and property, and damage to the environment. The Copernicus Emergency Management Service provides geospatial and monitoring information about natural disasters, human-made emergencies and humanitarian crises. The early warning component of the service consists of (1) the European Flood Awareness System and Global Flood Awareness System for monitoring and forecasting floods, (2) the European Forest Fire Information System for real-time and historical information on forest fires and (3) the European Drought Observatory for drought early warnings (European Commission, 2016b).

In addition, the Enhancing emergency management and response to extreme weather and climate events (ANYWHERE) programme is funded within the EU's Horizon 2020 research and innovation programme. Horizon 2020 aims to ensure that the EU produces world-class science, removes barriers to innovation and makes it easier for the public and private sectors to work together in delivering innovation. The ANYWHERE programme covers various risk management techniques. It will establish a pan-European multi-hazard platform providing state-of-the-art early warning information, which identifies the expected weather-induced impacts and their locations in time and space.

Italy has revised the seismic code and expanded the definition of seismic zones by using scientific knowledge following destructive events. Through the application of this code to new building and informing the retrofitting of existing buildings and structures, the country has become more resilient to earthquakes. The 1908 Messina earthquake and 1915 Avezzano earthquake killed some 80 000 and 30 000 people respectively. The number of casualties has decreased drastically in recent years.

The first seismic provisions were issued in 1909 after the Messina earthquake. The engineering committee, which the government established, proposed the first seismic code. The seismic code was revised in 1915 following the Avezzano earthquake. The code was updated in 1974 by incorporating knowledge developed in seismology and earthquake engineering. Following the Irpinia earthquake a new zoning system was enforced in 1984 (Stucchi et al., 2011). The seismic zone, which covered only two thirds of the country at the 2002 Molise earthquake, was expanded to cover the entire country in 2003. Following the 2009 L'Aquila earthquake, the code was upgraded to cover the design of new civil and industrial constructions, bridges and geotechnical structures and modification of existing structures (Santucci de Magistris, 2011).

Scientific and engineering knowledge are crucial in implementing risk reduction efforts as well (Izumi et al., 2019). Structural experts and geologists were engaged in seismic assessment and retrofitting activities in Lazio, Italy, following the 2002 San Giuliano di Puglia earthquake. The region established the Scientific-Technical Committee, which consisted of engineers and geologists from government organisations and universities. The committee supervised and supported seismic assessments and seismic design for retrofitting crucial buildings and infrastructure, and provided training to practitioners to master the technology associated with the updated seismic code. It conducted seismic assessments of some 1 170 buildings and retrofitted 17 schools and 13 other buildings (Colombi et al., 2008).

4 Monitoring and evaluation

Continuous monitoring and regular evaluation provide feedback to improve performance in risk management. The EU Member States and other stakeholders have identified complementary methods to measure the progress and impact of individual projects and programmes.

4.1 Systematic monitoring: United Nations Sendai Framework for Disaster Risk Reduction and European Union directives

Each country reports on 38 indicators to monitor the achievement of the seven global targets of the Sendai Framework for Disaster Risk Reduction (SFDRR) (UNISDR, 2015). The United Nations Office for Disaster Risk Reduction (UNDDR) assesses progress in implementation biennially, and presents analysis and trends in the Sendai Framework progress reports. The UNDRR issues to the states a self-assessment grid, which is based on criteria to assess the potential progress made by states. The European Commission reviews progress on the EU action plan on the SFDRR (European Commission, 2016a), and each Member State needs to report its progress to the Commission.

The EU has developed standards for risk management to ensure quality in the delivery of guidance. For example, the Floods Directive (2007/60/EC) requires the Member States to create flood risk management plans (FRMPs) to reduce the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods. All Member States have begun implementation of FRMPs (European Court of Auditors, 2018). The European Commission is monitoring the progress of implementation systematically, with variations in different local contexts. For example, the latest assessment report recommends that Member States include climate and socioeconomic changes, such as urban sprawl and soil-sealing land use, more widely in flood risk management (European Commission. 2015). In addition, the Member States report data on prevention and preparedness measures under the EU civil protection mechanism.

4.2 Evaluation of projects and programmes

Cost–benefit analysis is applicable to risk management projects and is a useful tool in choosing among different options and understanding the effectiveness of a project. While there are some limitations, such as difficulties in estimating the value of human lives and indirect economic effects, cost–benefit analysis is widely used. This analysis can be also used for post-project evaluation to improve policies and programmes for risk management. The typical approach for chemical incidents is to count the number of serious incidents that has occurred. Incident data are strong evidence of gaps in risk management, but in general are not adequate for proactive risk management. Probabilities of serious accidents are so low that a risk might not become manifest for years, i.e. when the accident has already happened. Other leading indicators are needed to obtain a more rounded picture of chemical incident risk, to also prevent incidents that arise from other hazard sources but have not yet occurred. There are several initiatives in industry and government that are under way to identify serious risks before they become accidents (hazard ratings, performance indicators, risk governance measures, near-miss data), but they are far from being widespread and many are still in the experimental stage.

5 Conclusions and key messages

The EU and Member States have been strengthening governance arrangements to efficiently implement risk management measures by engaging a wide range of stakeholders. These stakeholders share responsibilities and knowledge at the regional, national, local and community levels. Recommendations to the stakeholders are as follows.

Policymakers

Policymakers should establish stronger mechanisms of communication and knowledge exchange. At the regional and national levels, working in partnership with neighbouring governments is needed to face cross-border threats and implement effective cross-border responses. Good examples such as the EU CBRN centres of excellence can inspire the creation of regional networks of expertise to support strengthening institutional capacity to manage complex risks. At the local level, twinning arrangements between local governments can help provide expert support for emergency and recovery work. Policymakers should strengthen monitoring and evaluation mechanisms, which are the key to measuring the progress and impact of individual projects and programmes.

Practitioners

Practitioners in governments and industry should collaborate in identifying and implementing risk management measures because of the need for coordinated responses and for joint responsibility and control. This contributes to developing a culture of safety, which is essential to duly implement management measures against risks.

Scientists

Scientists should support the development of innovative and more effective risk management measures so that practitioners can use cutting-edge science and technology to count measures at all phases of the risk management cycle. Experience in Europe shows that science is vital for implementing strategies to mitigate the most serious consequences of hazards. Scientific knowledge and technology are used in several natural-hazard-monitoring and response systems that are already operating or being developed in Europe.

Citizens

Citizens are expected to be engaged more actively in community-based disaster risk management activities. A noteworthy case is the implementation of flood risk management, in which citizens are increasingly participating.

Practitioners and scientists

Practitioners and scientists can continuously improve the measures by receiving feedback from monitoring and evaluation efforts and learning from it. The EU has established monitoring and evaluation mechanisms to improve risk management policies and measures, of which the action plan on the SFDRR and the Floods Directive are the best examples

Conclusions

Disasters caused by natural and anthropogenic causes, particularly those on a large scale, drastically affect communities, infrastructure and ecosystems, often leading to adverse economic, societal, political and environmental consequences. The interest in improved models or pilot actions for the risk management cycle (RMC) is gradually increasing at local, national, European and global levels. In Chapter 2, the RMC is described from three main perspectives, each one being a prerequisite for the next: risk assessment (subchapter 2.1), risk management planning (subchapter 2.2) and implementation and monitoring (subchapter 2.3). Thereby, Chapter 2 synthesises the state of the science in each of those areas, highlights persisting gaps and challenges, and provides future directions for research and action.

Today it is widely acknowledged that efforts to reduce current risk and prevent future risk should be based on a solid understanding and assessment of the drivers, spatial patterns and dynamics of disaster risk. The participation in risk assessments of a large variety of disciplines and actors, such as scientists from the social and natural sciences, policymakers, practitioners, the private sector and citizens, is key to capture the complexity of disaster risk, but also to facilitate the mainstreaming of risk information into policy and practice. Over recent years, a number of concepts and approaches have been developed to assess risk associated with natural hazards and with climate change at and across different spatial (local to global) and temporal (past trends, present-day risk, future scenarios) scales. Despite recent advancements in the understanding and assessment of risk, a number of challenges persist. These include questions on how to better incorporate traditional/local knowledge as well as intangible factors (e.g. changing risk perception, values, norms and beliefs) into assessments, but also how to capture the systemic nature of risk in an increasingly interconnected world. Further, in order to be useful for decision-making, communicating risk information as well as associated uncertainties to relevant stakeholders in an understandable and actionable manner is of crucial importance.

Risk management planning is a complex, multilevel and multi-stakeholder practice. It requires the active engagement not only of public bodies and of the private sector, but also of civil society groups and of citizens, all in an effective synergistic way. As a consequence, risk management planning requires the development and preparation of specific capacities and capabilities by a variety of institutions based on evidence coming from risk assessment processes. Risk management planning covers the entire spectrum of the RMC, including the pre-disaster phases of prevention/mitigation and preparedness, the immediate response to the disaster and the post-disaster phase of recovery. In practice, however, some overlap is observed between the various RMC phases. As a consequence, the determination of clear responsibilities for specific tasks is vital for an effective and functional risk management policy. Although each agency has to organise risk management planning from its own perspective, responsibilities, budgetary restrictions and capabilities, vertical and horizontal coordination of mechanisms and interoperability between the different agencies and administrative levels involved in planning and decision-making are needed to increase societal resilience.

The implementation of risk management policies and measures relies strongly on risk assessment, risk management planning and support by advanced scientific and technological methods and tools. The EU, its Member States and other stakeholders have identified complementary methods to monitor, measure and evaluate the performance and impact of individual projects and programmes. Responsibilities and decision-making actions shared between the various stakeholders should be in place and clearly determined by governance arrangements at all administrative levels, i.e. from local to international. At the levels of the EU and Member States, relevant policies and legislative regulations have been developed for engaging stakeholders (including local communities, civil society organisations, the private sector and volunteers) in the implementation of risk management strategies in all phases of the RMC.

Continuous scientific and technological innovation supports more effective disaster risk management. In the preparation phase, one may include the elaboration of both hazard zones and disaster risk scenarios for different types of hazards, including multi-hazard risk. Improved management and analysis of data and inventories from past disasters support learning to further reduce exposure, vulnerability and, thereby, risk. Strengthening and enhancing early warning systems and risk estimation matrices constitute potential and promising tools for improving risk management, particularly when complemented by a comprehensive risk information communication strategy and effective response procedures, which in turn require well-designed standing emergency management plans and procedures.

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Introduction

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Chapter 3

Assets at risk and potential impacts

3.1

Methodologies for disaster impact assessment

Online Version

3.1 Methodologies for disaster impact assessment

CONTENTS

3.1 Methodologies for disaster impact assessment

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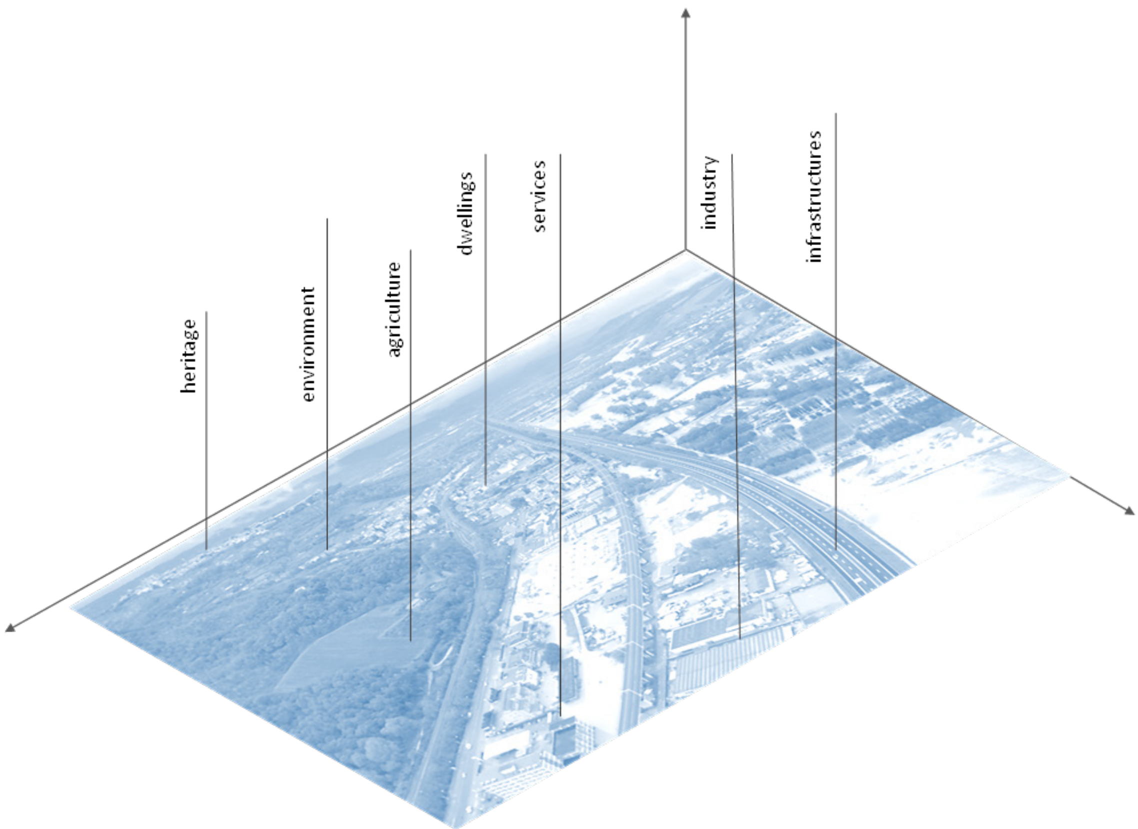
1 Introduction

'Impact' derives from the Latin impactus, meaning 'hit', and literally it refers to a body breaking into a rigid surface. The term has been widely used in physics, where it preserves its literal meaning, and in environmental sciences in a more metaphorical sense. The relevant branch of environmental impact assessment, which is also the object of a recently amended EU directive (Directive 2014/52/EU), can be recalled here and provides the basis for connecting sustainability to disaster risk reduction and climate change adaptation. In the latter domains, 'impact' refers to the consequences an event extreme and/or climate change may have on natural, social, economic and built systems. According to the UN General Assembly (2016) report on terminology prepared for the implementation of the Sendai framework, 'Disaster impact is the total effect, including negative effects (e.g., economic losses) and positive effects (e.g., economic gains), of a hazardous event or a disaster. The term includes economic, human and environmental impacts, and may include death, injuries, disease and other negative effects on human physical, mental and social well-being' The understanding of disaster impacts has significantly advanced in recent years. For too long they were limited to a few sectors such as residential buildings or agriculture; more recently, research and practice have targeted damage to economic activities, lifelines and services, and cultural heritage in a much more comprehensive way.

Figure 1. *Damage assessment should cover multiple sectors across different temporal and spatial scales.* ***Source****: Authors (*[1]*).*



([1]) *Figure developed as part of the Lode project, funded by the Directorate-General for European Civil Protection and Humanitarian Aid Operations (ECHO).*

It is clear now that, to better grasp and understand the real magnitude and extent of a disaster in a given territorial context, impact assessment must address multiple spatial and temporal scales while considering the whole range of sectors that may be affected, taking a systemic approach. For spatial scales, in an interconnected world, the impact is rarely restricted to the area that has been struck physically by the event. For example, the disruption of critical infrastructures may significantly disrupt mobility and strategic services in areas that may be very far away from the centre of the disaster (Mazzocchi et al., 2010; Nanto et al., 2011). For temporal scales, indirect and secondary damage must also be considered, therefore tracing damage that may become manifest some time after the triggering event, and even long-term damage, of which researchers are starting to find evidence (DuPont and Noy, 2015). Such a comprehensive assessment is essential to account for the role that each risk factor, such as hazard, exposure and vulnerability, have played as damage causes and drivers, providing an empirical foundation to choose among alternative risk mitigation measures. As shown by Pesaro et al. (2018), the full consideration of second- and higher-order damage may support much better the claim of a 1:4 or 1:7 ratio between mitigation expenditure and avoided damage in cost–benefit analyses.

2 Definition of damage and losses

Damage is usually related to the physical harm and destruction due to a disaster but it can also be triggered by a chain of cascading effects in time and space, including the effects of the decisions taken to mitigate the effects and facilitate recovery.

In the 2017 disaster science report, a framework was provided building on previous decades of research and studies to define damage and losses due to disasters (Menoni et al., 2017). First, a distinction can be made between damage and losses. The former is generally considered a more comprehensive term, including all sorts of negative consequences, ranging from physical damage to negative consequences for a range of societal sectors, such as interruption of businesses and services, health and psychological effects. Losses, in contrast, more frequently mean negative economic impacts, thus usually measurable in money. Even though such a distinction is not always respected in the literature, a tendency towards this use can be recognised.

For the unit of measurement of damage and losses, an important difference exists between tangible and intangible exposed assets and sectors. Tangible damage can be easily expressed in monetary terms, whereas for intangible damage it is either very difficult or controversial to assign a monetary value. It has been widely debated whether or not a monetary value should be assigned to loss of lives or permanent injuries, even though in principle this is possible using insurance premiums as a reference. For some assets, such as typically natural capital (including air, water and the quality of the latter) assigning a monetary value is hard, given the 'absence' of an exchange market. An extensive literature exists in environmental economics debating the possibility and the drawbacks of methods to determine a price for public goods, which include basic assets for human and nature survival. Similarly, determining the value of cultural heritage appears to be controversial, as it incorporates important elements constituting the identity of communities and provides multilayered testimony of past history, the disruption of which cannot be replaced by new or reconstructed artefacts.

A further distinction that is made in the literature regards direct and other types of damage. Direct damage refers to the physical harm and destruction provoked by a hazardous event.

Generally, such damage is relatively easy to link to the characteristics of the impacting phenomena, partly because the time span makes the relationship evident. However, longer-term relationships cannot be excluded: some physical damage may be delayed, for example in the case of flood damage if humidity causes mould, which may in turn affect human health or ruin mechanical and electrical components of machinery, equipment and products. Indirect damage is a very broad category encompassing disruption of normality leading to societal and psychological distress, and business and service interruption, including short- as well as long-term negative effects. Even though the term 'indirect' is still widely used in literature, alternatives exist that are perhaps preferable, as they point more exactly to the time of appearance and the specificities of what and/or who is affected. For example, Rose (2004, p.17) proposed to consider 'second and higher' consequences as a more precise way to refer to secondary short- and long-term damage. In particular, higher-order damage alludes to the fact that consequences such as distress or loss of function of entire systems and services are due to physical damage to one or more critical components either within the same system or even in other systems on which the ones disrupted depend. This leads to the consideration of cascading effects, which are consequences that follow, either temporally or functionally, not necessarily from the initial stress provoked by the hazardous event but more typically from the physical damage the event triggered. In a similar vein, Van der Veen and Logtmeijer (2005) defined systemic vulnerability not as the propensity to physical damage but rather as the inability to cope with the disruption that physical damage produces in components of highly interdependent systems. They were referring to economic systems; however, it has been shown how the concept can be easily extended to all systems (Menoni et al., 2012).

The concept of 'different orders' better accounts for the varied timing of damage, including longer-term negative consequences. In 1992 Di Sopra, studying the Friuli earthquake, raised the issue of longer-term damage, considering both the economic and the social negative effects some communities and municipalities were suffering many years after the earthquake occurred in 1976. Such damage was the consequence of the decisions made after the event, leading, for example, to urban sprawl and underutilisation of the reconstructed built stock. This is an aspect that should not be neglected. Damage is not provoked only by the physical phenomena that triggered a chain of cascading effects, but sometimes is also the consequence of the decisions that were made to mitigate both the physical and the indirect damage. Preventative measures taken before the impact of a hazard, or responses carried out during the emergency, recovery and reconstruction may entail significant costs for communities or for some social groups. This has also been the case in more recent cases in Italy. For example, analysing the market value of reconstructed houses in the L'Aquila region after the 2009 seismic event, Carbonara and Stefano (2019) showed that, despite the indisputable improvement of construction quality, their market value has dropped dramatically. On the one hand, this is due to the intensification of the trend of emigration from some of the reconstructed hamlets and villages and even from the city of L'Aquila. On the other, the focus on physical reconstruction, neglecting other equally if not more important aspects of economic rehabilitation, risks ending up as a remarkable waste of public money invested in the reconstruction. It is necessary to identify "gainers" and "losers" in different spatial scales in the long-term to assess the real effect of the impacts in the long-term.

The examination of longer-term effects introduces an important element to the present discussion on damage, as economists used to state that, in the longer term, losses due to the disaster could be considered negligible or even turned into gains. The latter would be the effect of investment in reconstruction, which brings resources to the area and boosts activities connected mainly with the construction and infrastructure sector. While this proved to be true in many cases, in others more recent research has highlighted that such recovery investment is not always able to restore economy to the pre-event levels (DuPont and Noy, 2015). An interesting comparison can be drawn between the case of Anchorage in Alaska after the 1964 earthquake and that of Kobe after the 1997 quake. In the former, the new port that was almost ready before the disaster was boosted by the need to restart shipping at the expense of the destroyed port of Valdez; in the case of Kobe, DuPont and Noy (2015) were able to demonstrate that, 15 years after the earthquake, the port's activities had not recovered to the full pre-event level. Hallegatte and Dumas (2009) seem to come to the same conclusions when analysing the positive side of disaster impacts. What emerges also from those recent studies is that a very clear spatial-scale standpoint must be adopted, as gainers and losers must be identified making reference to a precise local, regional, national or international level. Other positive impacts derive from lessons learned from the disaster, such as the improvement of building codes and the rebuilt/retrofitted building stock, the establishment or reorganisation of civil protection, or the introduction of better and more stable prevention mechanisms. However, benefiting from the window of opportunity created by the disruption is highly dependent on the capacity and determination of governments and on the social and human capital present in the affected areas. Therefore, the possibility of transforming the losses and disruption caused by the disaster into opportunities for a better recovery depends very much on the resilience of the entire system and on the capacity of decision-makers to take appropriate actions for the shorter and longer terms. This highlights the importance of recovery and reconstruction as crucial phases, as wrong and inappropriate decisions can instead produce longer-term higher-order damage, implying larger costs for the communities than those necessary to rehabilitate the physically disrupted assets.

2.1 Disasters' reported impacts at the European level in existing databases and reports

As declared in the United Nations Office for Disaster Risk Reduction strategic framework 2016–2021, disasters triggered by natural phenomena still claim a significant death toll, affect the well-being of entire communities worldwide and cause extensive economic damage. Losses due to disasters triggered by natural events average USD 250 billion to USD 300 billion each year worldwide. In Europe, causalties are mostly associated with earthquakes and heatwaves, while economic losses and annual numbers of affected people are caused mainly by earthquakes, floods and storms. Disaster occurrences and the reported damage are unevenly distributed across different regions of Europe, partly because of the different geographical distributions of hazards. Since 2006, storms (meteorological) and floods (hydrological) have been the most frequently reported in Europe, with significant differences between regions. Europe has experienced several extreme summer heatwaves in the last few decades. High numbers of fatalities due to heatwaves were recorded in western Europe in 2003, 2006 and 2015.

Overall, weather- and climate-related natural hazards such as heatwaves (climatological) and heavy precipitation (hydrological) have become more frequent and/or intense in Europe (IPCC, 2012; Donat et al., 2013; EEA, 2017a, 2017b). The number of very severe flood events in Europe has varied since 1980, but the economic losses have increased (EEA, 2017b). A total of 13 floods hit Europe in 2018, the second most frequently reported disaster, exceeded only by 15 extreme temperature events recorded in the same year. Floods are more common than they used to be in both eastern and western Europe. Earthquakes and volcanic eruptions (geophysical) occur less frequently by their nature; however, when they occur the impact, especially in terms of human losses, can be very high. Southern Europe is the part most exposed to such phenomena, in particular Greece and Italy (EM-DAT, 2018). Landslides are a natural hazard that causes fatalities and significant economic losses in various parts of Europe (EEA, 2017b). Projected increases in temperature and changes in precipitation patterns are likely to affect rock slope stability conditions and favour increases in the frequency of shallow landslides, especially on European mountains (EEA, 2017b).

Regarding technological disasters, an in-depth analysis of accidents (Directorate-General for Environment, 2017) reported in the Major Accident Reporting System (MARS) database shows that an average of 33 accidents per year occurred in the period under consideration, 2000–2014. Out of 490 reported cases, 421 were major ones. Given the relatively low number of occurrences, no clear downward or upward trend can be recognised.

On natural hazards triggering technological disasters (natech), Krausmann et al. (2017) point out that most studies have focused on earthquakes, because of their potential severe impact on hazardous installations, and on lightning and floods, which are the most frequent triggers of natech incidents in the EU. However, the reality is that in current databases it is very difficult to find a homogeneous, comparable set of data regarding different types of events and their relative impacts. Furthermore, owing to constraints in current methods of classifying hazards and initial events, it is virtually impossible to cluster complex, multi-hazard events, such as natech.

3 Damage data collection and estimation

Damage data collected after an event is initially required to respond to the most direct impacts and to deal with the recovery of it.

Damage data collection is usually carried out by public administrations in charge of emergency and recovery, and by insurance companies, to determine the level of expenditure/compensation that will be required to deal with the initial crisis and the subsequent recovery and reconstruction. Such assessment generally leads to the identification of monetary losses in order to find out what financial resources are needed, be it by insurance companies in the common pools and/or reinsurers, or by the state in ad hoc arrangements that are either fed by pre-allocated funds or redirected from other budget items. Initially damage is assessed through direct surveys of affected assets, buildings and infrastructures. A rapid reconnaissance is made a few hours after the event using various means. In Europe, the Copernicus service offers a first damage map within 6 hours after its activation, with regular updates made to verify and validate initial maps.

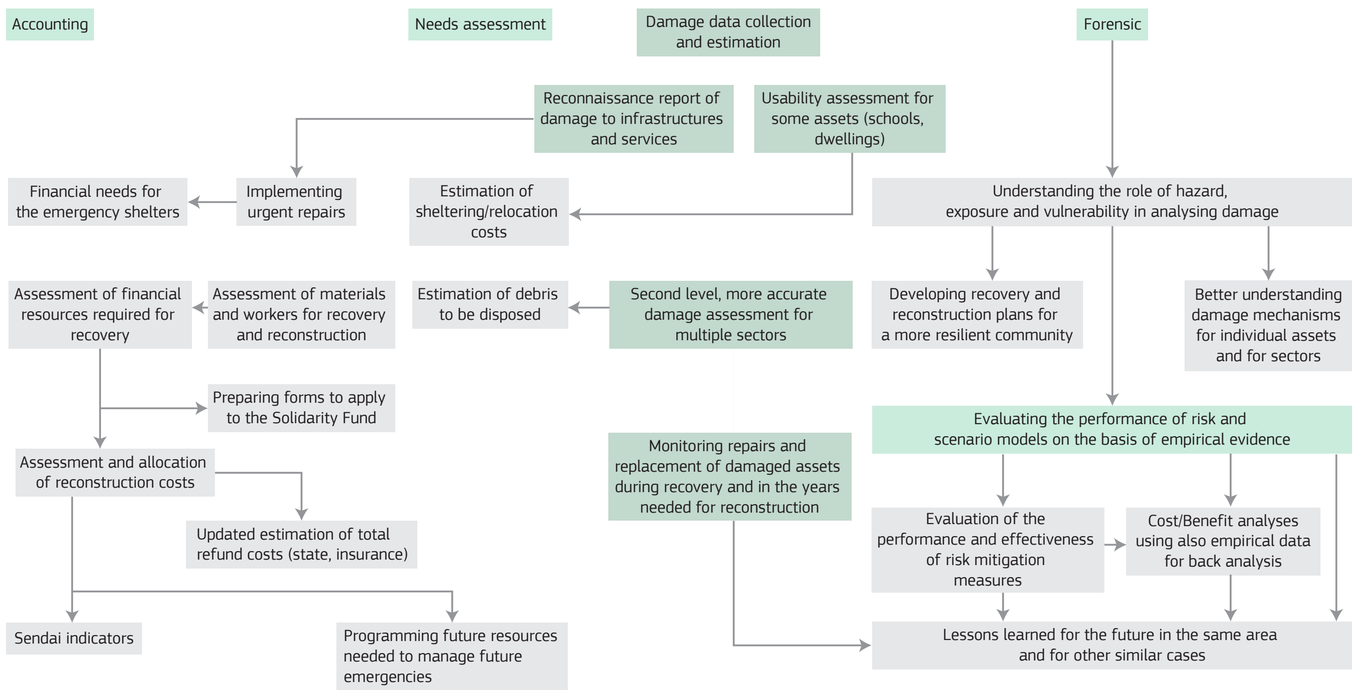
Other means can include maps derived from flights using drones, or field surveys in sampled areas. An activity that is often carried out especially in the aftermath of very destructive events is the assessment of the usability of dwellings, services and infrastructures, to determine their residual level of safety. The immediate uses of such assessment are the closure of access to certain areas, prioritisation of emergency repairs, and relocation and evacuation of affected people. On some occasions in the past, usability data were used also as a basis for determining compensation costs, a practice that should not be encouraged, as the purposes of usability and damage assessments are different. The inappropriate use of usability assessments to calculate costs of reconstruction may result in significant overestimation of financial needs (Boni, 2020). Usability assessments must be on the safe side, telling affected people whether it is safe or not for them to continue living in their houses or to send their children to school. Damage assessment, in contrast, can be carried out at a later stage, without significant liabilities being involved, and can therefore be more accurate in estimating the real costs that repair will entail. Similar considerations led Xue et al. (2011) to develop a rather advanced methodology for assessing earthquake damage suffered by reinforced concrete buildings in Taiwan to fine-tune insurance policies.

3.1 Data uses

Data about damages and losses serve to study the drivers and conditions that lead to disasters, to design models to estimate risk in the future and to learn about the actions taken before the hazard materialized

De Groeve et al. (2013) were the first to our knowledge to discuss the different uses of damage data in a structured and comprehensive way (see also Ehrlich et al., 2017). In a later report, Marín Ferrer et al. (2018) highlighted the value of damage data as the key to supporting informed decision-making and policy implementation at both EU and national levels. In Figure 2 an attempt has been made to correlate the different uses providing a framework to accommodate the rather wide range of applications and situations in which damage data become highly relevant.

Figure 2. *Different uses of damage data for multiple purposes and to support a variety of policies.* ***Source****: Authors.*



Needs assessment

Needs assessments evolve through time along with the disaster phases. Immediate repairs have to be prioritised for those assets, especially critical infrastructures, that are essential to carry out emergency operations and activate first recovery.

An initial assessment of the number of evacuees and services to be relocated derives from initial fast reconnaissance and usability reports. At a later stage, needs assessments encompass a wider range of aspects, including the re-establishment of basic services and the search for appropriate disposal areas for the debris if a large number of artefacts have been destroyed. Such assessments must be updated over time, including on the basis of more accurate damage assessment, permitting one to better establish what can be repaired and what must be totally rebuilt instead. In the framework we have decided to distinguish between needs assessment and financial needs estimation. For example, psychological support for victims and for workers coming from outside the area for the reconstruction must be considered together with the money that will be required to pay their salaries and for repair and reconstruction materials.

Accounting

In the immediate aftermath of a disaster the effort to provide a rough overall estimate of the financial losses associated with the disaster is of paramount importance, especially for insurance companies, which rely for this on their consultants, who are able within a few hours to provide a scenario of expected damage given the hazardous event that has occurred and the exposure and vulnerability of assets. At later stages, such financial estimation becomes more accurate and reliable, as loss adjusters estimate the actual payouts and states are able to get declarations from municipalities and other appointed administrations on the basis of paid invoices. Some countries carry out initial assessment on the basis of parametric coefficients that can be revised later on the basis of the real expenses borne by various private and public entities. At the same time systematic accounting carried out for different sectors is necessary to apply to the Solidarity Fund ([2]) that supports emergency expenses for public assets and services. In the longer run, keeping multi-sector damage and loss data is essential to compile the indicators in the Sendai framework. As shown by an exercise that has been conducted within the DRMKC for the Catalunya Civil Protection Authority ([3]), the Sendai indicators require rather accurate management of data not only about direct physical damage but also about second-order damage, such as lifeline outages and business interruption. Last but not least, systematic damage accounting is used by governments to be able to forecast the financial resources to be committed for emergency and recovery management in the future, given the experience of past disasters. This is the reason why countries are required not only to invest in developing and maintaining more advanced and performing databases to record and analyse future losses, but also to gather information regarding past events, going back in time as long as is possible given available reports. An example of this is the catalogue of past floods in Europe managed by the EEA (2018).

Forensic

Forensic investigation in the field of disaster studies encompasses a variety of different approaches, including engineering and geological investigations aimed at supporting judicial cases (Slosson and Shuirman, 1992), failure analyses in technological accidents (Livingston et al., 2001) and analyses carried out by insurance companies such as the post-event review capability (PERC) methodology developed by the Zurich Insurance Company (Venkateswaran et al., 2015). In 2010 the International Research on Disaster Risk (IRDR) (Burton, 2010) launched the Forensic Investigations of Disasters (FORIN) project aimed at providing a broad and comprehensive overview of causes of damage in a disaster. An advanced framework and methodology for identifying drivers and root causes of disaster damage has been developed and applied in Germany on both German and foreign cases by the German Committee for Disaster Reduction (DKKV, 2012). In France the 'Return of experience' reports have been developed with the idea of collecting and preserving crucial information on extreme events in order to develop knowledge regarding the cost of disasters across different economic and societal sectors (Territoriale Méditerranée du Cerema, 2014).

([2]) https://ec.europa.eu/regional_policy/en/funding/solidarity-fund/
([3]) See the service delivered to the Catalonia Civil Protection Directorate (https://drmkc.jrc.ec.europa.eu/innovation/SupportSystem).

The investigation of accidents has a long history, firmly rooted in the aviation industry but not only there, and may count on a significant apparatus for the identification and the analysis of causal links. In the analysis of the causes of an accident, one has to identify the key factors triggering the sequence of failures that led to the 'top event', and their interplay in the specific case given environmental, organisational and cultural settings (Livingston et al., 2001).

The main objective of FORIN is to find out the social and political root causes and drivers, meaning those factors such as poverty, corruption, poor practices and poor enforcement capability that are at the root of the damage suffered during and after severe disasters (Oliver-Smith et al., 2016).

The PERC methodology consists in a thorough analysis of some damaging events as part of the social corporate responsibility mission of the insurance company Zurich, but has inevitably as one of its main objectives to 'develop perspectives on appropriate risk transfer and risk management solutions in flood vulnerable areas, including the pre-requisites for their effective functioning' (Zurich, 2015, p. 15T).

Learning lessons and tacit knowledge elicitation

One important result of disaster forensic is certainly the ability to learn from events, in very detailed terms. Such learning can be used to improve risk models by fine-tuning how hazard, vulnerability and exposure are assessed and measured, and to better understand the disaster's context and implications. Such understanding should lead to the revision of emergency preparedness tools, as was the case for the Joint Research Centre (JRC) Nedies project (Colombo and Vetere Arellano, 2002). Not only short-term emergency mitigation but also long-term structural and non-structural measures can be improved on the basis of the lessons learned. Forensic investigation that has been carried out so far has shown the deficiencies of hazard maps or made it possible to evaluate the effectiveness of mitigation and adaptation measures that were put in place in the past. Such stress testing of mitigation measures in the light of damage that has actually occurred is important to provide an evidence base for cost–benefit analysis, which is usually developed to decide between alternative options. As is widely accepted, though, lessons are only 'identified' and not necessarily learned if they are forgotten or not attended to. In this regard, significant added value could be brought by knowledge management systems as a means to share, co-develop and maintain knowledge in a given field and especially within complex organisations.

Knowledge of disaster impacts, both actual and potential, resides in the minds of those, both organisations and individuals, that have experienced disasters in the past and can connect these experiences to current situations, and even project them into the future. It has been argued that a significant part of organisational knowledge remains in the minds of its members (Wah, 1999); organisations in charge of emergency and recovery are no exception.

It is important therefore to manage this tacit knowledge, as the process of impact assessment itself generates rich learning. Recognition of the importance of tacit knowledge, and subsequently capturing it and converting it into both tacit and explicit knowledge (Nonaka and Teece, 2001), will add richness to the field of risk assessment and management (Dorasamy et al., 2013). In this regard, knowledge management systems could, on the one hand, provide access to structured databases of losses incurred during and after disasters, as is done for example in the JRC Risk Data Hub. They could offer to users a wide range of tools and methods that have been developed to collect post-disaster damage data so that national and regional organisations can initiate their own processes and establish better procedures not only to gather the data but also to use them for the multiple purposes expressed above. On the other hand, such systems can be nurtured by tacit knowledge leading to innovation (Seidler-de Alwis and Hartmann, 2008), which in the disaster data management domain will consist of better procedures, improved understanding of indicators to be analysed and an influx of ideas on how to capitalise on citizens' experience of disasters.

3.2 From forensic analysis to the improvement/validation of risk models

Disaster risk models permit one to assess expected damage due to hazard impact, understood as a function of various variables, i.e. hazard, exposure, vulnerability, coping capacity, etc. Such expected damage can be assessed in qualitative, semi-quantitative or quantitative terms. Expected damage can be forecast as a probability of suffering certain losses given hazard intensity and probability in an area, or deterministically, as an event scenario produced by one event the features of which have been pre-identified (Simmons et al., 2017). Investigation of damage, that is, learning from real damage to assets, has been always a core activity to figure out indicators of vulnerability, especially physical vulnerability of buildings and infrastructures. Direct surveys after earthquakes, volcanic eruptions and floods have made it possible to develop fragility and damage curves correlating construction characteristics, main hazard variables and observed damage (Petrini, 1996; Pistrika et al., 2014; Jenkins et al., 2014).

Insurance companies use risk models that include high-quality data exposure, hazard, vulnerability and risk layers to calculate the insurance premiums for properties. Such models are translated into computer codes, which generate a set of simulations providing estimates of the intensity, magnitude and location of events and determining the amount of damage, before calculating the amount of insured loss as a result of each disaster event. More recently, post-disaster damage data have been used to assess the reliability of such forecasts (Yates, 2009). In order to further improve the reliability of damage estimates, a necessary step to be considered is increasing the transparency of underlying assumptions and adoption also of open source models in the insurance industry together with proprietary ones (Global [Re]insurance, 2013).

In recent years advances have been made in data-driven multi-variable impact models (e.g. Merz et al., 2013; Wagenaar et al., 2017, 2018). In such models the impact is calculated using much more information than just the dominant hazard variable (e.g. water depth or wind speed). For example, for floods this means that, instead of only a depth–damage curve, variables such as waves in the flood water, flow velocity, flood duration, building materials, warning time and the inhabitants' experience of floods are also taken into account. Such improvements enable questions to be addressed that previously could not be adequately answered. In the case of floods, for example, the differences in impact due to inundation duration, waves or warning time can be now be better estimated, providing a larger number of options for evaluating the benefits of measures such as improved building codes, improved warning or complex changes to the hazard (e.g. reduction in waves in the flood water).

New frontiers to extend the possibilities of currently used methods for risk assessment are provided by artificial intelligence and big data, the aim of which is to extract from large datasets and a large number of events data and information that can be organised and structured according to ontologies in such a way as to identify basic constant features and dynamics of disasters in order to be able to forecast what may be the expected impact given triggering phenomena or incidents. However, for the full development of such advanced techniques, major improvements must be achieved in the way post-disaster damage and loss data are collected, stored and organised.

4. Post-disaster impact assessment

To analyse the consequences of a disaster in the after-math of the event, it is necessary to have already in place a system to collect and share data of the event and its impact among different stakeholders, ensuring timely availability and in consistency, accuracy and interoperability among sources.

'Access to information is critical to successful disaster risk management. You cannot manage what you cannot measure' (Margareta Wahlström; United Nations Office for Disaster Risk Reduction, 2012).

To assess the diverse range of impacts on multiple sectors, data related to post-disaster impact should be shared among different stakeholders including governments, various levels of public administrations, private companies, social organisations and academic institutions, also with the aim of creating greater consistency, accuracy and interoperability among different sources. Data from countries, institutions and even the international databanks that already exist lack uniformity in the type of data and how to gather and report them. Currently such data are still fragmented and structured differently, and no authority is in charge of coordinating them, contrary to the recommendation of the EU Expert Working Group on Disaster Damage and Loss Data (2015).

Various initiatives have been promoted to improve the current situation. For example, the IRDR's Data Project aims to establish a general framework for data loss collection and utilisation, promoting a higher level of comparability and compatibility between data from different sources. The Disaster Risk Management Knowledge Centre of the European Commission at the JRC is developing the Risk Data Hub, providing on the one hand information layers that are needed to carry out risk assessments and on the other hand gathering and structuring historic data regarding past events and consequent losses. It also aims to establish harmonised, more standardised procedures at the European level for future improved post-event impact data collection and analysis.

Overall, innovative methods and tools to facilitate post-disaster damage data collection are needed, in order to facilitate and mainstream their use for the various purposes highlighted in Section 3, not only by the same collectors or the coordinating agency, but also by other organisations and administrations that for various reasons would benefit from such data as a way to support a variety of risk mitigation and climate change adaptation policies. For this, tools must include the indicators and data that are relevant to all societal sectors, which undergo different impacts from different events at various spatial and temporal scales.

For spatial scales, computerised systems allow upscaling or downscaling more easily, especially if data are collected at local or asset level. For temporal scales, an important challenge to be met relates to second-order, higher-order and longer-term losses, which tend to be harder to identify and measure. Various approaches are necessary to identify and assess longer term losses, as information is required from economic organisations and associations about business interruption and recovery, and from mental health systems to be able to track post-traumatic disorders in the affected population.

BOX 1.

Available databases and relevant indicators for assessing them

Global databases on disaster impacts
There are currently a number of (more or less) global information systems, such as:

- EM-DAT;
- The National Map (US);
- National Oceanic and Atmospheric Administration (NOAA) Natural Hazards Viewer (US);
- Asia-Pacific Natural Hazards and Vulnerabilities Atlas, Hawaii;
- Swiss Re Worldwide Natural Hazard Atlas CatNet;
- and Munich Re Natural Hazards Assessment Network (NATHAN).

Visual information repositories are also being developed for floods, fires, sandstorms, volcanoes, tropical cyclones and other natural disasters:

- Moderate Resolution Imaging Spectroradiometer (MODIS) Rapid Response system (NASA-US);
- Worldview Snapshots;
- Global Imagery Browse Services (GIBS);
- International Charter on Space and Major Disasters;
- National Aeronautics and Space Administration (NASA) Earth Observatory Natural Event;
- Global Earth Observation System of Systems (GEOSS) that is an international initiative comprising more than 100 countries and even a larger number of organisations;
- NASA Disasters Program;
- European Flood Awareness System;
- European Forest Fires Information System;
- Global Disaster Alerting Coordination System (GDACS);
- Radio Distress-Signalling and Infocommunications (RSOE) Emergency and Disaster Information Service (EDIS) provided by Hungary;
- Global Risk Map.

State and local information sources
An important information source is the databases and inventories supported at state and local levels. Good practices can be found, for example the Slovenian database for post-disaster damage and loss data management. However unfortunately most national databases are not as good and as comprehensive as would be required. Pilot experiences have been supervised in selected countries and cities by the JRC's Disaster Risk Management Knowledge Centre (Antofie et al., 2020).
Databases' accuracy and harmonisation
Accuracy and harmonisation of different datasets are essential, as very often there is no interoperability between various databases. The Inspire 2007/2/EC directive addressed this topic, significant steps forward have been achieved on this topic but gaps are still evident. Advancements can be expected following the 2019 (EU) 2019/1024
Data interpretation
Efficient data classification methods must make it possible to upgrade the data content and features. A good example is offered by the Land Cover Classification provided within the Corine Land cover Inventory.

4.1 Methods of post-disaster impact assessment

Despite the importance of disaster data for a variety of uses, and the fact that for a long time scholars have lamented the poor quality and availability of such data (White, 1945; Hoyt and Langbein, 1955; Pielke, 2000), available tools to collect such data extensively and comprehensively, in accordance with a standardised and structured methodology, are few, only recently released, or not yet fully operational and adopted as agreed standards. In the following, two will be considered, one developed in the field of industrial accidents and the second largely applied by international organisations after natural disasters.

A tool that is of particular relevance has been developed in the field of incidents involving hazardous chemicals (HazMat incidents) named the Flash Environmental Assessment Tool (FEAT) (UNEP/OCHA Joint Unit, 2017). FEAT resulted from the collaboration between practitioners from the United Nations Disaster Assessment and Coordination teams and experts on chemical incidents and risks. FEAT is a swift integrated impact evaluation intended to identify as early as possible the potential consequences of HazMat-induced chemical releases on human health (as a consequence of inhalation of toxic gases or consumption of toxic water sources or food), livelihoods and ecosystems (as a consequence of environmental pollution contaminating livelihoods such as drinking water or resources for fishing).

The first version of the tool, published in 2009, was meant to be used reactively in the aftermath of incidents. The second version of the tool also encompasses a priori evaluations of the risks posed by hazardous installations, so it is used in incident prevention by safe spatial planning (FEAT Preparedness), as well as in a posteriori incident assessment and management (FEAT Response).

Different distances for the various impact endpoints are the most important indicator that is assessed through FEAT, the specific impact distances being derived from scenario analysis, in which chemical incident experts listed hazardous facility types and substances used, environmental chemists derived distance–concentration predictions (as concentrations dilute with distance), and toxicologists and ecotoxicologists calculated the impact assessment at each distance. Different impact distances between hazardous chemicals and the various endpoints are plotted on a situation map, to look at overlays with, for example, population centres and various assets, so that field teams can prioritise and take swift action on the most hazardous chemical flows (followed by all others of relevance later, till all have been managed). On the basis of the mapping, back-office teams deliver provisional key insights, which are summarised as hazard identification tools and inform the field teams and local authorities; the use of FEAT by field teams facilitates prioritization and management of needs.

The post-disaster needs assessment (PDNA) method (GFDRR, 2013; GFDRR, 2017) was developed initially by the United Nations Economic Commission for Latin America and the Caribbean and then improved through the collaboration of several international entities, including the World Health Organization, the Pan American Health Organization, the World Bank, the Inter-American Development Bank, the United Nations Educational, Scientific and Cultural Organization and the International Labour Organization.

The PDNA is composed of two parts – the damage and loss assessment and the needs assessment – and is meant to be adopted in large disasters where international aid is required. Based on the assumption that the necessary basis for prioritising needs is a detailed, comprehensive and multi-sector assessment of damages, the PDNA provides a rather precise methodology in terms of the procedure for conducting surveys, the scale at which they should be carried out and the timing.

The PDNA recommends that damage and loss assessment be conducted at different stages of emergency and recovery: first, immediately in the aftermath of the event, to identify the most critical areas and impacts; then, later, to analyse funding requirements and get a more precise and reliable estimation of both physical damage and financial losses that must be covered for repair and return to normal. Monitoring damage over time is also recommended, to check what has already been accomplished during recovery and reconstruction, what is lagging behind and what has still to be addressed.

The PDNA methodology has been extensively applied in recent disasters, as it has been embedded as part of the intervention protocol shared by the UN, the European Commission and the World Bank, covering events such as Cyclone Nargis in Myanmar in 2008, the Haiti earthquake in 2010, the Nepal earthquake in 2015, the Fogo eruption in 2014–2015 and the floods in Serbia in 2014.

5 Conclusions and key messages

There are many challenges in collecting disaster loss data. First, data collection may not be seen as a priority in the aftermath of a disaster, especially if strategies and procedures have not been previously established and shared among all stakeholders involved. Second, this type of data must be coordinated among multiple stakeholders such as insurance companies and health services, and even in the government they may be spread across different levels, sectors and ministries to give rise to innovative data governance models.

Policymakers

Decision-makers must become aware that standardisation of methodologies for gathering and presenting disaster loss data are key, as confirmed at the fifth Global Platform for Disaster Risk Reduction in 2017. An effort to promote bottom-up collection and distribution of disaster loss data and a standardised method is warranted, and national governments as well as international organisations should stimulate activities that promote it. This effort should not only aim to collect at least data to fulfil the global targets agreed in the Sendai framework, but, as discussed thoroughly in this subchapter and the next, should provide evidence and an empirical base for implementing European and national policies and strategies in disaster risk reduction and climate change adaptation.

Practitioners

Practitioners, comprising officials of public administrations as well as professionals working for the insurance industry, lifeline management companies and critical infrastructures, would certainly benefit from enhanced damage data collection practices and from sharing and co-developing, through knowledge management systems, knowledge of the impacts of natural extremes and climate change on their assets and systems. Tacit knowledge of methods, and of aspects of damage that may occur in different systems and have been identified in the past, should be implemented in such knowledge management systems to preserve collective memory of best practices and methods.

Scientists

Researchers can contribute greatly to the whole effort of identifying, codifying and developing data models and information systems that are not only usable but also flexible and smart, to allow the maximum added value in terms of empirical evidence acquisition with relatively simple software and relying on what has been learned in the past and in contiguous fields (environmental impact assessment, for example).

Citizens

Increasingly, citizens will be asked to contribute to damage data collection efforts, with self-declaration using online platforms, easing the task of surveyors, and/or through crowdsourcing information through social media, which may provide significant benefits if such efforts are effectively coordinated (Roberts and Doyle, 2017).

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Super Case Study

1

Earthquakes in Central Italy in 2016-2017

Online Version

Super Case Study 1:

Earthquakes in Central Italy in 2016-2017

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CONTENTS

1 Introduction

Starting on 24 August 2016, a long-lasting seismic sequence struck a very large area of central Italy, partially overlapping the areas affected by the 1997 Umbria–Marche and 2009 L'Aquila earthquakes (Figure 1).

Figure 1. a) *Central Italy 2016–2017 seismic sequence projected on the National Seismic Hazard Map of Italy along with the nearby Umbria–Marche 1997 and Abruzzo 2009 seismic sequences.* ***Source:*** *Stucchi et al., 2004.* ***Figure 1. b)*** *Map of the average expected numbers of dwellings affected by Damage Level 5 (partial or total collapse) in 1 year in proportion to the total number of dwellings in the municipalities.* ***Source****: DPC, 2018a.*

Figure 1 a)

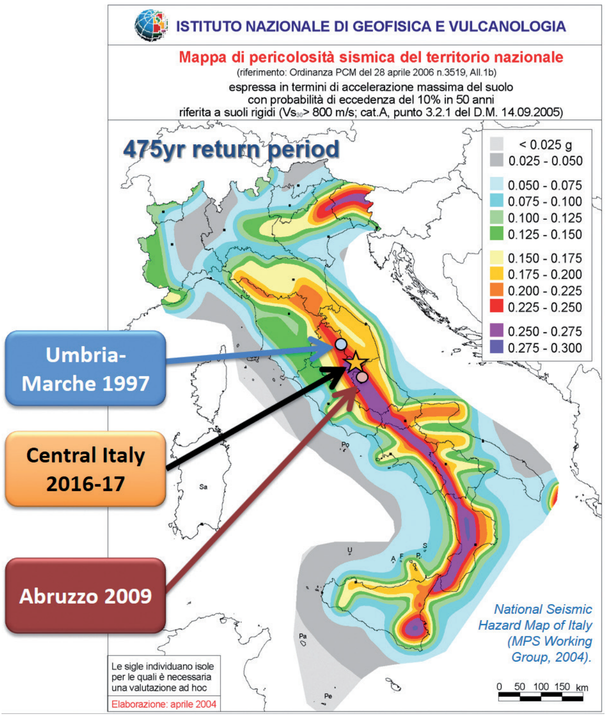
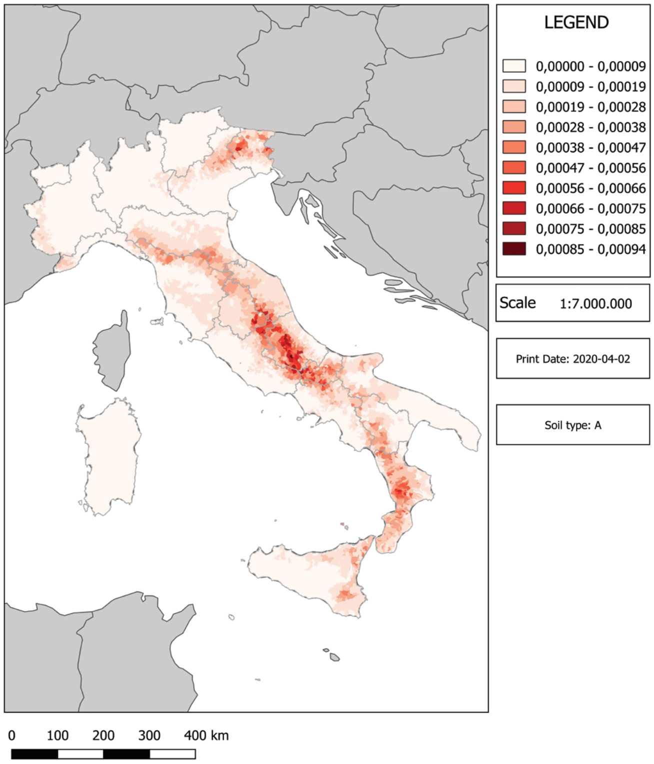


Figure 1 b)

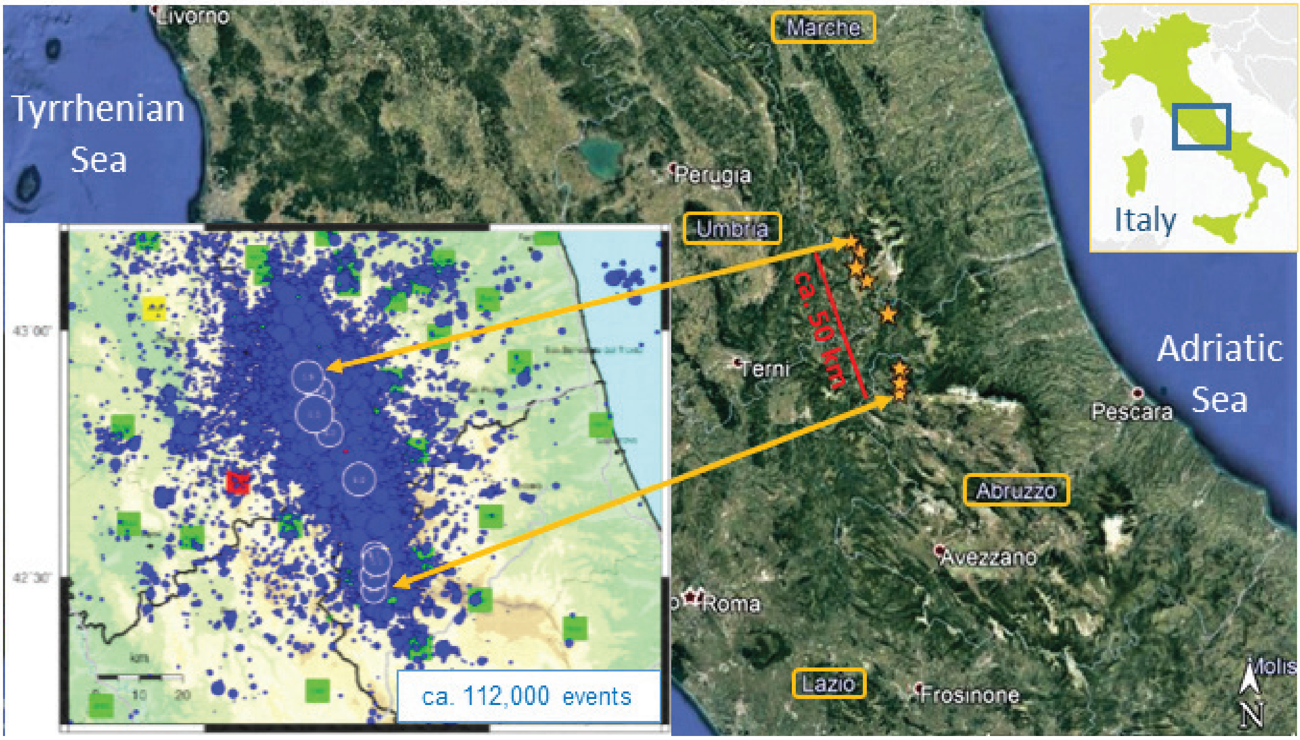


Nine major shocks with moment magnitude (Mw) greater than 5 occurred in 5 months (Istituto Nazionale di Geofisica e Vulcanologia, n.d.), with epicentres spread over c. 50 km following a NNW–SSE strike in the central Apennines (Figure 2). The two strongest earthquakes had Mw 6.0 (24 August 2016) and Mw 6.5 (30 October 2016).

After the first main shock, macroseismic (Mercalli–Cancani–Sieberg – MCS) intensities up to X or XI (ruinous or catastrophic) were observed (Galli et al., 2016). After 30 October 2016, the damaged area enlarged considerably. The maximum observed (cumulative) intensity was XI (Tertulliani and Azzaro, 2016a,b, 2017; Galli et al., 2017). The area with IMCS ≥ VII (very strong) was about 70 km long and 30 km wide (Figure 3). Very high values of peak ground

acceleration (PGA) (Table 1) and of other instrumental parameters were recorded (DPC, n.d.).
Co-seismic effects encompassed surface fracturing and faulting processes (Emergeo Working Group, 2017), which mainly reactivated already known pre-existing faults (e.g. Boncio et al., 2004; Pizzi and Galadini, 2009; Valensise et al., 2016). Many landslides and rockfalls affected the entire region and were in part responsible for disruptions of the transportation system.

Figure 2. *Central Italy 2016–2017 seismic sequence in the regional context. The four regions involved are marked in yellow. Bottom left insert: seismic sequence updated at 1 October 2019.* ***Source****: Authors, using Google Earth: Image Landsat / Copernicus - © 2018 Google - Data SIO, NOAA, U.S. Navy, NGA, GEBCO and Istituto Nazionale di Geofisica e Vulcanologia, 2019*



The first main shock killed 299 people and injured 392, whereas the strongest one did not cause any further fatalities, but injured only 38 people (Table 1). This occurred because (1) damaged buildings and highly damaged areas ('red zones') had already been evacuated, (2) the vulnerability of undamaged buildings near the epicentre of the strongest earthquake was low thanks to previous retrofitting and (3) emergency operators were not active yet at the time (7.40) the Mw 6.5 earthquake occurred.

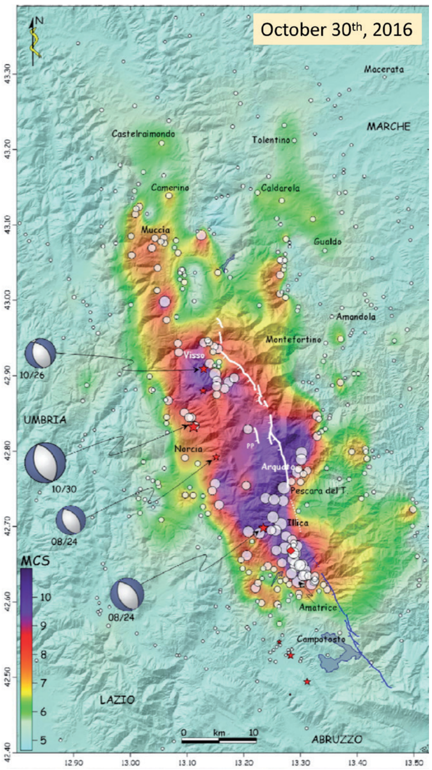
The emergency response of the National Civil Protection Service was coordinated by the National Civil Protection Department (DPC) until 7 April 2017, when the administrations of the four affected regions took over the management of most of the ongoing emergency activities. Meanwhile, the reconstruction process started on 9 September 2016, when a special commissioner for the reconstruction was appointed by the President of the Republic.

Besides search and rescue, civil protection activities were focused on assisting the population, by providing shelters and food. Up to 4 807 people were assisted in the first few days. At the end of August 2016, 43 tent camps had been set up, but their use was limited to a few weeks and then they were replaced by containers, because of the cold weather in the epicentral areas.

***Table 1**. 2016-17 Central Apennines seismic sequence: Mw≥5.5 earthquake.*
***Source**: Authors, based on Istituto Nazionale di Geofisica e Vulcanologia, n.d.; DPC, n.d.; DPC, 2018b.*

2016-17 CENTRAL APENNINES SEISMIC SEQUENCE: MW≥5.5 EARTHQUAKE							
Date	Mw	Zone	Lat.	Long.	PGA max (cm/s2)	Fatalities	Injured
2016-08-24	6.0	1 km W Accumoli (Rieti)	42.70	13.23	916	299	392
2016-10-26	5.9	3 km NW Castelsantangelo sul Nera (Macerata)	42.91	13.13	684	0	0
2016-10-30	6.5	5 km NE Norcia (Perugia)	42.83	13.11	650	0	38
2017-01-18	5.5	2 km NW Capitignano (L'Aquila)	42.53	13.28	584	0	0

Other temporary shelter solutions were set up in safe sports arenas and gyms available in the affected area, while most of the population was moved from the disrupted villages to the hotels in the Adriatic coast. On 25 October 2016, 1 136 people were assisted, but at the end of the same month the population directly assisted increased again, to 31 763 people, owing to the increase in damage and the widening of the affected area.



The aim of this chapter is to identify some practical actions for preparedness, prevention and mitigation that could be implemented in the very near future to achieve an overall seismic risk reduction in the long term. Focusing on the impact on the main assets, it identifies lessons learned and gaps to be filled.

A comprehensive exploration of all the possible insights is out of the scope of this work, but some lessons are drawn from the fields of emergency and recovery, prevention and mitigation, management and governance at national and European levels.

***Fig. 3.** Macroseismic survey of the 2016–2017 Central Italy seismic sequence in the Mercalli Cancani Sieberg (MCS) Intensity scale after the October 30th, 2016, strongest main shock **Source**: Galli et al., 2017.*

2 Impact on the main assets

Residential buildings, schools, hospitals, cultural heritage, livestock farms, roads and other lifelines were severely affected, with direct economic losses in the order of EUR 21 billion and considerable indirect social and economic impacts.

The damage to the various assets was devastating, owing to the cumulative effect of the several main shocks: residential buildings, schools, hospitals, cultural heritage, livestock farms, roads and other lifelines were strongly affected. Some relevant damage is shown in the photo reports released by ReLUIS([1]), the Laboratories University Network of seismic engineering , the Laboratories University Network of seismic engineering, e.g. those by Celano et al. (2016), Dall'Asta et al. (2016), Del Vecchio et al. (2016) and Menna et al. (2016), and in the works by Tertulliani and Azzaro (2016a,b, 2017). This damage resulted in huge direct economic losses, estimated at c. EUR 21 billion, accompanied by considerable indirect social and economic impacts.The impact on the main building assets was quantitatively well monitored through the c. 220 000 damage and usability inspections carried out after the main shocks (Dolce and Di Bucci, 2018). Some buildings were inspected more than once, because of the subsequent main shocks.

A total of 2 678 inspections of school buildings were carried out; 66 % of the buildings were judged safe and the remaining 34 % (27 % slightly, 7 % very) unsafe (Di Ludovico et al., 2018, 2019).

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Table 2. *Summary of the results of the damage and usability inspections on public and strategic buildings and structures* ***Source:*** *DPC*

Public and strategic buildings and structures	Safe	Slightly unsafe	Very unsafe	Total	Safe	Slightly unsafe	Very unsafe	Safe	Slightly unsafe	Very unsafe
					% of total			*% of category*		
Hospital and socio-health buildings	241	102	75	418	6	3	2	58	24	18
City hall buildings	240	167	89	496	6	4	2	48	34	18
Civil collective activity buildings	366	252	149	767	9	6	4	48	33	19
Military collective activity buildings	212	83	51	346	5	2	1	61	24	15
Religious collective activity buildings	92	109	129	330	2	3	3	28	33	39
Technological service buildings	80	25	45	150	2	1	1	53	17	30
Transportation structures	12	9	5	26	0	0	0	46	35	19
Other public sector buildings	768	382	355	1505	19	9	9	51	25	24
Grand total	2.011	1.129	898	**4.038**	**50**	**28**	**22**			

Almost 50 % of the 4 038 public and strategic buildings, excluding schools, were found to be unsafe, as shown in Table 2. The hospital system suffered serious consequences. Inspections on 18 complexes, made up of 80 different buildings, found 14 hospital complexes and 32 buildings to be unsafe.

The road network in the affected area has a total length of more than 15 000 km and serves a territory with 1 770 widespread towns and villages. The interplay between seismic events and associated geological co-seismic effects (e.g. landslides and rockfalls) had a strong impact on it (Dolce and Di Bucci, 2018; Durante et al., 2018). The rehabilitating interventions on the roads were all entrusted to the national road company ANAS, with EUR 769 million of total investment (Soccodato et al., 2019). Local electrical and telecommunication blackouts and

([1]) *http://www.reluis.it/index.php?option=com_content&view=category&id=80*

other issues were observed during the seismic sequence. However, the longest and most widespread blackout was caused by the extraordinary European cold wave of January 2017, probably connected to climate change, which occurred along with the seismic events of 18 January 2017 (parameters for the strongest of these seismic events in Table 1).

Local electrical and telecommunication blackouts and other issues were observed during the seismic sequence. However, the longest and most widespread blackout was caused by the extraordinary European cold wave of January 2017, probably connected to climate change, which occurred along with the seismic events of 18 January 2017 (parameters for the strongest of these seismic events in Table 1). Local unavailability of drinkable water and damage to gas infrastructure occurred during some stages of the seismic sequence. Hydrochemical changes in water have been described by Rosen et al. (2018) and De Luca et al. (2018). No or very limited damage to dams was observed. Infrastructure components are further discussed by Stewart et al. (2018). The limited impacts on, and the role of, the mobile telecommunication network in the different phases of the chain of events have also been pointed out (GSMA, 2017).

Some 5.200 damage inspections were carried out on immovable cultural heritage assets, 1 670 of which underwent post-earthquake stabilisation (MiBAC, 2018). These data do not include historic centres, such as those of the villages in the epicentral areas (see for example Sorrentino et al., 2018; Pessina et al., 2019). In these cases, there were significant impacts on tangible and intangible heritage. A huge number of movable cultural heritage assets were recovered: 22 131 artistic and archaeological assets, 5.44 km of archives and 15 229 books Before the earthquake, the affected areas shared a slow but inexorable demographic and productive decline, which involved at first the manufacturing sector, but also agriculture, tourism, craftsmanship, the food industry and, consequently, trade. However, the socioeconomic impact was different from zone to zone, both because of the different shaking intensity and because not all the sectors and productive activities reacted the same way to the earthquake (Esposti et al., 2019).

The landscape, understood as the fruit of the relationship between humans and nature (Council of Europe, 2000; Priore, 2009), is likely to be greatly affected too. The temporary abandonment of territories, if prolonged over time, will potentially cause the loss of the landscape in that sense (Sargolini, 2017a).

3 Lessons learned

Time turns out to be a critical factor in post-earthquake recovery scenarios, because of multiple socioeconomic and other external factors.

3.1 Emergency and recovery

The damage and safety assessment of buildings has an important role in both the emergency management and reconstruction phases. In Italy, it is usually performed in accordance with the AeDES inspection form and the associated procedure (Baggio et al., 2007; Dolce et al., 2009; Papa et al., 2016a,b), but, after the October 2016 earthquakes, a procedure based on a simplified inspection form had to be introduced to speed up inspections (Dolce and Di Bucci, 2017). A total of c. 8 000 operators were employed in the surveys. The continuity of school activity is crucial to avoid depopulation and support a rapid recovery to normal life conditions. Slightly damaged school buildings were quickly repaired, while alternative temporary solutions for seriously damaged schools were implemented, such as temporary allocation of students to safe school buildings or in temporary prefabricated schools. Moreover, many students attended schools in the Adriatic coast towns, where part of the population of the disrupted villages was hosted.

Strong coordination of the health emergency management turns out to be essential. A coordination centre for health rescue in case of disaster was established for the rational deployment of resources, health experts and materials required in the affected area, and to prepare the assisted evacuation of patients in a critical condition. Eight advanced medical points, supplied by the four regions involved, were deployed as well as a socio-health assistance point. Three further socio-health assistance points came later from other regions. The medical assistance in the affected area was directed to the main provincial and regional hospitals, since only minor hospitals had to be evacuated.

Infrastructure disruptions over time call for continuous adaptation of the response. In performing emergency and recovery infrastructural interventions, the dual aspect of urgent actions and long-term recovery had to be addressed. Public–private cooperation was very useful to handle infrastructure disruption and recovery. This was enabled by the organisation of the National Civil Protection Service, which includes companies dealing with road and railway networks, energy and telecommunication (Dolce and Di Bucci, 2018). Real-time monitoring of infrastructures can be very useful for emergency management. Indeed, some key infrastructure components (e.g. bridges, dams) were already monitored through the DPC-OSS and DPC-RAN national monitoring networks (OSS for Osservatorio Sismico delle Strutture, Seismic Observatory of Structures; RAN for Rete Accelerometrica Nazionale, National Strong-Motion Network; Dolce et al., 2015), giving potential insights into structural response that are useful for management decisions.

The production continuity of livestock farms is a priority for overcoming emergencies and for economic recovery. Many of them had their structures damaged. To allow farmers to continue their activities, most actions were aimed at assessing the safety of zootechnical constructions; evaluating the impact on zootechnical production and livestock health; conducting a livestock census; identifying solutions and tools to overcome zootechnical critical issues; and providing assistance programmes to farmers (see also United Nations, 2015). Temporary structures were placed near damaged farms to house farmers' families and to provide for recovery of livestock, storage of feeds and milk conservation.

Cultural and architectural remains from collapsed heritage buildings have to be recovered for future restoration work. The Cultural Heritage Ministry provided procedures for the removal, classification and recovery of huge amounts of valuable rubble. Safe housing of rescued movable cultural heritage assets also requires facilities for their restoration. Adequate pre-existing facilities were not available in all the four affected regions, thus delaying recovery operations (Osservatorio Sisma, 2018). Umbria had already constructed a 5000 m2 earthquake-safe storage facility, where c. 7 000 movable assets as well as heritage rubble remains of the region were stored.
For all the aspects dealt with so far, time turns out to be a critical factor in post-earthquake recovery scenarios, because of multiple socioeconomic and other external factors.

3.2 Prevention and mitigation

The poor quality of the masonry in general and of its mortar in particular, as well as the lack of retrofit measures in masonry structures, combined with strong shaking, led to high collapse rates (Sorrentino et al., 2018). In contrast, previous structural retrofits typically preserved structures from collapse, thus saving lives inside (Stewart et al., 2018). This was the case in the historical centre of Norcia, where extensive retrofitting was implemented after the 1979 and 1997 earthquakes. Adequate seismic performance was observed in modern masonry buildings made of hollow clay blockwork. Such a positive response is an encouraging indication for future building activity. The serious damage to non-structural parts (typically infill masonry walls) of reinforced concrete buildings implies high repair costs. Moreover, structural and non-structural damage was observed on several buildings previously subjected to energy efficiency upgrades, thus jeopardising the retrofitting investment. Therefore, in earthquake-prone areas, energy upgrading should be combined with seismic retrofitting in an integrated approach; otherwise, handling energy and structural/seismic retrofitting separately can turn out to be excessively expensive (Bournas, 2018; Gkournelos et al., 2019).

Awareness of interdependencies among different infrastructures was raised (GSMA, 2017). Mobile network operators reported that severe problems were caused by power shortages in the area. They asserted the importance of redundancy, in terms of both backup energy and mobile emergency equipment, as well as of prevention, training and communication.

The need to provide heritage assets with adequate seismic protection has to be emphasised. Aside from their cultural and socioeconomic importance, some of them, e.g. churches, can be crowded at certain times. Improving their seismic performance seems a logical step, but the reality is different. The complex structural behaviour of this type of buildings makes their seismic retrofitting technically challenging (e.g. Cardani and Belluco, 2018). Moreover, there is a cultural divide between the engineering and conservation views of cultural heritage preservation. Borri and Corradi (2019) refer to examples of conservation bodies promoting the restoration of internal assets in churches without improving their seismic behaviour, not even using simple, inexpensive seismic devices (Penna et al., 2019).

3.3 Management and governance at national level

Prevention and mitigation strategies have always been strongly influenced, in Italy, by the occurrence of catastrophic events. After the Mw 6.9 Irpinia earthquake in 1980, a new classification of the national territory was adopted and, in 1982, the DPC was established. During the Mw 5.9 Umbria–Marche earthquake emergency in 1997, the civil protection system positively tested both its organisation and a new technical emergency management system (Baggio et al., 2007). After the Mw 5.7 Molise earthquakes in 2002 (Valensise et al., 2004), a Prime Minister's ordinance enforced new seismic classification and seismic code aligned with the European Code (EN-1998, 2004). It also established that strategic and important public buildings and infrastructures had to be subjected to safety evaluations.

Following the Mw 6.3 L'Aquila earthquake in 2009 (Dolce, 2010), new technical standards were enforced and almost EUR 1 billion was allocated for microzonation and seismic upgrading of strategic public buildings and infrastructures and of private buildings (Dolce, 2012). The Mw 5.9 Emilia earthquake in 2012 (Dolce and Di Bucci, 2013) boosted initiatives for resilience improvement in the private production sector. Finally, after the central Italy 2016–17 sequence, technical standards were updated, and tax incentives for seismic retrofitting of private buildings were introduced, based on their risk classification (Cosenza et al., 2018).
Standard residential property insurance policies in Italy typically do not cover seismic damage (OECD, 2018). It is estimated that only 1 % of Italian residential properties are covered against earthquake risk. Introducing compulsory seismic risk insurance would allow the Italian state to save progressively money paid for damage and then invest more in prevention.

According to the Italian Senate (Senato della Repubblica – Ufficio Valutazione Impatto, 2017), about 75 % of the

EUR 13 billion budget allocated for the reconstruction is devoted to infrastructure and real-estate assets. A large amount of the budget (c. 20 %) is also committed towards the resumption of economic activities and supporting the economic needs of the population.

Emergency and reconstruction management are closely related. Many of the choices made in the emergency phase can affect the success of the reconstruction and vice versa, as they are partly overlapping in time and activities. At the national level, this was managed through close relations between the civil protection and the special commissioner for the reconstruction. Similarly, continuous and close collaboration is needed among the national, regional and local levels of governance on the reconstruction process. The commissioner issued ordinances to guide the decision-making activity of regions and municipalities. He also established a technical scientific committee, which provided advice on planning and realizing the interventions of seismic adaptation and restoration of destroyed buildings. The interventions must be compatible with the protection of the architectural and environmental aspects, to obtain eco-sustainable architecture and energy efficiency (United Nations, 2015; Stimilli and Sargolini, 2019).

The reconstruction process must take into account the need for reinterpretation of the landscapes, as not everything can be rebuilt where it was and how it was. Only the renewal of the landscapes will be able to support the conservation of the Apennines' culture (Gambino, 1997).

3.4 Management and governance at European level

Major European earthquakes over the last few decades – mostly in Italy (2002, 2009, 2012, 2016, 2017), Greece (2014, 2016), Iceland (2014) and Spain (2011) – have not only caused the loss of c. 1 000 lives, but also inflicted huge economic losses across Europe. The European Commission focused many European research projects on this topic, dealing with seismic hazard, vulnerability and risk assessment for buildings and critical infrastructures, and on real-time risk reduction. In particular, the SHARE (Seismic Hazard Harmonization in Europe) project developed the 2013 Euro-Mediterranean Seismic Hazard Model (ESHM13). Nevertheless, as observed in the vision paper produced by the Enhancing Synergies in the European Union (ESPREssO) project (Zuccaro et al., 2018), to support decision-making processes, such improved hazard models need to be integrated within risk/impact assessment approaches, to enable alternative mitigation and/or adaptation measures to be compared. In this direction, the ongoing SERA project (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe; European Commission, 2020), which builds on SHARE([2]) , is developing the ESHM20 hazard model and a new risk model for Europe.

From an emergency management perspective, the relevance of improved emergency communications and monitoring tools to effective coordination and deployment of response bodies is evident. Within the Union Civil Protection Mechanism (UCPM), the consolidation of the Emergency Response Coordination Centre Common Emergency Communication and Information System allows better interinstitutional coordination, providing a web-based alert and notification application. Moreover, the strengthening of the Copernicus Emergency Management Service can add value by rapid satellite mapping, responding to the need to support emergency response in the early operation phases, and to monitor recovery actions over time.

Structural prevention is one of the most important general policy targets for disaster risk reduction to be implemented in the coming years. For this reason, EU policy should consider incentivising seismic, as well as energy, retrofits in earthquake-prone regions. As of 2019, the Joint Research Centre is working on iRESIST+ (innovative seismic and energy retrofitting of the existing building stock; European Commission, 2019), a project

([2]) *http://www.sera-eu.org/en/activities/joint-research/*

for the development of a novel approach to the simultaneous seismic and energy retrofitting of existing buildings. Action 9 of the European framework for action on cultural heritage published in 2018 (European Commission, 2018) recognises that seismic upgrading of historical buildings in Europe is increasingly important. In the framework of the UCPM (European Commission, 2017), the European Commission finances prevention and preparedness projects, including for cultural heritage, which will enhance the collection of data and foster prevention, preparedness and response capacities in case of natural disaster.

4 Filling the gaps

National and local governments should seek new and creative ways to build awareness, by involving communities in disaster planning and preparedness activities, and in the decision-making process.

4.1 Understanding risk

Population ageing, the depopulation of some areas, the effectiveness of educational and health infrastructures, and either a cohesive or a disintegrated social fabric affect earthquake impacts (Ismail-Zadeh and Cutter, 2015; Sartori, 2017). The discovery of the different dimensions of the vulnerability of communities adds knowledge necessary to promote resilience, i.e. the ability to channel community energy and territorial resources positively. Social and psychological aspects are important components of this vulnerability. They are analysed and taken into account in Italy, for instance to prepare a more effective emergency management (see, for instance, activities by "*Psicologi per i Popoli*" ([3]) ; Vaudo, 2018). This issue should be more developed in order to build up communities' awareness and resilience. The policies for the affected areas should be designed so that post-earthquake reconstruction relaunches them strategically.

The Principles for the analysis, conservation and structural restoration of architectural heritage (ICOMOS, 2003, statement 3.5) state that 'each intervention should be in proportion to the safety objectives set, thus keeping intervention to the minimum to guarantee safety and durability with the least harm to heritage values'. The co-operation of several sectors and types of expertise is needed, including to deal with the considerable uncertainties in the knowledge of the construction, its old materials, its complex structural behaviour, and the interaction between the construction and the modern retrofitting solutions (Cardani and Belluco, 2018; Penna et al., 2019). Recent advances in some materials suggest interesting new solutions (Valluzzi, 2016; Rousakis, 2018), but a careful approach is necessary, promoting scientific tests to validate new retrofitting materials and techniques, as well as dissemination to professionals.

Structural response monitoring has shown its usefulness for understanding risk. During the three main shocks, 37, 59 and 60 structural monitoring systems of DPC-OSS([4]) (Dolce et al., 2015) were triggered. The scientific exploitation of the relevant records provides important contributions to understanding the seismic response of structures. Future advances in information and communication technology and lower instrument and telecommunication costs can hugely increase the number of constructions monitored.

Post-seismic surveys after major earthquakes are fundamental to learn lessons from the field, and train young

([3]) http://www.psicologiperipopoli.it/
([4]) http://oss.protezionecivile.it

specialists. Their objective is to collect factual information, draw important lessons and promote preventative recommendations (earthquake-resistant design, monitoring data, population information, town planning, socioeconomic aspects). From a regulatory viewpoint, the second generation of Eurocode 8, to be published in 2021–22, is an opportunity to step back and take stock.

4.2 Planning risk reduction

Only responsible regional and municipal planning offers a response to the increasingly complex realities faced by communities, by linking disaster risk reduction, emergency management and response with other policy fields (Sargolini, 2017b). Risk assessment and management should be an integrated part of the planning and governance process (Moroni, 2010).

A multilevel and multi-stakeholder participation approach would be most effective (UNISDR, 2015). Possible roles of territorial planning in disaster risk reduction are (Greiving et al., 2007) (1) classifying different land use settings for disaster-prone areas; (2) regulating and differentiating land use or zoning plans with a legally binding status related to a given hazard/vulnerability combination; (3) providing evidence bases, such as hazards and risk maps, and detailed datasets of information to evaluate territorial plans against, in order to understand the possible consequences of disasters on land use allocations, also considering some degree of risk acceptability. According to the Incheon Declaration (Incheon, 2009), the most appropriate level to implement the functions of territorial planning in disaster risk reduction is the local government level.

The seismic vulnerability of school buildings (Dolce, 2004; Di Ludovico et al., 2019) deserves special care for the social consequences that their damage and collapse bring about. A specific comprehensive plan is needed to seismically upgrade the huge number of inadequate schools within a reasonable time horizon. Moreover, a plan for school emergency management should be prepared by the ministry of education and the civil protection national authority.

4.3 Implementing risk reduction

National and local governments should seek new and creative ways to build awareness, by involving communities in disaster planning and preparedness activities, and, more generally, in the decision-making process (Johnson et al., 2005; Di Bucci and Savadori, 2018). The attention of the media after major events should be exploited to increase public awareness, disseminate basic technical knowledge and promote political actions to increase prevention, preparedness and resilience. It is necessary to engage the population in three disaster phases: (1) preparing for disasters, when risk awareness and resilience preparedness are key concepts; (2) reacting to a disaster situation, when emergency communication and community integration have to be ensured; (3) overcoming a disaster event, when the affected area should be integrated with community and recovery support.

For a true community-based support approach after a disaster, optimal use of local skills and resources has to be made. It is also important to consider recovery support as a process, and not simply as the supply of products and services. Currently, a substantial gap still remains in the research (Djalante and Thomalla, 2011; Banba and Shaw, 2017). More specifically, there is a literature gap on the connection between the notions of participatory governance, disaster governance and building community resilience. One specific design of reflexive and participatory governance is in the concept of transition management (Kemp and Rotmans, 2009; Loorbach, 2010).

5 Final remarks

The reconstruction process, while reducing risk, should preserve the specific characteristics and landscape of the territory, and promote innovation in production systems to avoid further depopulation.

The impact of the 2016–2017 moderate to strong earthquakes on assets and communities was high. Management of the emergency was made difficult by the long duration of the sequence, which struck a territory that was vulnerable from both physical and socioeconomic points of view. The main assets, especially dwellings, schools, hospitals, transport infrastructure and cultural heritage, were severely damaged, and the communities and the local production systems, mainly based on rural micro-enterprises, were severely affected.

Many important lessons can be learned in various fields, from the most technical ones to those related to the reconstruction process, which should also preserve the identity and the landscape of the territory, while promoting innovation in the production system to allow people to remain there.

The recurrence of strong earthquakes for 5 months made the emergency and recovery phases extremely complicated, and time has turned out to be critical owing to multiple socioeconomic and other external factors. Damage and safety assessment is crucial for both phases, since its outcome is needed to ensure safety and the continuity of residence, schooling and production, especially by zootechnical firms in the central Italy case. This continuity and effective infrastructures are fundamental to avoid depopulation and to support a prompt recovery to normal life conditions. In this case study, the repeated infrastructure disruptions over time called for continuous adaptation of the response, and public–private cooperation was very useful to handle infrastructure disruption and recovery.

Structural prevention is sorely needed, especially because of the high vulnerability of old masonry buildings. Indeed, seismic retrofitting of old buildings, as well as the use of modern masonry in new buildings, has turned out to be effective in avoiding collapse and reducing damage. Non-structural parts of modern reinforced concrete buildings not designed in accordance with the most recent codes underwent severe damage. Special attention is required when energy efficiency upgrading is carried out. Generally speaking, in future it should be combined with seismic retrofitting. In any case, the interventions must be compatible with the protection of the architectural and environmental aspects, to obtain eco-sustainable architecture and energy efficiency. A specific comprehensive plan is especially needed to seismically upgrade the huge number of inadequate schools within a reasonable time.

Cultural heritage requires a great effort in the emergency phase, not only to secure damaged immovable assets but also to recover cultural and architectural remains from collapsed heritage buildings for future restoration work. Facilities are also needed to safely house rescued movable cultural heritage assets, and to restore them. The need to provide heritage assets with adequate seismic upgrading is emphasised once again. However, a careful approach is necessary, promoting scientific tests to validate new retrofit materials and techniques for built heritage, as well as dissemination to professionals.

Interdependencies among different infrastructures were demonstrated, and there is a need for greater attention to them and for public–private cooperation to deal with this problem in a more comprehensive way.

Disaster risk reduction, and particularly structural prevention, is one of the most important general policy targets to be implemented in the coming years. For this reason, besides energy retrofitting, EU policy should consider incentivising seismic retrofits in earthquake-prone regions. Discovering different dimensions of the community's vulnerability adds knowledge that is necessary to promote resilience. National and local governments should seek new and creative ways to build awareness, by involving communities in disaster planning and preparedness activities. Optimal use of local skills and resources should be looked for. Only responsible, regional and municipal, comprehensive planning offers a response to the increasing complexities faced by communities.

Emergency and reconstruction management are closely related. Many of the choices made in the emergency phase can influence the success of the reconstruction and vice versa as they are partly overlapping in time and activities. The reconstruction process must take into account the need for reinterpretation of the landscapes, since not everything can be rebuilt where it was and how it was. A continuous and close multilevel collaboration is needed among local, regional, national and EU governance on the reconstruction process.

Not all issues related to the disaster caused by the 2016–2017 central Italy earthquakes could be considered in this chapter. However, the wide variety of issues discussed provides an example of complex emergency management, prevention activities and governance at national and European levels, and shows how long the process is to reach an effective disaster risk reduction strategy.

ACKNOWLEDGEMENTS
The 7th contributing author would like to acknowledge the financial support from POCI-01-0145-FEDER-030469 - RIACT – Risk Indicators for the Analysis of Cultural heritage under Threat, by FEDER through COMPETE2020 - Programa Operacional Competitividade e Internacionalização (POCI) and by national funds through FCT - Fundação para a Ciência e a Tecnologia, and the financial support from Base Funding - UIDB/04708/2020 of CONSTRUCT - Instituto de I&D em Estruturas e Construções, by national funds through FCT/MCTES (PIDDAC).

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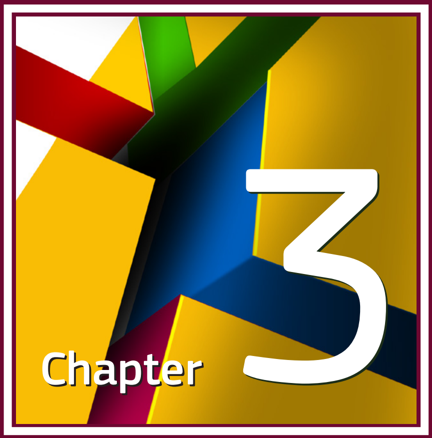

Assets at risk and potential impacts

3.2

Population

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Online Version

Kemper, T., Freire, S., Petrucci, O., Schiavina, M., Zuccaro, G., Çoşkun, A.M, Frigerio, I., 'Population', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

3.2 Population

CONTENTS

3.2 Population

Introduction

Natural and human-made disasters affect and disrupt the lives and livelihoods of people in different ways. This is at the core of the Sendai Framework for Disaster Risk Reduction. The expected outcome of the framework is a 'substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries' (UNISDR, 2015, p. 12). In order to monitor this, the first two targets of the framework address the people killed or affected, because people are the most important asset to protect from risk and disaster. People are the ones we ultimately want to protect from the impact of disasters. As the Sendai Framework states, there are not only the direct and immediate impacts of hazards on people such as death or injury. There are also a number of indirect and long-term impacts on people that may not injure or kill directly, but instead may cause long-term impacts on individuals or entire societies. The impacts of disasters may deprive people of their homes, their livelihoods and impede the functioning of society as a whole.

Consequently, this subchapter will address the population at risk and the potential impacts of disasters on populations by analysing the different dimensions, from the individual to society as a whole. Starting from the individual,

Section 3.2.1 analyses how hazards threaten human lives in Europe, and the wider impacts of disasters on people's health and well-being, considering how different hazards interplay with the effects beyond immediate impacts. This section addresses the relations between the disaster management cycle and hazards causing death, injury or health damage across Europe. The temporal dimension plays a central role here; the speed of hazard onset (quick/slow onset) has to be linked to the duration of effects on humans (short/long term). The section proposes new approaches such as biomonitoring methods and biomarkers for improved assessment of exposure and human health risk; it also addresses the importance of human behaviour and measures of self-protection as factors influencing impacts, illustrating this with the example of the heatwave in Europe in 2003.

Section 3.2.2 enlarges the view from the individual to the immediate habitat of the people – their homes and immediate neighbourhood. It takes the housing/habitat as the asset at risk and analyses the impacts of three different disasters: the Toll Bar flood 2007 in the United Kingdom, the Grenfell Tower fire in 2017 in the United Kingdom and a series of earthquakes in Italy. The primary measure of impact analysed in this section is relocation or displacement of population from their homes. This takes into account the different spatio-temporal scales of displacement. The analysis highlights the importance of hindsight analysis and implementation of the lessons learned.

Section 3.2.3 finally expands the analysis of the impact of disasters to the entire society. By 'society', we refer to all the people that live together, have a common history and cooperate to carry on their lives and pursue fundamental interests. This can be a local society, but also parts of a nation or the entire population of a country or region. Society has a complex structure with uncounted social and economic relationships. The structure of society is dynamic, with many external and internal factors that are constantly changing and developing it. When disasters strike, they also affect societies and may lead to disruption of the way societies function. This section explores the Van earthquake in Turkey (2011) and a toxic cloud after a technical accident in Zevekote (Belgium) in 2017 to review the impacts of different types of disasters at the community/society level based on the results of case studies, to show social reactions to disasters and to better illustrate social patterns and vulnerable groups in society.

3.2.1 Threat to life

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Freire, S., Petrucci, O., Scheepers, P.T.J., Neuvel, J.M.M., Rocklöv, J., Åström, C., 'Threat to life', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Introduction

People are the most important element to protect from risk and disaster, being at the centre of three of the Sendai targets (UNISDR, 2015a). Human exposure to hazards has been increasing in magnitude and complexity as a result of population growth and expansion to hazardous areas (Ehrlich et al., 2018) and is likely to be the main factor inflating disaster risk in the near future (Peduzzi, 2019).

Disasters affect lives and livelihoods in different ways and with diverse intensities. From a social point of view, hazards may negatively affect people beyond those directly exposed to events, such as their families or social circles, or emergency responders. Spatially, even people living far from the damaged sites but having some relationship with affected communities can be affected. On the other hand, people exposed to a particular hazard can be less affected than expected, thanks to their ability to either reduce their vulnerability or increase their coping capacity. From a temporal point of view, besides direct and instantaneous impacts, disasters can also have gradual chronic effects. The latter can remain hidden or be underestimated in the immediate aftermath of events, and surface at a later stage, making it challenging to assess and address them fully.

In recent decades, the systematic collection of disaster-related data has become a crucial concern, with the recognition that comprehensive disaster loss data are essential to inform disaster reduction policies that are based on the impacts of past events and aim to calibrate and validate forecasting models (Faiella et al., 2020). Several international organisations and EU Member States collect information on people killed or injured by a number of severe disasters (De Groeve et al., 2013, 2014). However, data collection on the human impact of disasters is not a legal obligation in EU Member States, at either national or regional scale, and smaller events or those with few victims are generally omitted from statistics. Scientific groups create databases of effects on people for selected areas and events in order to model human behaviour and establish good practices and recommendations to improve safety (Petrucci et al., 2018; 2019).

Whereas data on direct impacts on people – albeit fragmented in space and time – are available, in contrast there is a shortage of data to monitor long-term effects of disasters, especially those related to climate change. In Europe, ongoing environmental and socioeconomic changes may combine to increase vulnerabilities and risk, leading to the creation of scattered risk hotspots (e.g. more frequent and/or intense droughts and heatwaves combined with ageing and depopulation of settlements, increasing the risk and impacts of rural fires).

This section addresses how hazards and vulnerabilities threaten human lives in Europe, and the wider impacts of disasters on people's health and well-being, considering how hazards' characteristics interplay with the effects beyond immediate impacts.

2 The determinants of effects on humans

HolisticHolistic and integrated disaster risk management (DRM) should be tailored to specific types of hazards. Mitigation and prevention of hazards should consider specific human vulnerabilities.

2.1. Characteristics of the hazard

Each type of hazard has different potentially dangerous effects on people. Despite the intrinsic differences between hazard types, the time in which the event develops and its spatial development can vary by orders of magnitude (Figure 1).

The speediness of the event affects the ability to evacuate the affected area. For example, a fluvial flood may allow more time for evacuation than a flash flood. Similarly, a slow-onset landslide may allow time for evacuation, whereas a rockfall develops almost instantaneously, giving no time for early warning, evacuation and protective actions. Figure 2 presents indicators of potential damaging effects on people, sorted according to the type of hazard.

Typically, slow-onset events, such as drought, affect large populations throughout long periods, and the exact beginning and end of the disaster are difficult to identify. In contrast, fast-onset events can affect both small and large numbers of people in a more specific interval of time, ranging from seconds or minutes, in the case of earthquakes, to weeks, in the case of fluvial floods. Nevertheless, there are also hazards lasting for years, such as either bradyseism or large slow-moving landslides characterised by quiescent periods and acceleration phases. Regarding biological risk (included in CBRN - chemical, biological, radiological and nuclear), the rapid spread of infectious diseases into global pandemics has the potential to cause millions of casualties in a relatively short time (months). Disease outbreaks can also arise in the aftermath of, and as result of, other disasters.

In addition to the onset, the effects of hazards are influenced by the intensity or magnitude and duration of the event. For example, the potential harm of a fire to a person depends on both the heat radiation and the duration of the fire. Short fires with low heat radiation have less impact than long-lasting fires with high heat radiation. Similarly, long seismic sequences can have effects on the mental health of people and can strongly affect the quality of life (Catapano et al., 2001).

Figure 1. *Main temporal and spatial characteristics of hazards (CBRN: chemical, biological, radiological and nuclear)* ***Source****: Authors.*

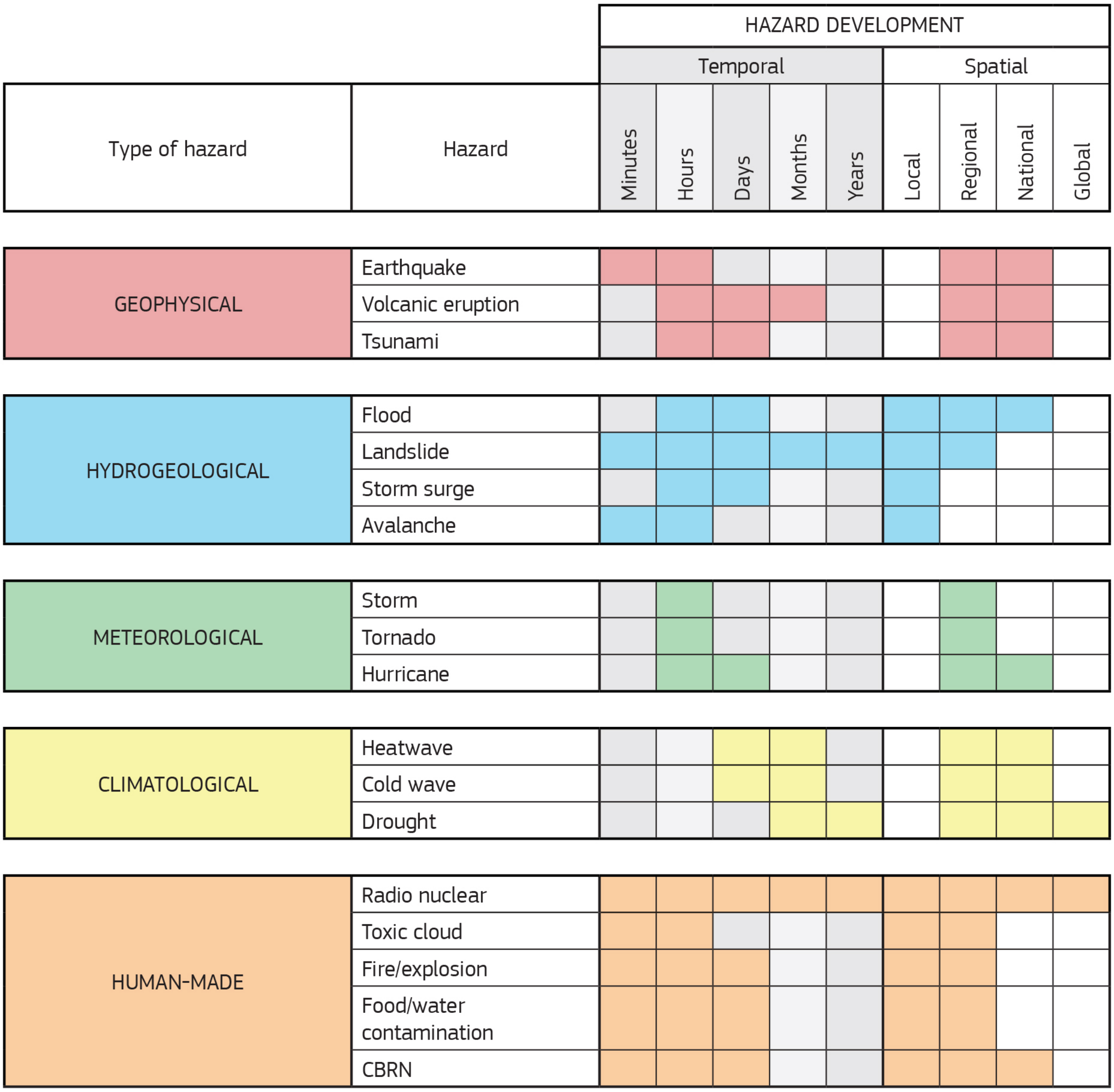


Figure 2. *Indicators of potential damaging effects on people sorted according to the type of hazard (CBRN: chemical, biological, radiological and nuclear)* ***Source****: Authors.*

HAZARD		INDICATORS OF POTENTIAL DAMAGING EFFECTS ON PEOPLE											
Type of hazard	Hazard	Magnitude	Rapidity	Velocity	Duration	Wind velocity	Rain	Temperature	Water depth	Volume	Area of invasion	Gas/ash	Debris carried
GEOPHYSICAL	Earthquake	■			■								
	Volcanic eruption		■	■							■	■	
	Tsunami	■	■						■		■		■
HYDROGEOLOGICAL	Flood		■	■					■				■
	Landslide		■	■						■	■		
	Storm surge			■					■		■		
	Avalanche		■	■						■	■		
METEOROLOGICAL	Storm					■	■						
	Tornado					■							■
	Hurricane					■	■						
CLIMATOLOGICAL	Heatwave				■			■					
	Cold wave				■			■					
	Drought				■								
HUMAN-MADE	Radio nuclear	■	■	■	■						■		
	Toxic cloud		■	■									
	Fire/explosion		■	■									
	Food/water contamination	■											
	CBRN		■	■									

2.2 Exposure and vulnerability

Population vulnerability can be subdivided into direct physical population vulnerability (injuries, deaths and homelessness) and indirect social vulnerability (Van Westen, 2013). For different types of hazards, empirically derived relations of vulnerability exist, although most information is available for earthquakes (Coburn and Spence, 2002; FEMA, 2004). For volcanic hazards, such relations were established by Spence et al. (2005) among others, for landslides by Glade et al. (2005), for drought by Wilhite (2000) and for flooding and windstorms by FEMA (2004) (Van Westen, 2013).

Individual biological or physical capacities, such as the ability to run or tolerate heat, may influence a person's vulnerability to a particular hazard. In addition, individual behaviour can reduce fatalities. For example, respondents who perceive a flood risk as threatening and feel that risk-mitigating options are feasible and useful will engage in risk-mitigating behaviours that may increase their self-protectiveness (Kievik, 2017). On the other hand, people who are not aware of flood risks are more likely to take chances and may have a higher likelihood of becoming victims.

At community level, socioeconomic aspects such as age, income and formal education can indicate individual and social vulnerability (Cutter et al., 2003). Socioeconomic inequalities can lead to different vulnerability and resilience patterns. Moreover, socioeconomic status has also been found to be correlated with exposure to hazards. Hazard-prone areas, for example, are in general characterised by lower land values and, consequently, are occupied by lower-income households (UNISDR, 2015b). In countries where the family, societal and economic roles of males and females are dissimilar, the genders have contrasting mortality rates. An analysis of fatalities from landslides and flooding in Italy, for example, showed that in most age categories males are more vulnerable to floods and landslides (Salvati et al., 2018).

Moreover, risk reduction measures also improve the capacity to deal with hazards. For example, flood risk can decrease through structural measures such as flood retention basins, reducing peak water levels or improvement of levees. Furthermore, non-structural measures such as zoning can also prohibit new developments in flood-prone areas to prevent a further increase in exposure. For slow-onset disasters, e.g. floods in large catchment areas, effective early warning can increase the ability of the people exposed to the imminent flood to evacuate in time, assuming that suitable evacuation routes and/or suitable buildings for a shelter-in-place area are available.

2.3 Classification of disaster impact

The effects of disasters on people can be classified according to severity levels but the boundaries between levels are difficult to define. Except for the most severe effect, death, there is a continuum of severity including injuries of different levels of gravity, more or less serious psychological distress and discomfort of different sorts. The impact of disasters on people can be classified as direct, causing physical harm (death and injury), or as indirect, related to impacts on well-being due to, for example, loss of home and/or job, or health deterioration owing to contamination of air, water, soil and food. Some impacts can be intangible, such as reduced quality of life linked to psychological stress caused by disaster-related losses or by temporary evacuation or relocation.

These types of impacts on people are mostly related to the length of time over which they develop. Direct impacts are immediate and can be quantified by the number of people killed and injured. Such figures are typically available quite soon, after the missing people are found or their deaths are confirmed. Indirect impacts develop on a short/medium temporal scale and their duration depends on the possibility of repairing damage to houses, workplaces and public services, thus restoring the pre-disaster condition.

The duration of intangible impacts can vary from short to long. In worst cases, people forced to undergo changes involving habits, house and work can suffer permanent impacts. Some follow-up studies indicate that first responders may suffer from health effects that may be in part unexplained. In this context, biomonitoring methods and biomarkers allow the assessment of exposure and human health risk. For chemical incidents, guidance was developed in the Netherlands to support the use of human biomonitoring following such events (Scheepers et al., 2011; 2014). More than 200 biomarkers reflecting exposure to more than 150 chemical substances can be measured in blood, urine and exhaled air (Scheepers and Cocker, 2019). The next subsection presents some case studies in which biomonitoring was used.

3 Case studies: gaps and lessons learned

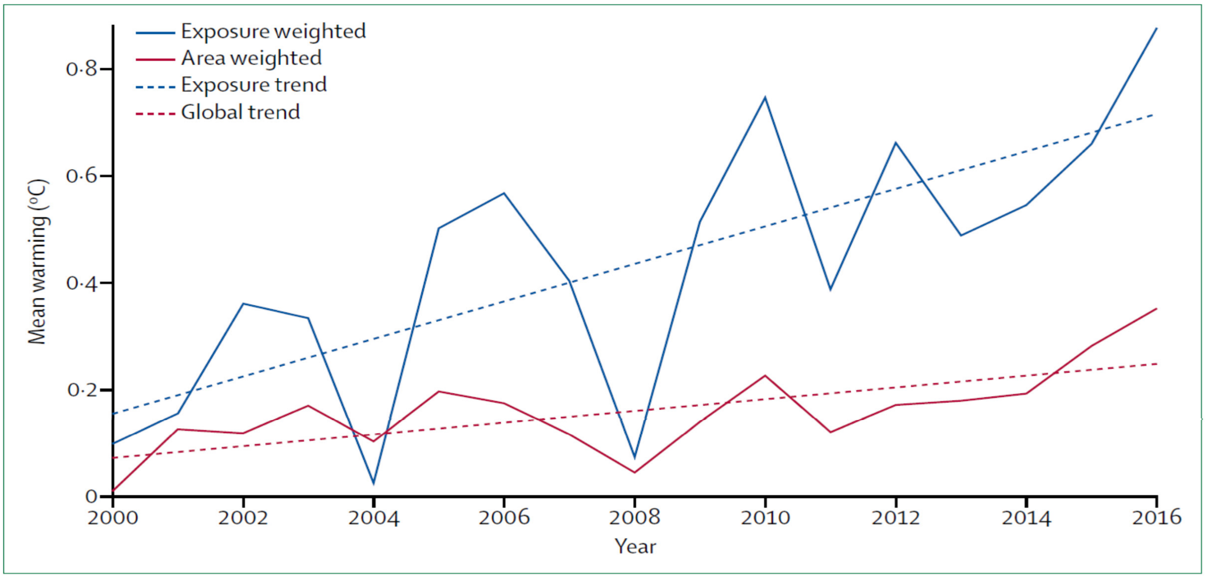
3.1 The 2003 heat wave in Europe

Prevention and mitigation actions should be especially directed at vulnerable population groups. Implementing a targeted heat action plan is the key to reducing human impacts.

Record-breaking temperatures occurred in the summer of 2003 in large parts of western and southern Europe. Temperature anomalies were observed during June and July, with the greatest deviation in June (Black et al., 2004). In the first half of August, temperatures reached a peak and generated unprecedented heat-related health impacts (García-Herrera et al., 2010). The excess deaths throughout Europe during the summer exceeded 70 000 (Robine et al., 2008). This event triggered the introduction of a wide range of adaptation efforts in those countries that were most affected. Studies suggest that, following the 2003 heatwave, several European cities have become less vulnerable to heat-related mortality (De' Donato et al., 2015). How much this is the result of successful adaptation strategies, community awareness and resilience, and how much the result of transient changes in vulnerable groups, is hard to quantify. Since 2003, many European countries have implemented early warning systems for heatwaves (Lowe et al., 2011), and the impact of the heatwave of 2018 created further incentives to improve the capacity to adapt to and mitigate unexpected, excessive heat among the countries of northern Europe as well (Åström et al., 2019). Implementing adaptation and mitigation measures is especially important because the proportion of Europe's population at very high risk of heat stress is expected to increase substantially by 2050 (Rohat et al., 2019). The impacts of the record-breaking temperatures in Europe in 2019, with above 45 °C observed in France, are not yet well understood.

As global temperatures increase, the frequency and intensity of heatwaves will also increase (IPCC, 2013).
The Lancet countdown on health and climate change has found that human exposure to abnormally high temperatures is increasing at a faster rate than the increase in global temperatures (Watts et al., 2018) (Figure 3). Between 2000 and 2016, the average human temperature exposure increased by 0.9 °C, double the overall global average. As populations and urbanisation continue to increase, this trend is likely to continue.

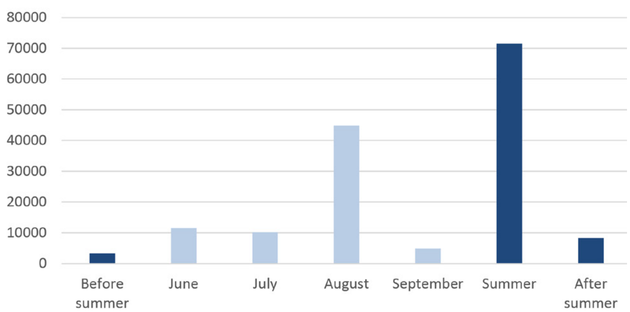
Figure 3. *Population exposure to abnormally high temperatures in response to global warming* ***Source****: Watts et al., 2018.*

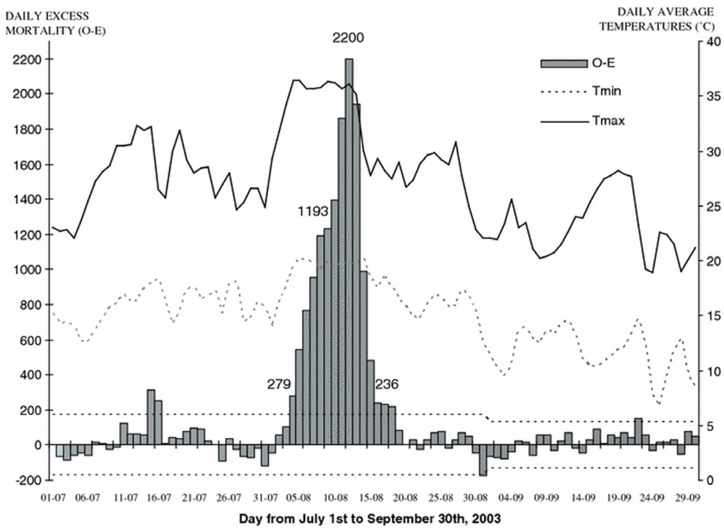


Timeline

The temperature extremes of summer 2003 were the result of the simultaneous occurrence of a range of meteorologically anomalous conditions, including widespread and persistent urban heat islands. This resulted in record-breaking temperatures mainly in southern and central Europe, with the severe health impacts in France, Germany, Portugal, Switzerland and the United Kingdom (García-Herrera et al., 2010). In the countries most affected, mortality increases were observed during June and July and peaked in August (Figure 4 ad 5). Among the 70 000 excess deaths, more than 20 000 occurred before the peak of the heatwave in August (Robine et al., 2008

Figure 4. *Left: excess mortality in Europe during 2003. Right: timelines of excess mortality in France during the 2003 heatwave overlaid with temperature recordings.* ***Source:*** *left, Robine et al., 2008, right Vandentorren et al., 2004.*





In Spain, excess deaths during the summer of 2003 in the 50 provincial capitals have been estimated at 3 166–4 151 (Simón et al., 2005). These cities represent approximately 48 % of the population and, assuming the temperature–mortality relationship is similar in the rest of the country, estimated excess mortality for the entire country would be between 6 596 and 8 648. The excess mortality occurred during June (9 %), July (5 %) and August (17 %). Switzerland experienced an increase of 7 % in mortality for June–August, resulting in 975 excess deaths (Grize et al., 2005).

In France the death toll was the highest among European countries (Vandentorren et al., 2004). There was a small increase in mortality during the middle of July, but the most devastating impacts occurred in the beginning of August. Temperatures increased during the first week of August and remained excessive for an additional week; mortality rapidly increased accordingly, peaking at an excess of 2 200 deaths on 12 August.

These patterns suggest that not only the intensity but also the duration of the heatwave affects the mortality patterns during a heatwave. These results have been found to be consistent with results from later studies. In the Netherlands, the highest temperatures were observed in less-populated regions. This may have resulted in a relatively modest increase in mortality compared with other European countries. Excess mortality was estimated to be between 1 400 and 2 200 for the summer of 2003 (Garssen et al., 2005). In Portugal, the main effects were observed in the first two weeks of August, when excess mortality was estimated to be 37.7 %, resulting in an additional 1 316 deaths for the mainland (Nogueira et al., 2005).

Vulnerable groups

The one common factor according to studies of the excess mortality during the 2003 heatwave is that the greatest impact was on elderly people. Age can act as an effect modifier by itself, but is usually interpreted as a proxy for underlying health conditions that are likely to increase vulnerability during a heatwave. In France a case–control survey was conducted among elderly citizens in four communities in and around Paris, analysing age, sex and residential area (Vandentorren et al., 2006). A number of factors were identified that increased mortality risk during the 2003 heatwave, such as chronic diseases, lack of mobility, lack of thermal insulation, sleeping on the top floor and ambient thermal characteristics of the surrounding area (Vandentorren et al., 2006). Similar results have been presented by studies from varying geographical contexts (Bouchama et al., 2007).

Heat wave action plans

The experience of the heatwave of 2003 motivated several European governments to implement heat action plans to reduce the health impact of heatwaves. No European country had implemented heat action plans prior to the summer of 2003; the first ones appeared in 2007. Unfortunately, inventories on the presence of established warning systems have used different criteria to define what constitutes a heatwave early warning system. Lowe et al. (2011) defined a heatwave warning system by heat-triggered interactions between meteorological institutions and health departments, and identified heat action plans in 12 of 33 European countries present in the study.

Eleven countries identified vulnerable subgroups such as children, elderly people, chronically ill people and people with existing health conditions. A majority of the systems identify in their plans people with obesity, disabilities and cognitive disorders and outdoor workers. Some include strategies related to homelessness, socioeconomic status and social isolation. The World Health Organization (WHO, 2008) has identified eight core elements of a heat action plan:

1. agreement on a lead body (to coordinate a multipurpose collaborative mechanism between bodies and institutions and to direct the response if an emergency occurs),
2. accurate and timely alert systems (heat–health warning systems trigger warnings, determine the threshold for action and communicate the risks),
3. a heat-related health information plan (about what is communicated, to whom and when),
4. a reduction in indoor heat exposure (medium- and short-term strategies; advice on how to keep indoor temperatures low during heat episodes),
5. particular care for vulnerable population groups,
6. preparedness of the health and social care system (staff training and planning, appropriate healthcare and the physical environment),
7. long-term urban planning (to address building design, and energy and transport policies that will ultimately reduce heat exposure),
8. real-time surveillance and evaluation.

Remaining gaps

Most studies investigating the heatwave of 2003 and heat-related health impacts in general focus on mortality. The effects on morbidity are less studied, and the long-term consequences for individuals even less. Even though Vandentorren et al. (2006) found evidence that housing conditions, apartment locations and surrounding thermal environments could play a role in estimating individual vulnerability, such studies face challenges in gathering individual data on these factors. In addition, there is a need to document the cost-effectiveness of interventions to mitigate heat impacts using randomised trials.

3.2 Overview of recent disasters and lessons learned

An example of different event management concerns two accidents that occurred in the Netherlands. In 1992, the crash of an aeroplane carrying apparently hazardous cargo in a densely populated area in Amsterdam caused 43 fatalities. The concerns of survivors were not well addressed and caused ‘toxic fear’ and the occurrence of medically unexplained physical symptoms, both in the local population and among first responders (Boin et al., 2001; Yzermans and Gersons, 2002). In 2000, in the same country, survivors of a fireworks explosion in Enschede received much more attention from authorities. A health surveillance programme was issued (Van Kamp et al., 2019) and the information and advice centre supplied support to survivors and rescuers to address mental health needs (Roorda et al., 2004). Four years later, the incidence of mental health problems among affected residents was still higher than in the general population, whereas rescuers recovered their pre-disaster mental conditions within 18 months (van Kamp et al., 2016). The health surveillance programme indicated that the relocation of residents who lost their homes and a pre-disaster history of psychological problems were the risk factors for post-disaster psychological problems. Affected residents with mental health problems were using healthcare services more often than unaffected residents, showing that this support was necessary.

The benefit of analysing biomarkers in the aftermath of a disaster was demonstrated in a 2003 train crash in Wetteren, Belgium, involving a fire that caused a toxic cloud of smoke and toxic chemicals, including acrylonitrile. Many inhabitants, after staying at home, had symptoms of cyanide intoxication in locations apparently unrelated to the incident. The exposure was caused by contaminated water that had been used to fight the fire and that had exceeded the capacity of water buffer tanks, resulting in toxic gases entering homes from the sewage system. The authorities evacuated these residents and shifted the response capacity to indoor measurements. When they plotted on a map the homes of residents with elevated blood values, it became clear that these were along the main sewage pipe system (De Smedt et al., 2014). Blood analyses for protein adducts of acrylonitrile indicated that some residents who reported to hospitals had very low values, suggesting that their complaints could be related to the incident but not to the primary chemical exposure (Colenbie et al., 2017). Moreover, relatively high blood values were observed in some residents who had not reported to accident and emergency. This mismatch clearly shows that a considerable number of persons with confirmed elevated exposures do not seek support from the healthcare provided. Then, the biomonitoring results did not match with the registries of victims who self-reported to the hospital emergency room (Simons et al., 2016; WHO, 2009). Self-reported health complaints should also be followed up, since they could be related to the incident but stemming from factors other than the exposure to the confirmed chemical emission of acrylonitrile.

These experiences suggest that the use of medical registries combined with questionnaires in the aftermath of a disaster is the most promising form of health surveillance (Korteweg et al., 2010). The authorities should acknowledge the situation of the survivors and address their health-related complaints. The European Human Biomonitoring Initiative (2017–2021) will make information available on the background levels of exposure to many priority substances in the general population of the European Union ([1]). These data can be used for interpreting the outcome of biomonitoring surveys related to chemical incidents.

4. Possible strategies to improve resilience

Designing and implementing hazard-specific action plans improves coping capacity, increases resilience, and reduces human impacts.

Projections show a rapid rise in the death toll due to weather-related disasters in Europe during the 21st century under a scenario of climate and population change (Forzieri et al., 2017). Building disaster-resilient societies, which are prepared for natural disasters and secure themselves against them, should be a common goal in line with the Sendai framework for disaster risk reduction. The most effective strategies to increase the resilience of communities lie in education, teaching individuals how to behave in case of disaster and to avoid risky situations, which can vary depending on the hazard. This goal involves several groups: the scientific community, policymakers, emergency management organisations and citizens. Outside Europe, Japanese society has a long history of good practices of prevention and preparedness for disasters (e.g. earthquakes) taught to children in schools. In the USA, the Federal Emergency Management Agency (FEMA) issues behavioural guidelines for citizens to protect themselves from a wide range of disasters, from floods to hurricanes.

Petrucci et al. (2019) analysed flood mortality in eight countries (Czechia, France, Greece, Israel, Italy, Portugal, Spain and Turkey), where, between 1980 and 2018, 812 floods killed 2 466 people. Flood fatalities were mainly among males, aged between 30 and 64 years. The victims were mainly working-age people, killed most frequently outdoors, and particularly on the roads, when travelling in motor vehicles. In contrast to other age group classes, elderly people are not particularly vulnerable: the few fatalities over 65 years of age were mainly killed indoors, when sleeping. The primary cause of death was drowning and the second was collapse/heart attack, which was detected in all the age classes. Hazardous behaviours, such as fording rivers, were more frequent in males than females. Further data can also be collected on people injured and 'people involved' (not killed or hurt but witnesses of the event) (Aceto et al., 2017; Petrucci et al., 2018), representing people who either managed to keep safe or behaved in a risky manner. Regarding their age, in Calabria (Italy), people involved were younger

([1]) *See www.hbm4eu.eu.*

than people injured or killed, perhaps because of the greater promptness of younger people to react in dangerous situations.

These outcomes can be used to strengthen the strategies aimed at saving people, and to customise warning campaigns according to the local risk features and people's behaviour. The results can improve understanding of the potential impacts of hazards on the population, increasing awareness among both administrators and citizens.

In some types of disasters, lives need to be saved in the initial moments, by alerting the public to an imminent threat. On a small scale, users of a building should learn how to respond to a fire alarm, so they can do so in large-scale incidents. Prior communication of what people must do in a particular scenario makes such signals effective, as does having local communities co-design emergency management plans. There is a shortage of research on how the public responds to the first communications following an emergency.

Television and radio still have a function, but, thanks to the widespread use of mobile phones, text messaging makes it possible to send out alerts tailored to the type of emergency or even brief video messages (Bandera, 2016). These communication technologies have the advantage of reaching persons who would not receive an audio signal, including persons with a hearing disability. An important limitation is that persons would receive this message regardless of their location. To overcome this limitation, the method of cell broadcasting, using radio frequencies in the mobile phone network, is an interesting alternative that has been used for tsunami warnings in Sri Lanka, for earthquake warnings in Pakistan and for general emergency purposes in Israel (Jagtman, 2010; Malik and Cruickshank, 2016).

Research using fictitious messages indicated an increased intention to adopt protective behaviours. Respondents reported increased risk perception, greater self-confidence and greater confidence in the effectiveness of the advice given, and indicated higher credibility/reliability of the sender (Gutteling et al., 2014). Information provided by cell broadcasting was perceived as more complete and reliable, and their responses were less emotional. Additional communication channels, such as websites and social media, can reinforce the resilience of citizens by sharing information and knowledge to a large audience. Having strong national public health systems is critical to build resilience to epidemics.

5 Conclusions and key messages

There remain several challenges to reducing threats to life and the human impacts of disasters. These include the erosion of public attention and support for continued measures beyond the immediate aftermath of events, confidence in official institutions in the context of uncertainty, and conflicts of interest due to concurrent stakeholder roles. This subsection summarises recommended practices and approaches that each stakeholder group should focus on in order to reduce the impacts of those threats.

Policymakers

Policymakers should ensure that complete data on human impacts of disasters (including on spatial and temporal descriptors, and demographics of victims) are collected over the long term and shared openly, by creating legal and technical frameworks, and by promoting information campaigns and training. Such information can increase risk knowledge and awareness, and supports mitigation, preparedness and response to events.

Practitioners

Practitioners must improve the prevention and mitigation of human impacts, focusing on potentially vulnerable and exposed populations. This can be accomplished by identifying specific human vulnerabilities, by better addressing psychological trauma and the mental health of victims and emergency responders, by making use of existing medical registries and questionnaires in DRM, and by biomonitoring people exposed to toxic substances.

Scientists

Scientists should focus on improving modelling of human exposure and vulnerabilities, by considering individual, social and locational aspects, and analysing factors that cause human impacts, including the roles of adaptation and risk awareness. It is also important to improve understanding of complex and cascading disasters, including how their spatio-temporal dynamics determine human losses. These objectives can be aided by DRM practitioners having a better understanding of needs through having a closer involvement in DRM activities beyond risk analysis and assessment.

Citizens

Citizens can contribute by investing in risk knowledge and self-protection, and accepting greater involvement in DRM, e.g. as local safety officers in their communities. Their proactivity can be increased by including personal safety and disaster prevention in school curricula.

3.2.2 Threat to housing and habitat

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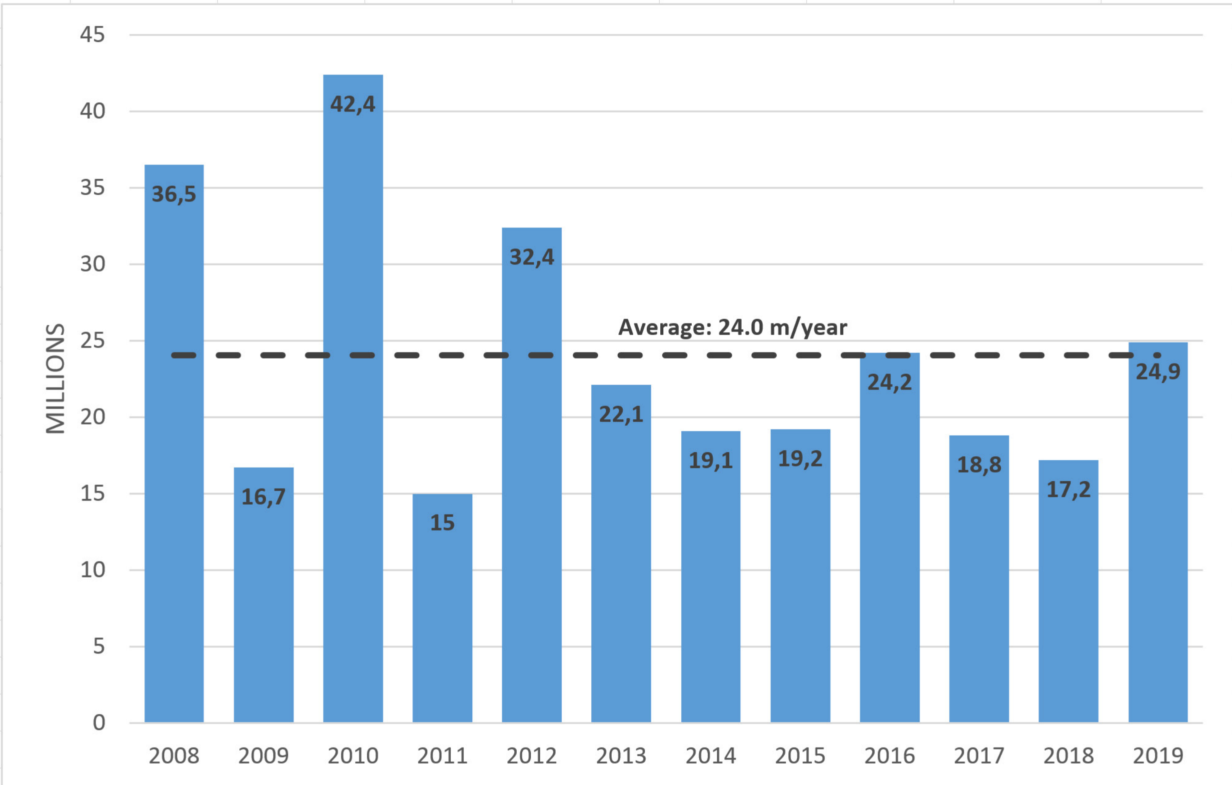
1 Introduction

Natural hazards and human-made disasters influence people's lives considerably. In particular, they can affect people's living environment, from their dwelling (i.e. housing) to the surrounding environment (i.e. habitat) composed of socioeconomic relationships (family, friends, neighbourhood, work, services). The consequences for populations of habitat and housing being under threat are the focus of this section. Population displacement is the primary measure of impact analysed in this section. This displacement works on various spatio-temporal scales, from temporary relocation (i.e. short evacuation) to semi-permanent relocation (i.e. long evacuation) or permanent relocation (i.e. impossibility of returning home). In cases of permanent relocation, post-event habitat conditions could allow people to be rehoused in the same area (e.g. rebuild the damaged or destroyed housing, use other buildings), but sometimes physical conditions (e.g. access limitations in the affected area, failure of basic services) or socioeconomic circumstances (e.g. loss of income/employment or social network, costs of reconstruction) lead people to resettle elsewhere.

Population exposure to natural hazards is constantly increasing (Ehrlich et al., 2018) and, in a scenario of climate change, they are forecast to uproot large numbers of people. Excluding pre-emptive evacuations, displacement due to disasters is a condition that currently affects globally about 24 million people each year (Figure 1; IDMC, 2020), 35 000 of them in EU (IDMC, 2020). Data on people displaced (e.g. number of people homeless, number of people who need their houses to be repaired) are often available after most disasters, as they are collected during response actions and for post-disaster compensation.

Figure 1. *People displacements by year due to disasters. .* ***Source****: Authors, with data from IDMC, 2020. .*



In a given area, the number of people displaced by disasters is a function of (1) hazards occurring (typology and intensity); (2) exposure (people, buildings, infrastructures); (3) vulnerability of assets exposed (including physical and socioeconomic vulnerabilities); and (4) institutional coping capacity. In a particular area, for a given entity of a disaster, building vulnerability influences the degree of displacement, from temporary (lower vulnerability, less damage) to permanent (higher vulnerability, more damage or collapse), while socioeconomic vulnerability could affect building vulnerability (e.g. maintenance) and determine the socioeconomic consequences of a relocation, even a long time after the event. Most people displaced after a disaster, when housing is damaged or destroyed, generally return to the same place to rebuild in the short term (IDMC, 2017), with the result of no reduction in exposure. The reduction of potential future hazard impacts through disaster risk reduction (DRR) strategies, by taking more risk-informed decisions, is the focus of the Sendai framework for disaster risk reduction (UN, 2015), which sets three targets for reduction of impacts on population (A, B and G), and two specific indicators (B-3, B-4) on dwellings. Reducing the number, frequency, intensity and duration of disasters is also an essential component of the 2030 agenda for sustainable development and its thematic agreements (UN, 2016, 2017), with a specific target (11.B) on settlement resilience to disaster.

2. Vulnerability of housing and habitat in relation to hazard conditions

Housing and habitat vulnerabilities determine the levels of spatiotemporal displacement during and after hazardous events and the consequences of displacement.

Housing and habitat vulnerability directly influence the impacts on population affected by hazard events. The capacity of the built environment to safeguard the inhabitants is one of the main factors in a risk assessment. The resistance of structures to natural phenomena (e.g. earthquakes, landslides or floods) or human-made disasters (e.g. dam failures, factory explosions, fires) strongly affects the numbers of people killed, injured and homeless, as well as the capacity of buildings to defend people from extreme events (e.g. heatwaves or intense cold) and the functionality of transport infrastructures and communication networks. Moreover, it could determine the duration of people's displacement after a hazardous event and the consequence on people's lives. The vulnerability of habitat and housing affected by a given hazard can be grouped into physical and socioeconomic conditions. Physical vulnerability is the probability that a group of people (e.g. children, adults, elderly people, people with disabilities) will be affected at a certain level by the consequences of a given hazard on buildings, critical infrastructures and environment. Socioeconomic vulnerability is the result of the interaction between individuals and their environment and/or social structure and its modifications.

2.1 Physical vulnerability

Physical vulnerability of habitat and housing affected by a given hazard means the 'indirect' consequences on people induced by physical damage (e.g. buildings, infrastructures), determining the number of casualties and the magnitude of the displacement of people. In this category it is also possible to include evacuation vulnerability (Cova and Church, 1997) (i.e. the physical conditions of the environment influencing transport in fast-onset events, like wildfires, volcanic eruptions, tsunamis).

Housing and habitat may be vulnerable because of different drivers. First, a fragile physical environment weakens populations in certain contexts (Wisner et al., 2004). When buildings collapse because of an earthquake, causing deaths and damage, the collapse may have various causes: absence of building codes or non-adherence to them, lack of maintenance, or lack of skills and knowledge on the part of workers (Wisner et al., 2004). Non-engineered buildings (i.e. buildings that are built with little or no intervention by engineers, or buildings with specific social or economic obstacles to improving their resilience) are often particularly vulnerable. All over the world, this type of construction suffers much damage when hazards materialise, and this damage tends to lead to a higher number of casualties than the damage to engineered constructions (UNESCO, 2016).

A set of reasons can therefore create a certain level of vulnerability of housing and habitat. Identifying appropriate construction technologies, material and measures that can easily be introduced into the habitat appears therefore crucial (Morrow, 2008; UNESCO, 2016). For more information on direct tangible impacts on residences see 3.3.1. Residential sector, in subchapter 3.3.

In emergency management, the evaluation of the expected number of homeless people and people seeking public shelter is an essential input. The probability that casualties will occur and/or people will be forced to leave their houses can be assessed as a function of the level of damage to buildings and infrastructures caused by a given hazard. In cases of earthquakes and hurricanes, multi-hazard loss estimation methodology assesses displaced persons as a linear consequence of building damage, based directly on damage to the residential occupancy inventory (e.g. Zuccaro and Cacace, 2011). In cases of floods, it assesses the displaced population on the basis of the inundation area, as a function of the depth of flooding at which travel into the area is restricted.

For all hazards, especially in human-made disasters (e.g. ionising radiation, toxic wastes, chemical spills), the number of displaced persons also results from utility losses (water and power). In cases of volcanic eruptions, given the destructiveness and rapidity of the phenomena, the areas potentially affected by pyroclastic flows (red zone) and/or lahar must be evacuated before the start of the phenomenon in question, and the displaced population is assessed on the base of the invasion sector of the flows (Zuccaro and De Gregorio, 2019). The same approach is replicable for some sudden human-made disasters (e.g. nuclear plant failure). Instead, for the areas hit by fallout deposits (depending on the strength and direction of wind), the number of displaced persons can be evaluated on the basis of roof collapses (Spence et al., 2005a,b).

Evacuation vulnerability measures the consequences on population during an evacuation event and it is affected by the whole context (e.g. transport network characteristics, quality of evacuation plans, evacuation behaviour). In cases of pre-emptive or forced evacuations (because of urban fires and wildfires, volcanic eruption, floods, tsunamis, nuclear power plant failure, etc.), urgent displacement can be impeded by limited road infrastructure (Cova et al., 2013) and evacuation behaviour is influenced strongly by perception of hazards and perception of readiness (Lechner and Rouleau, 2019). Increasing investments in early warning systems, models of community evacuation plans and effective evacuation communication can reduce evacuation vulnerability.

2.2 Socioeconomic vulnerability

Socioeconomic vulnerability describes 'the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard' (Wisner et al., 2004: p11). Past events show that the number of displaced persons is much larger than just the occupants of severely affected buildings (Pitilakis et al., 2014) because of households' internal socioeconomic and individual factors (Khazai et al., 2011).

Socioeconomic vulnerability in the context of housing is more than location and mere spatial exposure to hazards. Rather, culture, social structure and everyday practices of communities, developed to fit the place, influence the form of settlements and the design of houses (Oliver-Smith, 1990). Thus, as all aspects of housing have profound social and cultural meanings, 'social space and the character of houses and other structures within it may have profound implications' (Oliver-Smith, 1990: p9) for vulnerability as well.

Places of residence, housing types, DRR and preparedness measures depend on (1) the broader political, economic, social and cultural context (Wisner et al., 2004) and (2) the resources of individuals and households to afford safe housing. Research studies (Zhang and Peacock, 2010; Highfield et al., 2014; Hamideh et al., 2018) show that higher levels of damage can be found in low-income and marginalised communities.

Once a disaster has struck, social vulnerability plays a crucial role in the recovery process (Peacock et al., 2018). Insurance can be the primary funding for repairing and rebuilding housing but its availability and affordability for houseowners discriminate against most vulnerable communities (Brody et al., 2017). Poverty is an important aspect of increased social vulnerability, as it is directly associated with access to resources to cope with the impacts of disasters (Fatemi et al., 2017). For instance, in Chile the 2010 earthquake's impact on housing was greater in the low-income population: 12 % of the population in the poorest quintile experienced major damage to or destruction of housing, compared with 4.6 % in the richest quintile (Larrañaga and Herrera, 2010).

Empirical evidence indicates that people with subsistence incomes are very prone to be trapped in a cycle of poverty, and find their limited resources exhausted in facing repeated or catastrophic disasters (Tselios and Tompkins, 2019). Structural maintenance and mitigation initiatives are often out of reach for low-income households (Burton, 2010). In addition, lack of access to resources (e.g. information, knowledge and technology), limited access to political power and representation, social capital and networks, beliefs and customs, and frail and physically limited individuals (Singh et al., 2014) are factors that can contribute to increasing or reducing vulnerability.

Another important factor identified in the literature is that homeowners and renters have different patterns of social vulnerability in the recovery process, with the latter often recovering slower (Fussell and Harris, 2014). Moreover, as research from the United States shows (Comerio, 1997; Fussell and Harris, 2014; Peacock et al., 2018), disaster recovery polices and schemes can produce social vulnerabilities when unevenly distributed.

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3 Examples of relocation and rehousing

Examples show different ways of managing relocation: the quality of response can mitigate short- and long-term consequences.

Temporary and permanent relocation are presented through various examples: a flood in the village of Toll Barr (United Kingdom), the urban fire at Grenfell Tower (United Kingdom) and recent major earthquakes in central Italy.

3.1 Toll Bar floods, June 2007

In June 2007 large parts of the United Kingdom experienced devastating and unseasonal storms and rainfall. South Yorkshire was one of many areas that experienced severe flooding, and 48 areas of the large borough of Doncaster were affected. In the borough, 3 286 homes were flooded, with 2 275 suffering 'major damage', as defined by the local council (Easthope 2018: p11), which rendered them uninhabitable for many months. Moreover, 283 businesses were affected. There are 41 parishes in Doncaster, with Toll Bar being described as one of the most deprived. At the time of the floods in 2007, there were 440 properties in Toll Bar and 164 were council owned. Toll Bar had a population of 1 084 people. In total, 272 properties, mainly residential, were damaged. Over 52 households, which had resided in council-owned properties, were relocated to a temporary caravan park. Charity organisations and local government worked with the community to support those who had lost all of their personal possessions. As is often the case with flooded homes, the residents could not stay in their original homes until they were made habitable again, as the damage was so severe (Easthope, 2018).

3.2 Grenfell Tower fire, 14 June 2017

The Grenfell Tower fire in North Kensington, on 14 June 2017, was a disaster resulting in significant loss of life, with bereavement, displacement and trauma experienced by many, residents of both Grenfell Tower and the surrounding buildings. Seventy people and a baby in utero died on the night of the fire, and there was a further death from the effects in January 2018 (Strelitz et al., 2018). Their collective connections extend to many thousands of people, living locally, around London and the United Kingdom, and around the world.

The fire resulted in 373 people being made homeless, as the high intensity of the fire rendered the tower unfit for habitation. Families have been relocated across London. The approach taken to relocation involved the use of hotel rooms for over a year followed by a move to either a temporary home or a more permanent solution. People's traumatic experience of the night and bereavement was compounded by the loss of their homes and possessions, and of their community network. Several thousand people in both the tower and surrounding areas have engaged with the mental health support teams in the ongoing aftermath (Strelitz et al., 2018).

Government ministers directly influenced housing policy and were keen that survivors were moved quickly to four- and five-star hotels in the most affluent area of the United Kingdom. This ad hoc approach was fraught with a series of practical and logistical difficulties: survivors had to move regularly and were separated from neighbours and support structures. They were moved when rooms became harder to find as a result of international events such as the Wimbledon tennis tournament.

Suggestions of the creation of temporary villages (possibly in the large royal parks nearby) using high-quality prefabricated cabins, as seen after a number of other recent disasters, proved unpopular. Seven households have been in temporary accommodation for 3 years (Bulman, 2020). Important everyday rituals were impossible. In the area around Grenfell Tower, residents face challenges of low income, poor housing and difficulties in education and the labour market (Strelitz et al., 2018).

The health effects of relocation following a disaster are a growing trope in the disaster literature, and the effects previously described, e.g. physical health deterioration and psychological disorders such as anxiety and depression, continue to feature in this case (Uscher-Pines, 2009).

3.3 Italian major earthquakes, 1976-2017

Italy is a country at high seismic risk, and frequent past earthquakes have had several consequences on people (Table 1).

Table 1. *Most disastrous earthquakes in Italy since 1976.* ***Source****: Authors.*

Region	Year	Maximum magnitudes of events	Buildings rendered unusable	Dead	Injured	Homeless
Friuli	1976	6.5; 6.0; 5.9	48 000	993	3 000	80 000
Irpinia	1980	6.9	360 000	2 900	8 850	280 000
Umbria-Marche	1997	5.7; 6.0	80 000	11	100	40 000
Molise/Puglia	2002	5.7; 5.7	9 400	30	100	12 000
L'Aquila	2009	6.3; 5.5; 5.4	37 650	309	1 600	67 500
Emilia	2012	5.9; 5.4	7 500	27	300	45 000
Central Italy	2016-17	6.0; 5.9; 6.5	90 000	237	365	32 000

The first attempt to plan the management of people displacement was made after the devastating seismic sequence that occurred in the Friuli-Venezia Giulia region in 1976 (Boschi et al., 2000), highlighting the need to organise three different relocation approaches: temporary relocation, semi-permanent relocation and rehousing.

Initially hosted in makeshift camps (railway carriages, tents or caravans), homeless people were moved to more comfortable temporary housing (e.g. resorts near the earthquake areas) after other seismic events. Meanwhile, provisional prefabricated settlement areas were prepared along with the planning of the restoration of buildings that had suffered minor damage. In 5 years, half of the homeless people already had a final settlement.

The 23 November 1980 Irpinia earthquake, which affected over 6 million people, in over 680 municipalities, highlighted serious delays in the Italian state's response to the emergency. In some areas, relief operations started only after 5 days, when it was too late for many (Gizzi et al., 2012). One of the most urgent problems was the accommodation of the homeless, given that makeshift camps were not suitable for the harsh winter conditions.

Based on the experience of Friuli, the families were moved to hotels or second homes located on the Campania and Apulia coasts. In December 1981 almost all the homeless people moved from tents to prefabricated houses. However, many of them (130 000 people) preferred to resettle in other areas of Italy and EU as part of the major emigration that characterised the south of Italy in those years.

The 2009 L'Aquila earthquake occurred in the Abruzzo region. The main shock occurred on 6 April 2009, and its epicentre was near L'Aquila (Di Ludovico et al., 2017a,b). The response of the civil protection system (CP) to this event was very rapid. The same day, about 500 tents were set up and another 500 were under construction. By 19 April, the homeless were housed in 70 hotels (20 000 persons) and 120 tent cities (about 40 000 persons).

In terms of rehousing, some different solutions were set up. In the main city of L'Aquila, a project called Sustainable, Environmentally Friendly and Anti-seismic Complexes (CASE) aimed to provide, in 5–12 months, semi-permanent accommodation built using innovative seismic techniques. One year after the earthquake, about 14.462 relocated residents of L'Aquila were living in the apartments of the CASE project. In the other villages and municipalities (141 different locations), temporary residential emergency modules (MAPs, 4 650 single-storey wooden houses) were built, hosting more than 8.500 people. Another significant measure was the granting of an autonomous accommodation contribution (CAS) to households that chose to provide for their relocation themselves. Today, most of the private reconstruction is complete, but long delays occurred in the historical centre because of the complexity of the reconstruction operations on buildings bounded for historical and artistic interest.

The 2016–2017 central Italy earthquakes, characterised by a sequence of strong shocks (Mw 5-6.5) (see super case study 1), constitute the most recent critical Italian seismic event. The numbers of relocated people in June 2018 (2 years after the main event) were the following: 689 in containers, 488 in temporary evacuation/ accommodation centres, 2 253 in hotels, 38 596 having used CAS, 7.291 in emergency housing solutions and 781 in rural MAPs (MAPRE), which are useful to protect livestock from the harsh winter.

Thanks to the framework agreement for the supply, transport and assembly of emergency housing solutions and related services, the average delivery time was 245 days. More details of that event can be found in the Super Case Study 1 on the earthquakes in Central Italy.

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4 Social consequences of relocation and rehousing

Temporary relocation, rehousing and resettlement have profound psychosocial and social consequences, sometimes reinforcing existing social vulnerabilities.

A body of research after hurricanes in the United States (Abramson et al., 2008; Hori and Schafer, 2010; Patel and Hastak, 2013) documents that rehousing and resettlement are in many cases associated with chronic stress, post-traumatic stress disorders and poor mental health outcomes, as shown for the Grenfell Tower fire.

Even temporary relocation may cause psychological distress and can result in mental disorders or aggravate them (Nitschke et al., 2006; Munro et al., 2017). Depending on the duration, the quality of temporary housing and the severity of mental health effects, people can be affected physically too (Patel and Hastak, 2013).

Social effects of losing housing can be analysed using an extended capital approach (Bourdieu, 1986) that takes into consideration economic, social, cultural and symbolic (social status) capital. The loss of housing translates into the loss of different forms of capital or assets, as reported in Table 2. Already vulnerable groups (e.g. people with disabilities or with specific medical needs) especially may lose vital support networks.

Moreover, the already existing vulnerabilities of people that have lost their housing can redouble if they face additional stigmatisation, as research after the 2004 tsunami shows (Fernando, 2018). All these social consequences often interact with each other (e.g. relocation might result in a loss of social networks, which can also aggravate the loss of economic capital due to reduced business opportunities and so on). Therefore, an overall downward spiral is to be expected among all kinds of capitals and assets, significantly limiting individuals' recovery potential.

***Table 2**. Different forms of relocation (temporary, permanent, resettlement) and different forms of capital*
***Source:** Authors, based on Hoffman (1999); Nitschke et al. (2006); Levine et al. (2007); Abramson et al. (2008); Hori and Schafer (2010); Peek and Richardson (2010); Lein et al. (2012); Pardee (2012); Patel and Hastak (2013); Forino (2014); Fussel and Harris (2014); Munro et al. (2017); Fernando (2018); Peacock et al. (2018).*

Capital	**Temporary relocation**	**Permanent relocation**	**Resettlement**
Psychological	Distress Mental disorder	Chronic stress Mental disorder Health-related effects	Chronic stress Mental disorder Health-related effects
Economic	Loss of: - income	Loss of: - housing assets - income - government benefits	Loss of: - housing assets - employment - income - government benefits
Social	Temporary disruption of: - social networks - social support and services - primary healthcare	Loss of: - social networks - social support and services - access to primary healthcare providers	Loss of: - social networks - social support and services - access to primary healthcare providers
Cultural	Loss of: - educational continuity - feeling of security	Loss of: - educational continuity - feeling of security - known environment	Loss of: - educational continuity - feeling of security - known environment and culture - knowledge associated with place-based hazards
Symbolic	Social stigmatisation: - being dependent	Social stigmatisation: - living in shelters - being dependent on financial/ - housing support	Social stigmatisation: - being alien - living in shelters - being dependent on financial/housing support

The consequences of hazard events as described can also set free broader sociopolitical dynamics and processes. Relocations, for instance, can result in changes of sociodemographic structure such as the outmigration of certain segments of the population. Other areas, especially host communities, can be affected by the number of people migrating there and 'difference in composition of society, cultural characteristics, and economic conditions. Thus, re-location affects social and economic structures of both regions' (Patel and Hastak, 2013 p.96).

Oliver-Smith (1990), for instance, discusses the effects of urban sprawl as a result of losing housing in a disaster, and aggravated social inequalities due to social stratification in the recovery process. This could become a new cause of social vulnerability in terms of physically vulnerable housing, unsafe living conditions and reduced coping abilities in the future. Furthermore, economic and political repercussions of these social effects can be expected at the different political levels (regional and state). For more information on societal impacts 3.2.3. Threat to society, in this subchapter.

5. Lessons from past events

Decentralised emergency management usually guarantees to reduce the impact on the population, but converting lessons identified to lessons learned is sometimes problematic.

5.1. Toll Barr: successful disaster management

Disaster research from the last 50 years has emphasised the importance of keeping stricken communities in close proximity when relocated (Easthope, 2018). Despite the logistical challenges with this approach, it turned out to be highly effective in Toll Bar: it kept a close community together and followed the advice of a number of charities about avoiding the severance of close local ties after a humanitarian disaster (Easthope, 2018). A further lesson that proved beneficial was the high-standard specification of the caravans, linked to other community centres and with a cabin offering neighbourhood support. Recognising the importance of community ties, and the meaning of a place of safety and something akin to home, allowed people stability and a place to live, granting education and support for children. This contrasted starkly with the long-term use of hotels, where children and their parents noted severe impacts on their well-being (Strelitz et al., 2018).

The heritage and structure of the damaged physical forms that the community had inhabited were also protected; the caravans were placed in the same order as the damaged homes so that neighbours stayed as neighbours, and replica street signs were installed. The caravan park set up in Toll Bar was seen to have worked well and drew on international experiences. Similar successful attempts to keep communities together, albeit on a much larger scale, were replicated in New Zealand in 2011 (MBIE, 2013).

5.2 Grenfell: A failure of hindsight

Despite over a decade of requests to lead government departments to develop a coherent UK post-disaster housing strategy, at the time of the Grenfell Tower fire in 2017 this had still not been developed. The conversion of lessons identified into lessons learned is generally problematic. We quite often know what lessons to learn but, as Donahue and Tuohy (2006) suggest, not how to learn them. For instance, Turner and Pidgeon (1997, p.4) suggest a 'failure of foresight' whereas Toft and Reynolds (2005, p.66) suggest a 'failure of hindsight', which is a significant issue with regard to this event. Research shows other barriers exist: interoperability during response, and those difficulties that occur between responding organisations, from government to emergency services, that are unable to accept their own vulnerabilities, or that debrief without sharing the results with others (Donahue and Tuohy, 2006).

After the 7 July bombings in London in 2007, the UK government initiated the joint emergency services interoperability programme (JESIP) in 2012 in an attempt to deal with these issues and avoid them happening again. Consequently, joint principles, joint decision-making protocols, joint training and joint organisational learning have been put in place. Nevertheless, the same problems are still being experienced (Kerslake, 2017; Moore-Bick, 2019).

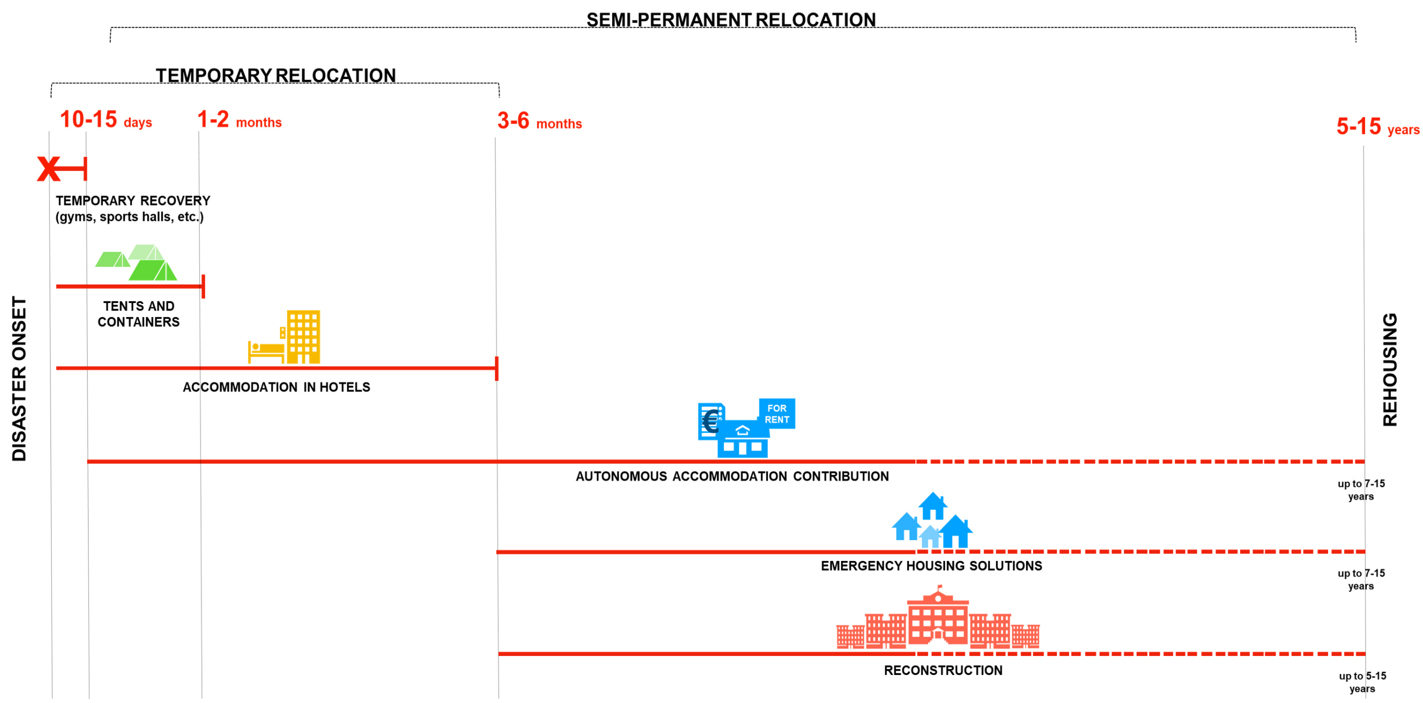
It is becoming increasingly apparent that when the Grenfell Tower fire happened in June 2017 there was neither policy-level nor organisational learning. Yet the signals were already there regarding what could happen. They had been gathered over many years but these lessons were forgotten and not implemented. Being able to pick up on such signals and learn from them is what Toft and Reynolds (2005, p66) refer to as 'isomorphic learning'. Over several decades, from the 1973 fire on the Isle of Man to the 2009 Lakanal House fire in south London, lessons were identified but not acted upon (e.g. the fire risk from external cladding of high-rise buildings was known, but there was no training for the fire service on evacuating such buildings; Moore-Bick, 2019).

This demonstrates a lack of learning by all response organisations, from the government to the emergency services. Indeed, in some cases when recommendations were made they were simply pushed aside until a new disaster happened (Bulman, 2019; Davies et al., 2019). Moreover, problems experienced in London between 2017 and 2019 would suggest that further consideration is needed to manage and mitigate the challenges of post-disaster relocation and specifically the use of hotels. Residents complained of not being able to start any sort of recovery and that the solution was a problem and had not considered their cultural and religious needs. The 'total' loss of personal effects, including all mementos of the lost relative, was a further devastation that is often overlooked in traditional emergency response plans (Easthope, 2018).

5.3 Italian earthquakes: learning from recurrent events

The numerous earthquakes that have occurred in Italy provided valuable lessons on which the current framework for management and planning of seismic emergencies is based. An appropriate model for the management of people displacement has been consolidated over time and, even if not yet structured in a specific law, clearly identifies three relocation steps (Figure 2)

Figure 2. *Timeline of people displacement management in the event of seismic emergencies in Italy* ***Source****: Authors.*



After the Friuli earthquake in 1976, in the early hours of the seismic emergency the displaced people were hosted in temporary accommodation (e.g. gyms, sports halls). Subsequently, the population was housed in tents and/or containers (up to 1 or 2 months) and in hotels (up to 3 or 12 months) closer to the earthquake areas in order to reduce the economic and social unease. Conversely, after the Irpinia earthquake (1980), people were moved to locations very far from the areas hit and many of the inhabitants did not agree to separate themselves from their livestock or from their own land. After the L'Aquila earthquake (2009), the emergency management adopted different solutions: (1) CAS for the families that chose their own temporary relocation using the economic contribution; (2) the MAP (and MAPRE) prefabricated buildings; and (3) the CASE semi-permanent rehousing.

In parallel with the management of housing for displaced persons, the seismic reconstruction phase integrates other crucial aspects deduced from past events.

- Decision decentralisation. Quick reconstruction could be encouraged by decentralising decisions and en trusting responsibility to municipalities, as shown in the 1976 Friuli event. This depends on the capacity of local management and the characteristics and severity of the specific event.

- Emergency technical management. During the major seismic sequence in the Umbria and Marche regions in 1997 (Dolce et al., 1999), the CP tested its organisation, with favourable results and laid the basis of an articulated system of technical management of the emergency for rapid and effective damage assessment and evaluation of the post-earthquake structural safety check, by an ad hoc form, called AEDES (*Agibilità E Danno nell'Emergenza Sismica* - First level form for damage detection, first aid and usability for ordinary buildings in the post-seismic emergency, Papa et al., 2014) through the integration of resources in collaboration with the regions and based on working tools and training programmes for technical operators (researchers and private or public technicians). The structural safety check determines the length of the wait in temporary shelter before returning to one's home. Since 1997, it has constituted the standardised way to produce a database on buildings' seismic damage, available to institutions and researchers, and it is the key for access to private reconstruction funds (Albanese et al., 2019).

- Updating of technical building standards. The most emblematic effect of the 2002 Molise Region earthquake (Maffei and Bazzurro, 2004) is represented by the collapse of a school building in the village of San Giuliano di Puglia: 27 children and 1 teacher died. The tragedy, caused by human negligence, accelerated the reorganisation of Italy's seismic legislation and technical codes for structural design, especially for strategic and relevant buildings. Since then, Italian technical legislation has undergone rapid development through a progressive code aligned with the standards by Italian National Unification (UNI) and the Eurocodes (MIT, 2018).

- Speeding up the recovery of productive activities. The resumption of productive activities is very important for the relaunch of a territory hit by seismic events. The 2012 Emilia earthquake constitutes a positive example. The event was characterised by heavy damage to rural and industrial buildings, with a strong impact on the regional economy (Meroni et al., 2017). For the reconstruction of productive activities (industrial and agricultural), EUR 1.9 billion was granted to fewer than 3 500 approved projects (Emilia Romagna Region, 2019). Eight years later, the productive activities are going better than before the earthquake, thanks to effective policies supporting the growth of economically more resilient activities by stimulating the reconstruction and the seismic adaptation of buildings and by developing projects that encouraged research and innovation. Moreover, this event induced the development of the standardised AEDES procedure applied to industrial buildings, and highlighted the need for internal emergency plans for companies.

- Revitalisation of urban centres. The reconstruction of L'Aquila's historic centre after the 2009 earthquake was rather slow compared with the suburbs, owing to the complexity of the reconstruction work on buildings of great architectural value. Instead, it would have been better to promote the revitalisation of the historical centre immediately, as essential to the civil and social recovery of the city, regardless of its housing function. In this perspective, during the Emilia (2012) and central Italy (2016–2017) earthquakes, specific measures were envisaged for the revitalisation of urban centres, aiming to create new attractive service hubs that could host better functions than those prior to the earthquake

6 Technology and vulnerability

Remote sensing techniques have potential for assessing impacts and reducing vulnerabilities, but the use of all these techniques is still on a small scale

There is a large range of available remote sensing techniques to assess the impacts of disasters and the state and vulnerability of a single building or infrastructure (e.g. Constanzo et al., 2016; Infante et al., 2016; Luzi et al., 2017; Schröter et al., 2018; Gonzalez-Drigo et al., 2019). These techniques, including satellite-, drone- and ground-based sensors, are non-invasive and can be used avoiding social unrest. They can provide valuable information (e.g. building stability, thermal behaviour, humidity, cracks, damage or anomalies) to improve the efficiency of response and reduce cost in the emergency phase (i.e. assessing the damage and losses) and to increase resilience for prevention purposes. The use of these techniques for prevention purposes is still minor compared with the development of new technologies.

Data from the European Ground Motion Service (Copernicus) has encouraged a step forward in the use of satellite data for the whole urban hazard management cycle, allowing continuous assessment of its potential impact. A good example of this is the use of Sentinel-1-based synthetic aperture radar interferometry. Sentinel-1 is an operational satellite constellation that provides useful data for natural hazard risk management and disaster impact assessment. Projects of the Directorate-General for European Civil Protection and Humanitarian Aid Operations (ECHO) such as Safety and U-Geohaz have contributed to the development of procedures that are nowadays used operationally by the CP. In Italy, the regional CPs of Tuscany, Valle d'Aosta and Veneto use these data to continuously assess the activity of ground instabilities and their potential impacts (Raspini et al., 2018; Solari et al., 2020). Europewide, countries as Germany and Norway have implemented nationwide ground motion services for mapping rock slide risks and subsidence of infrastructure. Ground motion services are also close to operation in Denmark and the Netherlands.

The success of these initiatives has been endorsed by the creation of Copernicus, which is an ongoing project aiming to monitor ground displacement at the EU level (EU-GMS Task Force, 2017; Larsen et al., 2020). These initiatives are complemented by others focused on data gathering and sharing, such as the Group on Earth Observation. This group has significantly contributed to making more Earth observation datasets openly accessible and exploitable via the Global Earth Observation System of Systems (GEOSS), a worldwide system aiming to use Earth observation data to improve the lives of citizens and help governments make good, evidence-based decisions. EuroGEO is the EU contribution to GEOSS, with Copernicus as a major element.

7 Conclusions and key messages

Past events have highlighted a lack of awareness among citizens, and a lack of shared and common procedures on post-crisis disaster risk management. The dissemination of a standard protocol related to the impact expected and reducing housing/habitat vulnerability can improve the resilience of housing and habitat. There is a need for common short- and long-term procedures to minimise post-event population disturbances. For example the 'safe village' programme developed in Portugal aims to reduce impacts on population by creating collective shelter during wildfire events. Italy showed how it is possible to consolidate a flexible model, even if it not structured in a single ad hoc regulation, by learning valuable lessons from numerous past events with an effective system of civil protection. On the other hand, the identification of lessons without learning could lead to disasters, as happened in the Grenfell tower fire.

The need to overcome political constraints and the lack of policy/legislative change is urgent, but in some cases political or other factors constrain the ability to redesign policies and to incorporate the required changes. Moreover, all stakeholders should know their roles, as risk is everybody's business. Horizon Europe (the EU's research and innovation framework programme from 2021 to 2027) will incorporate research and innovation missions to increase the effectiveness of funding by pursuing clearly defined targets.

Preparations for Horizon Europe are proceeding, with a cluster on civil security for society planned under Pillar II, Global Challenges and European Industrial Competitiveness, as can be found in the Partial General Approach on Horizon Europe (Council of the European Union, 2019). In addition, Earth and environmental observation, which can inform decisions and actions for the benefit of humankind, is included in two clusters (4 and 6).

The newly available satellites and the development of ground- and drone-based sensors have resulted in a noticeable increase in the use of these techniques for assessing the potential impact of natural hazards in urban areas. The development of new remote sensing techniques has been endorsed by intensive research activity focused on the exploitation of these data for natural hazard risk management and by several initiatives from regional to EU level to exploit this data in a massive way. Initiatives such as GEOSS also contribute to this exploitation, aiming to develop a new generation of measurements and spatial statistics products in support of post-2015 international processes on sustainable and urban development, climate change and DRR.

Policymakers

- Pay greater attention to a systemic approach to risk analysis and emergency management.
- Social and economic policies need to be informed by vulnerability in order to not increase existing vulnerabilities, but rather reduce them.
- Adapt policies according to lessons learned:
    - learning lessons generally means organisational change, and that enduring change needs to address the structure, system and culture of an organisation so that patterns of behaviour can be adjusted;
    - listen to the advice of experts and act upon it;
    - trust is critical to the success of learning, so develop trust relationships with your stakeholders and interested parties;
- Make remote sensing techniques for impact and vulnerability assessment fully operational by promoting among the different actors educational courses, workshops and demonstration exercises.

Practitioners

- Follow professional updating and training in accordance with shared standards.
- Challenge mental models:
  - test ‘taken for granted’ assumptions;
  - learn from others;
  - use inductive rather than deductive approaches to training;
  - consider cross-training to develop shared mental models for multi-agency teams.
- Relocation should be supported by social assistance, especially for the most vulnerable groups.

Scientists

- Methodological synthesis of the complexity of the problems to provide information (mainly quantitative)
- Focus on past issues and share results:
  - what went wrong or was a mistake and why,
  - develop new models of learning.
- Research needs to take into account the complexity and multifaceted importance of (the loss of) housing.

Citizens

- Be aware of:
  - the hazard in their territory;
  - the vulnerability of their buildings;
  - health and safety rules and evacuation plans.
- Be prepared: have a plan for yourself and family.
- Report safety issues and/or act to reduce them.

3.2.3 Threat to society

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Çoşkun, A.M, Frigerio, I., Dell'Aringa, M.F., Vandenbroucke, N., Blauhut, V., 'Threat to society', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Introduction

Thousands of people die every year because of disasters globally; societies suffer social and economic losses. Institutions are d amaged and therefore the social structure becomes unsustainable. In this section, society and institutions will be examined sociologically. Then, vulnerability at the community level will be examined, displaying how disasters affect institutional structures with examples of past disasters. Based on that information, the role of the society in disaster risk management (DRM) will be briefly examined and, in the final part, the effects of disasters on society will be analysed and crucial messages will be given to different segments of society.

2 Society and institutions

Formal institutions have a vital role in ensuring regulations and action to avoid disaster impacts on multiple sectors and services.

Society is a concept used to describe the structured relations and institutions among a large community of people which cannot be reduced to a simple collection or aggregation of individuals (Giddens and Sutton, 2017). According to Maclver and Page (1959), society is “a system of usage and procedures, authority and mutual aid, of many groupings and divisions, of controls of human behaviour and of liberties. Society involves the whole gamut of relations. It is structural and functional arrangement. From structural point of view it concerns role, status, norms, values, institutions.

In addition, society is described as a network of organisations and connections that are formed by a large number of people who interact to address their needs and share a common culture. This network of connections has to act by means of the institutions it composes. In this context, each member of society has a basic relationship with institutions and also has to playa part, abiding by social rules. Institutions are the basic mechanisms that ensure the continuity of society. Besides designing its inner arrangements, they also manage its external interactions. Commonly, the word ‘institutions’ refers to schools, hospitals or public enterprises. Sociologically, however, an institution is not only a special place with specific physical features. In broad terms, an institution is a social unit dealing with social problems and requirements in the economic, social and cultural fields. Conceptually, institutions, is described as rules and standards aiming to satisfy social needs as a whole,have links among them in an organized manner, and also have permanent values (Türkkahraman, 2009).

Disasters are events that influence social life and institutional structure in societies. Hazards of natural or human-made origin cause damage to the social structure and lead to disruption of institutions, property and the environment (Akyel, 2007). The role of institutions in DRM is to reduce uncertainty for people in cases where there are many different economic, social and environmental variables (Raschky, 2008). Moreover, institutions lend support for people to deal with an issue or need when they cannot overcome it alone, to an acceptable level of satisfaction and in less time, with less effort. Continuity, stability and harmony in society are achieved only through social institutions. Institutions constrain and limit human behaviour in line with the standard functioning of society and optimum expectations (Türkkahraman, 2009).

Institutions are grouped in three classes by Giddens (1984): legal, economic and political. These groups also include subsectors such as family, religion, politics, the economy, health, education, science, law, civil society, mass media, transport, energy, food, water, land use, and environmental regulation and protection. In this framework, the main aim of this section is to display the various impacts of disasters on society and to detect possible degeneration in social structures. The key question is: “how do disasters affect society and institutions?” Two case studies, the Van earthquake in 2011 and the Belgian nitric acid leak in 2017, are used in order to find answers to this question.

3 Vulnerability of society

The socio-economic and environmental situation of a society before the disaster determines the potential consequences of the event.

Vulnerability is described in the general literature as a condition that determines the characteristics and situations of a person or group that affect their ability to cope, to resist and to recover from a natural hazard (Oliver-Smith, 1994; Weichselgartner, 2001; Cutter et al., 2003; Wisner et al., 2004; Adger, 2006; IPCC, 2014).

If the issue of vulnerability is addressed at the societal level, it is essential to consider many agents. Donner and Rodríguez (2011) underline in their study that population increase, urbanisation and lack of settlement and infrastructure in disaster risk areas increase vulnerability. In addition, they emphasise that the proportions of poor people, migrants, women, children, people with disabilities and elderly people in society are factors that increase social vulnerability.

The Natural Disaster Report of the Centre for Research on the Epidemiology of Disasters (CRED) (2018) illustrates that aggregated losses in lower-income countries will inevitably remain below those in higher-income countries, because of lower asset values. The costs in human and financial terms can, however, be enormous at the household and community levels, especially when damaged or destroyed property is uninsured. Lost crops and damaged agricultural land also have the hardest impact on the poorest, with long-term consequences. Similarly, Raschky (2008) illustrates that economic growth is an important factor in determining the vulnerability of institutions, and higher-income countries experience a lower death toll from disasters. In other words the mortality rate is lower in societies that have strong institutional structures,because institutions play an important role in preparation for disasters, prevention of them and protection of society against their effects. He also remarks that there is a non-linear relationship between disaster losses and economic development.

To sum up, there are many factors influencing vulnerability of countries,such as population ratio, geographical location, economic conditions and disaster risks. Therefore, a multi-factor evaluation is essential to illustrate countries’ vulnerability.

4 Impacts of disasters

Disasters, whether they arise from natural hazards or are of human-made origin, hit social structures and lead to damage to assets. Disaster impacts are not only physical; they have social, economic and political dimensions. Since disasters potentially influence all of us and occur frequently, it is important to understand their complex forces from every perspective in depth. A primary stage of DRM is to understand the conditions of disasters and examine their impact. This subsection investigates how disasters harm the institutional structures of the society physically, politically, socially and economically.

Disaster risk cannot significantly reduce unless the impacts on society are fully understood scientifically.

According to the Emergency Events Database, a total of 23 704 natural or human-made disasters occurred between 1900 and 2017 globally. Approximately 40 million people died. However, Table 1 showsthat, although more disasters occurred in the Americas than in Europe, and the economic losses were higher, the mortality rate was lower.In addition, the rates of economic losses in Asia and the Americas appear very similar, but the mortality rate was disproportionately low in the Americas. In short, we can say that disasters do not cause the same results in every society. Some societiessuffermore than others, being deeply affected.

***Table 1**. Disasters' total effects worldwide, 1900–2017* ***Source**: EM-DAT, n.d.*

Continent	Occurrence	Total deaths	Injured	Damaged people	Homeless	Total affected	Total damage (1 000 USD)
Africa	4 881	1 498 567	470 766	544 266 429	9 649 874	554 387 069	35 770 093
Americas	5 197	893 757	3 179 794	413 872 512	12 426 131	429 478 437	1 458 288 554
Asia	9 874	27 016 807	5 350 323	6 837 443 687	149 486 584	6 992 280 594	1 480 081 715
Europe	3 008	9 209 146	179 306	65 265 086	3 574 533	69 018 925	413 427 640
Oceania	744	21 765	19 328	25 478 923	470 565	25 968 816	90 766 908

4.1 Physical Impact

Disasters can cause deaths and injuries to people, and also strike buildings, facilities and infrastructure. In 2018, globally 315 natural disasters happened and USD 131.7 billion in economic losses resulted. Between 2008 and 2017, an average of 348 natural disasters occurred each year, with an average economic loss of USD 166 billion per year (CRED, 2019). At the individual level, the major damage is loss of life, injury or damage to house or property. If the issue is addressed at the social level, impacts are more widespread and should be considered regionally, such as by neighbourhood or district, or on a sectoral basis, such as public facilities, energy, roads, communication, water, food, transport and health.

4.2 Critical Infrastructures

Infrastructures are designed to satisfy the basic needs of people and guarantee to sustain cities and social life in regular order. Factors such as wars, disasters or migration lead to failures in and destruction of these infrastructures, endangering the progress of society. Therefore, the resilience of cities should be the main interest in the planning stage of DRM. In addition, the Sustainable Development Goals (SDGs) indicate the importance of building and managing urban areas to achieve sustainable development.Theyalso state that infrastructure investment and innovation is the critical driving force of economic growth and development. In order to make cities safe and sustainable, countries should aim to improve safe and accessible cities and infrastructures (United Nations, 2016). In developed countries, economic damage is typically covered by restructuring, insurance company payments and the financing of national government investments and payments. Restoration of infrastructures is vital for business to re-open and recover after an event. In this way, the infrastructure can be quickly replaced by the national government (Luke, 2011).

Infrastructure systems provide citizens with services such as energy, potable water, sewage, transport and communication. Continuity of infrastructure systems is extremely important in disasters because they influence recovery in all parts of a country, including businesses (Chang and Rose, 2011). Infrastructure services are so rooted in modern life that they tend to be wide spread everywhere, so the damage may be often disproportionately extensive.

Nowadays, damage to systems – especially electricity, potable water and sewage – may be the main reason for people to move from cities after a disaster materialises. Even if housing survives storms, earthquakes or other hazards, without services a place becomes uninhabitable. It is important to emphasise that these systems are not only vital for people and businesses, but also a significant input to other infrastructure systems (Chang, 2016). In general, degradation in infrastructure services may be greater than predicted,so the restoration process may take a long time, depending on the magnitude of the disaster. During this period, communities may overreact to this circumstance when responding to the local authority or municipality in the short term. However, long-term disruptions may result in more extensive social consequences; many people may escape or migrate from the disaster zone.

For example, the Marmara earthquake in 1999 damaged 490 km of power lines, 60 km of highway, potable water and sewage infrastructure, 25 schools and some health facilities (Aktürk and Albeni, 2002). In the Gölcük district, the epicentre, approximately 25 000 people migrated from the region because of the catastrophe and lack of services (Südaş, 2004).

Similarly, Hurricane Katrina,a natural result of climate change, displaced an estimated 645 000 people in Louisiana and 66 000 people in Mississippi (US Census Bureau, 2015). Table 2 shows that exchanges in some sectors in Louisiana and Mississippi within a year period. In general, bussiness numbers experience a downward trend in all sectors between 2005-2006 except building.

Table 2: *Damage from Hurricane Katrina in Louisiana and Mississippi, by sector.* ***Source****: adapted from US Census Bureau data, 2015.*

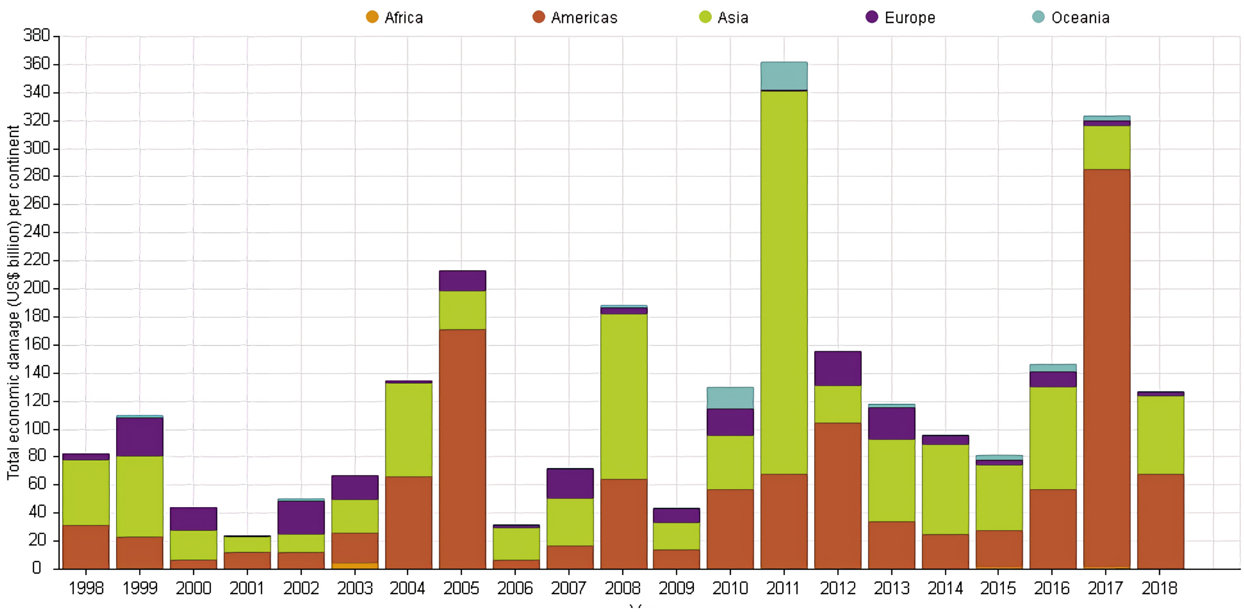
Sectors	Louisiana		Missisipi	
	2005	2006	2005	2006
Grocery stores	573	430	71	62
Gasoline stations	447	407	194	164
Pharmacies and drug stores	221	165	105	72
Hotels	259	227	259	227
Restaurants and eating places	2 138	1 860	547	471
Residential building construction establishments	535	652	156	201
Nonresidential building construction establishments	189	220	38	48
Highway, street and bridge construction establishments	28	26	16	21

In sum, disasters are severe and costly, and particularly damaging to cities. In terms of sustainability, it is vital to protect the social fabric. The Sendai framework for disaster risk reduction (2015–2030) prioritises the local and national levels for the identification of risks to public services and vital infrastructures, and the allocation of resources to strengthen them, and it emphasisesthe importance of doing better (United Nations Office for Disaster Risk Reduction, 2015).

4.3 Economic Impacts

Disasters do not just strike society physically; they can also resultin economic troubles for countries. The Centre for Research on the Epidemiology of Disasters (CRED and UNISDR, 2018) reported that countries were exposed to multiple disasters between 1998 and 2017 worldwide, and recorded the volume of economic damage as USD 2 908 billion. In addition, Figure 1 shows the distribution of economic loss by continents in detail between 1998-2018. The report also stresses that, although fewer disasters had happened in the United States in the previous 20 years, the economic damage totalled USD 945 billion, more than in China (CRED and UNISDR, 2018). So having more financial assets or value, which are mostly destructible, can lead to more economic damage. Botzen et al. (2019) conclude that economic and population growth have been the key driver increase in direct losses due to natural hazards, although studies with longer time-spams would provide more light to measure the economic effects of disasters due to natural hazards in the long-term.

Figure 1. *Global economic loss ratio 1998-2018* ***Source****: EM-DAT, n.d.*



Raschky (2008) highlighted that economic growth is an important factor determining vulnerable areas. In particular, disasters cause less mortality in high-income countries. Moreover, it is noted that economic growth means good protection against natural hazards, but the connection between them is not linear.

Major disasters can have devastating consequences immediately. The type of event, its magnitude and extend can cause varied and important changes in the economy of the place (Chang and Rose, 2012; Panwar and Sen, 2019). In addition, when they occur frequently, they can have negative consequences in reducing economic growth and increasing poverty in the long term (Benson and Clay, 2004). Actually, Chang and Rose (2012) indicate that pre-disaster trends, in terms of economic growth, are often accelerated, exacerbated or intensified during recovery, highlighting the importance of the pre-disaster state for understanding the effects of the disaster on the economy of the place. In terms of climate-related disaster losses per income group compared to GDP losses 1998-2017, while high income countries reported US$ 1,432 billion in climate-related disaster losses, or 65% of the global total, that only represented 0.41% of their gross domestic product (GDP). The US$ 21 billion in climate-related disaster losses recorded by low income countries amounted to an average of 1.8% of their group (1) GDP (CRED and UNISDR, 2018).

On the other hand, disasters can influence the labour market indirectly. Usually, it is expected that there must be shrinkage in terms of the labour market when disasters strike the business sector. However, in the examples studied in this section, we can observe unusual results. There is no great difference in employment rate before and after the Van earthquake of 2011 in Turkey (Kalaycıoğlu et al., 2015). Although the unemployment rate was 43.4 % in 2011, a year after the earthquake it decreased to 42 % (AFAD, 2014). The decrease in unemployment is attributable to some victims migrating from the region, and another key factor is supportive policies for the workforce. Another example is among the evacuees due to Hurricane Katrina in 2005; the unemployment rate was 30.6 % for people who left the disaster area and resettled elsewhere while this figure was of 6 % among the evacuated that had returned to their home (Groenand and Polivka, 2008).

Finally, if we look at the agricultural sector, the report on the impact of disasters on agriculture and food security by the Food and Agriculture Organization of the United Nations (FAO, 2015) remarked that, between 2003 and 2013, 140 major catastrophes in developing countries caused the loss of crop and animal production worth a total of USD 80 billion. This loss of 83 % of Gross domestic product (GDP) was a result of floods and droughts. This loss happened in countries where agriculture was one of the main economic drivers and often contributed 30–40 % of national GDP and employment.

4.4 Political Impacts

Disasters not only threaten lives or damage assets but can also destroy sociopolitical structures (Albrecht, 2017). Furthermore, they can open political space for the contestation or concentration of political power (Pelling and Dill, 2010). Owing to government policies, sufferers can experience a reduction in the quality of life related to their housing when a disaster occurs or afterwards. This negative result can reflect politically on the governments. For example, Hurricane Katrina increased the national political dissatisfaction rate in the United States (Wilson, 2015). In contrast, after the work to rescue people from the 2002 flood in Germany, the government obtained positive results, as it increased its share of the vote (Bechtel and Hainmueller, 2011; Bytzek, 2008). Similarly, even if Albrecht (2017) underlines that disasters have the power to influence government support and political trust, he remarks that there is no clear evidence of which kind of disaster damage directly influences public opinion about trust in and satisfaction with the state.

4.5 Social impacts

If society understands all aspects of disasters, it can develop the right strategies and manage risks.

The social impacts of disasters need to be addressed under a few headings. The best example of the social impacts is the 2010 Haiti earthquake. Approximately 300 000 people died and 1.3 million people were made homeless by the disaster. All segments of civil society, such as government, schools, universities, businesses, health clinics, non-governmental organisations and churches,were damaged. It was not clear who could provide

(1) List of countries/territories per income group (World Bank, 2018).

assistance to victims.The destruction was so large that not until a year later were institutions were able to coordinate with each other again (DesRoches et al.,2011). Another recent example of big magnitude in the society is described in the Super Case Study 6 on the COVID-19 emergency.

Jones and Faas (2017) display the added value of analysing social networks for more effective recovery actions. It seems to be necessary to understand what individual, families and groups have lost and need (which can be tangible or not) after the disaster and to adequately facilitate how people would interact to give or receive those resources.

Education

Disasters have a significant impact on education systems. Every student has the right to high-quality education, recognised as one of the SDGs (United Nations, 2016), but many students cannot attain this right under the influence of disasters. Many students cannot be educated for months after disasters strike. In this way, they have a negative impact on all school experiences. Disasters directly destroy schools located in the wrong place or built poorly.Another reason for interruption is that some schools are often used as evacuation centres. Furthermore, disaster preparedness is often not a priority in the curriculum and the repairing of schools is often delayed. The fundamental issue is, however, that, if training activities are promoted before the disaster, it can save lives, protect children and benefit all communities. Schools can be a catalytic force strengthening human effectiveness, reducing vulnerabilities and promoting risk reduction for future hazards (Save the Children, 2016).

Healthcare

Disasters may affect healthcare for diverse reasons. These events may cause immediate direct injuries that require health interventions and are also linked to long-term increases in health conditions ranging from infectious diseases to non-communicable diseases and mental health. Depending on the existing services and their surge capacity, an increase in health needs may lead to the over crowding of services, impairing their quality and availability, thus affecting healthcare capacity. Moreover, healthcare may be affected by direct destruction of health institutions, migration of health personnel and suffer from economic constraints. Disasters strike healthcare and, in the following period, interrupt services, damage physical assets, cause loss of workforce, make income chaotic and destroy operations.

The physical consequences of the disaster are obvious and can be more or less predicted. Health facilities that are empty after being evacuated or because they have suffered damage can become targets for burglars. Reconstruction can be delayed as demands met slowly. When the disaster ends, the sector can face a possible drop in credit supply, reducing transactions and constraining finances. Drug supply chains can be disrupted by product operations going offline, which can lead to product and labour shortages. During this period, health systems and pharmaceutical companies can improve the pace of recovery and avoid making early decisions that can cause long-term harm. The main concern toaddress in damaged hospitals is about the continuity of patient care. After the disaster, providers may be held accountable for the death and suffering of patients. Therefore, comprehensive physical checks of health assets should be made, with good emergency planning and a public relations unit for a more resilient health system (PwC Health Research Institute, 2018).

Migration

Disasters can cause demographic movements in society. Migration has always been a traditional response or survival strategy for people when they faced disaster threats (Hugo, 1996). People, in general, migrate for various reasons: to survive, to live a better life, to have prosperity or to escape from environmental degradation due to disaster. Of the 28 million new displacements recorded in 2018, 10.8 million were linked to conflict and 17.2 million to disasters, 16.1 million being linked to weather-related disasters (IDMC, 2019). These displacements may be temporary or permanent, voluntary or involuntary, and maybe a response to both physical and economic damage.

In addition, Oliver-Smith (2006) categorises demographic movements into four types.

- Flight or escape means urgently leaving risky areas for the nearest safe place.
- Evacuation is like flight but more organised,in the face of an approaching threat from internal or external agents.
- Resettlement can result in permanent housing in a new area.
- Forced migration often covers permanent, longer-distance movements to completely different environments for a long period.

As an example of evacuation, the 2002 European floods led to the evacuation of 50 000 residents of Prague (Czech Republic), on 13th August, and a total of 200 000 Czechs during the second week of August (BBC, 2002). Elsewhere in Europe, more than 120 000 people were evacuated in the German city of Dresden, 36 000 in the German state of Saxony-Anhalt and 1 500 in Hungary (Euro-Atlantic Disaster Response Coordination Centre, 2002). In another case, in 2011, climate change led to amajor drought in East Africa. Failed rains in Somalia, Kenya and Ethiopia led to high livestock and crop losses. Hence, the residents migrated to seek food and water, motivated by an inability to maintain traditional lifestyles.

Family

Disasters have unusual effects on the family, which is a basic institution of society. The study by Cohan and Cole (2002) demonstrates that the year after Hurricane Hugo, in 1989, marriage and birth rates rose in the region affected. Similarly, marital stress, depression and anxiety in couples were adversely affected and therefore divorce rates increased significantly. Particularly after the disaster, in the acute period, children experience much great psychological disorder and they become more dependent on parents. The exposure of parents to trauma influences children's psychology negatively. In disaster times, if parents display unstable moods or behaviours, it can raise the child's anxiety. Concerned parents may have difficulty in perceiving the current emotional needs of children. Traumatic processes can lead to behavioural disorders and attention deficit in children. Children's reactions to disasters can be panic and great fear or more severe prolonged stress disorder. These reactions depend on gender, social circumstances and severity of exposure to trauma. Finally, Bryant et al. (2017) relates higher risk of depression in the after-math of a disaster among individuals who were related to depressed people, had few social connections or were connected to community members that emigrate.

Religion

People who suffer from disasters seek an answer to the question of 'why this happened to me'and feel a significant gap in their spiritual world. Religious foundations provide moral support for victims in such cases. However, there is no single view on spiritual support for people in Europe. In the United Kingdom, a significant number of professional social workers advocate secular social work rather than supporting spiritually based social work. In Germany, however, emergency spiritual service is more inclusive than in the United Kingdom

(Seyyar and Yumurtacı, 2016). Societies have religious needs and so this issue should be taken into account in DRM, accepting the diversity of communities.

5 Case studies

If the disaster risks are unknown to society, it is like travelling on a dark road that ends with a cliff edge. Public awareness must be raised to learn about risks and be more resilient.

5.1 Van earthquake, Turkey

On 23 October 2011, an earthquake of magnitude 7.2 occurred in the province of Van,which is located in the east of Turkey. According to official data, 38 515 houses were heavily damaged, 1 966 people were injured and 604 people were killed. While people were trying to deal with the suffering from the first earthquake, asecond earthquake hit the same region on 9 November 2011. Including two hotels, 25 dwellings collapsed. Forty people were killed under the debris and the total loss of life rose to 644.

There was one question in people's minds: why did the earthquakes cause so much damage? The main reason is that, although similar quakes had occurred previously, and scientific data existed on the earthquake history of the region, unfortunately society had no earthquake awareness and was unprepared for a great catastrophe. Many factors contributed to the scale of the catastrophe. The city was not built under the zoning laws. The development plan included no measures to protect against, prevent or mitigate earthquake risk. In the city, many dwellings were built illegally without engineering, without any control, and used poor materials. The Disaster and Emergency Management Authority (AFAD) noted that the damage was devastating and approximately 77 of every 100 buildings had been destroyed (Figure 2).

Figure 2. *Damaged buildings due to earthquake in Van province, Turkey.* ***Source****: photos courtesy of Aslan Mehmet Çoşkun.*

Unfortunately, the governor's office and the municipality had no risk reduction strategies or plan for the city. Furthermore, the response plan did not clearly define responsibilities in detail so local units were not prepared for an event of such magnitude. It also had no possible disaster scenario.

Therefore, during the intervention, full coordination among the responsible companies was not ensured. Moreover, key staff in the plan did not know anything about their duties or have experience of it. Nobody knew what to do except for the Civil Defence and Search and Rescue Unit.

Although all officials worked hard forhours, unfortunately this effort was not enough to prevent the chaos and problems effectively. Thereafter much work was supported and performed by national units. Within the first 24 hours, 3 221 staff were sent to the region to carry out search/rescue and first aid. National and international teams made great efforts and they rescued 252 victims alive from under the debris (AFAD, 2014).

Seventy-two hours after the shock, 17 836 tents were urgently transferred to the region because there were no pre-stocked shelter supplies locally. However, it was observed that some distribution problems were observed in some districts.There was chaos during the distribution and some people tookmore than one tent (Zaré and Nazmazar, 2013). These unfair events together with the winter condition pushed the people to chaos, and nobody wanted to see anything like distribution crisis, which lasted for days, ever again.

Although camps were established in the region after the first earthquake, the people affected refused to stay in them. They were afraid of leaving their homes and not being able to protect them from thieves,because they considered that security issues had not been solved fully. Therefore, everybody wanted to have special tents to stay near their homes.

Over the following days, the need for tents become the main challenge in the city.This urgent need was supplied fromthe national source and also using international channels. Ultimately 13 tent cities were built in the region and approximately 290 000 people stayed there for days. Hot food, hot water, toilets and showers, social areas, pre-school education, health and religious areas, and psychological support services were provided in the tent cities (AFAD, 2014).

The government found new solutions for shelter in winter conditions, moving 40 000 victims who volunteered from the disaster zone to other cities. They stayed in public guesthouses and all their essential needs were covered by AFAD. In addition, many charity campaigns were organised by non-governmental organisations.
The community welcomed the earthquake victims. Many people living in other cities voluntarily accepted the affected people as guests.This campaign found hosts for 15 000 people and it was a great case of solidarity in society.

On the other hand, the council decided that the victims should stay in containers instead of tents in severe winter conditions. For this purpose, 30 000 containers of 21 square metre each were purchased, which had kitchens, bathrooms, toilets, hot water and electric heating (Figure 3). During the winter, 175 000 people stayed in these containers and their needs were covered by the state.

Many school buildings were damaged, so primary and secondary education stopped for 2 months. Universities were closed for 3 months.Four undamaged hospitals and six tent hospitals continued to work for victims. Electricity and telephone lines were interrupted after the first shock but these services had returned to normal within a few days (Zaré andNazmazar,2013). Critical infrastructures in Van city were not completely damaged.

Figure 3. *Photos of the container city, built after the earthquake in Van province, Turkey.* ***Source****: Photos courtesy of Aslan Mehmet Çoşkun.*

Ten months after the earthquakes, people wanted to come back to normal life as soon as possible. Therefore, 15 332 houses were built by the Housing Development Administration.The new residences were distributed to the disaster victims on 4 September 2012, considering the rights of the victims according to the law. The Van earthquake caused economic losses of approximately TRY 4.9 billion.

In summary, this case tells us that the Van earthquake caused deep social losses in society. The people of the region showed great solidarity among themselves. The whole community mobilised for the region nationwide. Although conditions were hard, society spent a great deal of effort on overcoming these troubles and improving the situation.

If the disaster risks are unknown to society, it is like travelling on a dark road that ends with a cliff edge. Public awareness must be raised to learn risks and be more resilient.

Lesson learned

After this devastating disaster, not only people in the region and the response units but the whole of society gained significant experience. First of all, the earthquake demonstrated that society and the city were not ready for a severe earthquake. In particular, the community lost control in the acute period and peopledid not know what to do and where to go. Unfortunately the local government failed to carry out work correctly. There was no institution to guide society correctly. The importance of communication at the social level was better understood. Based on this experience, society understood that the priorities were to learn the disaster risks very well, to take individual and social measures, to support non-governmental organisations and to strengthen social networks. Immediate capacity building was required at all levels, technical, institutional and governmental (Ergünay and Özmen, 2013).

First, disaster hazard and risk maps were prepared for the regions in order to determine risk.Inaddition,the building code was updated and disaster response plans were extensively revised in accordancewith the lesson learned. New strategies and plans were developed for the challenges encountered in the disaster.

Much scientific research was conducted for the region by universities. Damaged buildings were demolished and sturdy residences were built in the city. In order to raise public awareness, in 2015 a comprehensive project was launched nationwide. The project aimed to create disaster awareness invarious sections of society. By 2020, more than 200 000 people in Van city (students,families,workers,volunteers) had been trained on 'the basic disaster preparedness (Van AFAD, 2020).

These projects good motivate the people of Van, and they are more aware of earthquake hazards and more ready for them. But education projects such as that are not enough; society needs radical changes on strengthening of living space.City administrators need to become aware of the need for and importance of DRM. New strategies must be developed in many fields, especially city planning, strong building and infrastructure.With the support of the central government, many projects and good practices were implemented, in order to restorethe city and societyto normal in a short time.

5.2 Toxic cloud over the town of Zevekote, Belgium

On the evening of Friday 31 March 2017, around 17.30,a tank containing nitric acid leaked on a farm in Gistel, Belgium. The farm used nitric acid to process manure. The leak caused a big yellow gas cloud that could be seen from afar. Nitric acid irritatesthe eyes and lungs and causes chemical burns on contact with the skin. Several policemen experienced this irritant effect of the poison cloud. There were no fatalities. Various measurements were taken during the intervention at various locations. The gas cloud did not reach concentrations that would cause alarm about the safety of the food chain. At the time of the incident, it was unclear what had caused the crack in the tank.

At the news of theemergency,a crisis response groupwas called together and decided to evacuate the village of Zevekote. A safety perimeter of 1 km had been set and the municipal contingency plan was activated. The local fire brigade was first onsite but had to seek help because of the dangerous situation. Later the fire brigades of Gistel, Ostend, Middelkerke and Leke and civil protection operatives arrived on site. Meanwhile, all 570 inhabitants of Zevekote were evacuated to the reception centre in Gistel or went to family and friends. In the reception centre the Red Cross offered psychosocial support for the evacuated and was on standby for medical attention if needed. Later, because of the wind, the cloud with nitric acid also reached another village, Sint-Pieters-KapellenearMiddelkerke. Around 21.00its350 inhabitants also had to leave their homes. These people were also evacuated to the reception centre in Gistel.

People had a lot of questions at the reception centre. They wanted to know what was happening, if their pets would be unharmed, and especially when they would be able to go back. This ambiguity over when they could return remained until the next day and was considered very frustrating by the inhabitants of Zevekote. Communication during the first hours of the disaster was poor. This resulted in frustration and sometimes anger among the people who were waiting for news,especially people with crops and animals that might be at risk. The absenceof the municipality from social media and the lack of an emergency number that people could call to with their questions were considered a great loss. During the relief effort, people took these frustrations to Twitter. Among the people affected there were also farmers whose livelihood depended on their infrastructure within the perimeter. People had the feeling there was a lot at stake, but at the same time felt powerless and did not know what to expect. According to the implementation principles of Hobfoll et al. (2007), one might say that the perceived lack of information here for some people opposed the principles of safety, calmness and hope. The communication with civilians proved a difficult point in the beginning. This is why oneof the lessons learned bythe local government was to develop and use a municipal Facebook page to communicate with civilians. Although some people felt it was too late, the setting up of an emergency number and overall communication, later on, were considered favourable for people's future prospects.

The Red Cross Psychosocial Intervention Service has three main tasks: providing reception, information and guidance. This translates into offering people a listening ear, meeting their needs at that moment, giving information about their relatives, connecting people and facilitating their resilience. Together with giving social support, the volunteers started to register who was in need of a place to sleep. During the registration, other inhabitants came by and offered places to sleep in their homes outside the perimeter.The Red Cross facilitated this process by structuring it. Volunteers registered the offers, while other volunteers registered the people in need of a place to sleep. After this, the coordinator of the reception centre made the match. In the end, apart from a very few individuals, everyone inthecentre found a place to sleep without the help of the government. Normally the local authorities, after consultation, would decide to reorganise a location as a dormitory or to turn to private accommodation services. But, social solidarity came out in groups as natural reaction and people found accommodation quickly. This act is a clear example of what group efficacy, resilience and connectedness after a disaster means.

Another fact worth mentioning that clearly responded to the need for hope was the visit of the mayor to the reception centre. The mayor spoke to the evacuated persons and answered their questions as far as possible. The presence of an authority figure who could assure people to a certain level was considered added value for the inhabitants. While people were leaving the reception centre, they received the information that at 10.00 an information sessionwas going to be organised in the reception centre. All residents of the municipalities of Zevekoteand Sint-Pieters-Kapellewere welcome. They could ask their questions and receive the latest updates. The next day, the inhabitants of Sint-Pieters-Kapelle were the first to be allowed to return to their homes. Around noon the tank was pumped empty and the governor ended the emergency. Shortly after noon, the residents of Zevekote were also allowed to return home under the guidance of the fire department.

By ending the provincial phase of the emergency and intervention plan, Gistel switched back to the municipal phase of the emergency and intervention plan. But that plan was also terminated at 16.00. The situation wasunder control; only traces of nitric acid were still being measured at the site ofthe tank. None was found in the surrounding zones.

Lessons learned

Compared withother disasters, this intervention can be seen as a rather small one, but it is a nice example of the resilience of citizens. Nearly 1 000 evacuees found shelter with neighbours, family or friends. In a culture where people tend to be very closed off and isolated, this act of groupefficacy is remarkable. Furthermore, it is a good opportunity to try to understand and apply the five principles of Hobfoll et al. (2007).

- A sense of safety. The visualisation of the danger (the big yellow toxic cloud), the memory of another disaster in Belgium with toxic chemicals in 2013and the lack of information gave rise to an unsafe feeling. People did not know if the gas cloud was dangerous for their health and that of their pets. On the other hand, the evacuation and the caregivers, who assured people that they were safe in the reception centre (safe zone), promoted a sense of safety.

- Calming. Most of the people were calm once in the reception centre. The lack of information and the ambiguity over when people could return home caused frustration in some of the people affected. There were a lot of uncertainties and for some people there was a lot at stake. Bringing calmness was more difficult without certain assurances. The emergency information number, the information in the reception centre and the information through social media gave people the opportunity to calm down. Other solutions thatmet their needs at that time (medication, babyfood, nappies, etc.) were also able tobringabout a sense of calm.

- A sense of self- and community efficacy. The biggest example of supporting self- and community efficacy is probably the moment where the volunteers from the Psychosocial Intervention Service matched the needs for and offers of sleeping places for inhabitants. Although disaster relief would normally have taken care of this need, the solution sprang from the inhabitants in and around the affected area. The role of the caregivers was to facilitate and support this already ongoing process, so that it could be easier for the inhabitants involved.

- Connectedness. The media caused connectedness simply by reporting the news. The fact that all the people in the reception centre were evacuated immediately also caused a form of connectedness within the group of evacuees. Letting them sit together at the tables they chose (e.g. a table where their neighbours were sitting) supported this feeling. But it was not only limited to the reception centre; there was also clearly a sense of connectedness with the people who lived outside the perimeter and offered a place to stay the night.

- Hope. This principle was harder to promote, since there was only little information, especially in the early hours of the disaster. For a long time, the evacuated families had no clue when they could return home. The information sessionthe next morning is seen as a good action to promote this principle, because it gave people the chance to put things in a broader perspective and let them start planning ahead again. For the same reason, the emergency number and the visit from the mayor to the reception centre also instilled a sense of hope.

6 Role of society in disaster risk management

Disaster risks cannot be managed through trial and error. Societies should learn from disasters they have experienced and develop risk reduction strategies. The main responsibilities of societies in DRM should be protecting individuals, families, institution and assets for the continuity of social structures.

To be resilient, a society should be built on strong institutions, define rules, produce a strong policy as a legal basis, motivate people and guide them.

Public awareness is the key to achieving these. If a society raises awareness, it can easily interact with other societies and learn mutually. A conscious society can also motivate people and push them towards individual preparedness by using social channels. In addition, it can create pressure on the policy area for the right prevention and mitigation strategies and policies to be developed. Hence, we can say that a conscious society can cope better with the effects of disasters so most of the efforts in DRM should be towards enlarging their understanding and engaging them.

Data are an important resource when driving the decisions to be taken by the institutions and communities after an event. Data collected in advance, such as the indicators set for the implementation of the SDGs, loss databases from statistical offices in the country, can be an interesting source of data to exploit to guide the planning of recovery. Indirect impacts on society can be of greater magnitude than the direct effect of the event in the first hours and weeks, so the indicators and the goals established before the event should propose which capacities to strengthen and which vulnerabilities to reduce in the aftermath of an event, following the concept of 'building back better' (UN, 2016). Moreover, the availability of data on several sectors and aspects of society can be useful not only for compensation but to identify the drivers and causes of disasters (De Groeve et al., 2013), to, to design more resilient societies.

7 Conclusion and key messages

In summary, the effects of disaster risks have been found to cause significant losses in many different areas. Depending on the characteristics of disasters, they change daily life, goals, expectations of individuals, priorities and individuals' perspective on life because of physical, economic and social losses, and these effects remain in society's memory for many years. Individual priorities can prevent people from accepting social responsibilities and lead to the reshaping of individuals' decisions.

Major disasters cause rapid and massive destruction in all areas and cause disruption to many services. On the other hand, it is seen that disasters that occur relatively slowly can create a chain effect and affect a wider area and greater numbers of people. In addition, when the threshold of survival in the disaster-affected area is exceeded, migration emerges as a necessity.

Consequently, raising public awareness of these threats, by better communication about the regional and local impacts of disasters, should be a priority for disaster risk reduction. Training and exercises must be organised to raise individual awareness. However, even if individual preparedness for disaster risks is a critical beginning, it does not provide adequate protection for the whole society. Dissemination throughout the whole society and its institutions should follow a collective resistance approach in all areas.

Society is generally unaware of its important roles and responsibilities in DRM. Society can actively reduce risk and provide protection against disasters by using internal dynamics, which have a vital role in the recovery phase. Therefore, it is necessary to provide motivation for families and individuals to increase awareness and prepare the ground for collaboration among all actors of society, reinforcing prevention and mitigation action while preparing communities to face events better.

Policymakers

There is a need to design and implement the right DRM strategies at national and other relevant levels, so policymakers should build policy frameworks that promote coherence and sustainable policies while covering all the dimensions of society. Having DRM strategies is mainly relevant to reinforcing prevention and mitigation of disasters.

Practitioners

International dialogue is rarely sufficient on DRM. To overcome the existing challenges for preventing and mitigating risk, practitioners should play a more active role in the dialogue between societies to facilitate mutual learning from past events.

Scientists and practitioners

Scientific groups play an important role in the planning of prevention measures. They must understand the patterns of societies and their dynamism, exploring the development of new tools for educational programmes, to implement together with practitioners.

Citizens

The level of awareness of citizens is still low for many events that they could possibly face, although progress has been made. Citizens should engage more actively in the prevention of risk, by learning from the events that could take place where they live, taking individual precautions against disasters and participating in local community work for collective protection.

Conclusions

People are the most important element to protect from disaster. This chapter assessed the impact of natural and human-made disasters on population in all its facets, from the individual to society as a whole. The chapter covered case studies at various spatio-temporal scales. There is the slow-onset, long-duration example of the heatwave in Europe in 2003, which affected many countries for a rather long time. At the other extreme, there is the impact of rather local events such as the fire in the Grenfell Tower (United Kingdom) in 2017 or the toxic cloud in Zevekote (Belgium) in 2017. In terms of hazards with fast onset and short duration, there is the analysis of the earthquakes in Van (Turkey) in 2007 and a number of earthquakes in central Italy.

The spatio-temporal dimensions of onset, intensity and duration are central points when analysing the impact of disasters. The most obvious impacts (and the most reported and discussed) are the direct impacts causing death, injury or loss of livelihood. They affect the individual strongly. The indirect losses are related to changes in everyday life due to loss of homes and/or jobs, or even health deterioration through environmental effects such as contamination of air, water, soil and food. Indirect losses affect individuals and their habitat, but they may also influence the functioning of entire societies. Finally, the intangible impacts reduce the quality of life by psychological stress caused by the disaster, such as losses or temporary evacuation or relocation. The intangible impact is often neglected, in particular the long-term effects such as post-traumatic stress disorders.

Populations are not equally vulnerable to any specific hazard. Individual capacities and behaviour influence a person's vulnerability to a particular hazard. While the direct physical vulnerability of the individual to death, injury or homelessness is well understood (for example through physical building vulnerability studies), indirect social vulnerability is often overlooked. At the community level, socioeconomic aspects such as age, income and formal education can indicate the social vulnerability of specific groups. Socioeconomic inequalities can lead to very different vulnerability and resilience patterns, which calls for better incorporation of socioeconomic aspects in vulnerability assessments and research.

A common feature from the analysis of the case studies is that the population (individual citizens, policymakers, society as a whole) is often unaware of disaster risk reduction and prevention measures. Policymakers should invest in risk knowledge and awareness creation as well as in self-protection. This could be achieved by systematically including personal safety and disaster prevention in education curricula.

Although a lot of information is already available for the prediction, assessment and possible mitigation of the effects of hazardous events relating to population, researchers should exploit the increasing data available to investigate the still existing gaps, trying to get the full picture and develop tools for informed decision-making. At the same time, policymakers should create legislation to

support systematic data collection on all human impacts of disasters over a longer period, beyond death and physical injury, including the location, the demography of the affected population and temporal descriptors of the event. Specific attention should be given to the indirect impacts such as long-term effects on people exposed (including emergency responders), with a focus on psychological trauma and mental health.

The wealth of information provided by new data sources such as social media, mobile phone data or Earth observation should be used by scientists to improve the modelling of human exposure and vulnerabilities, addressing individual, social and locational factors. For example, Earth observations can inform decisions and actions for the benefit of humankind. The new satellites available as well as the development of ground- and drone-based sensors has resulted in a noticeable increase in the use of these techniques for assessing the potential impact of natural hazards. Initiatives such as the Group on Earth Observation also contribute to this exploitation, aiming to develop a new generation of measurements and spatial statistics in support of post-2015 international processes on sustainable and urban development, climate change and disaster risk reduction.

Horizon Europe (the EU's research and innovation framework programme for 2021–2027) will incorporate research and innovation missions to increase the effectiveness of funding by pursuing clearly defined targets.

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Introduction

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3.2.1 Threat to life

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Super Case Study

2

Fukushima Daiichi accident in 2011

Online Version

Super Case Study 2:

Fukushima Daiichi accident in 2011

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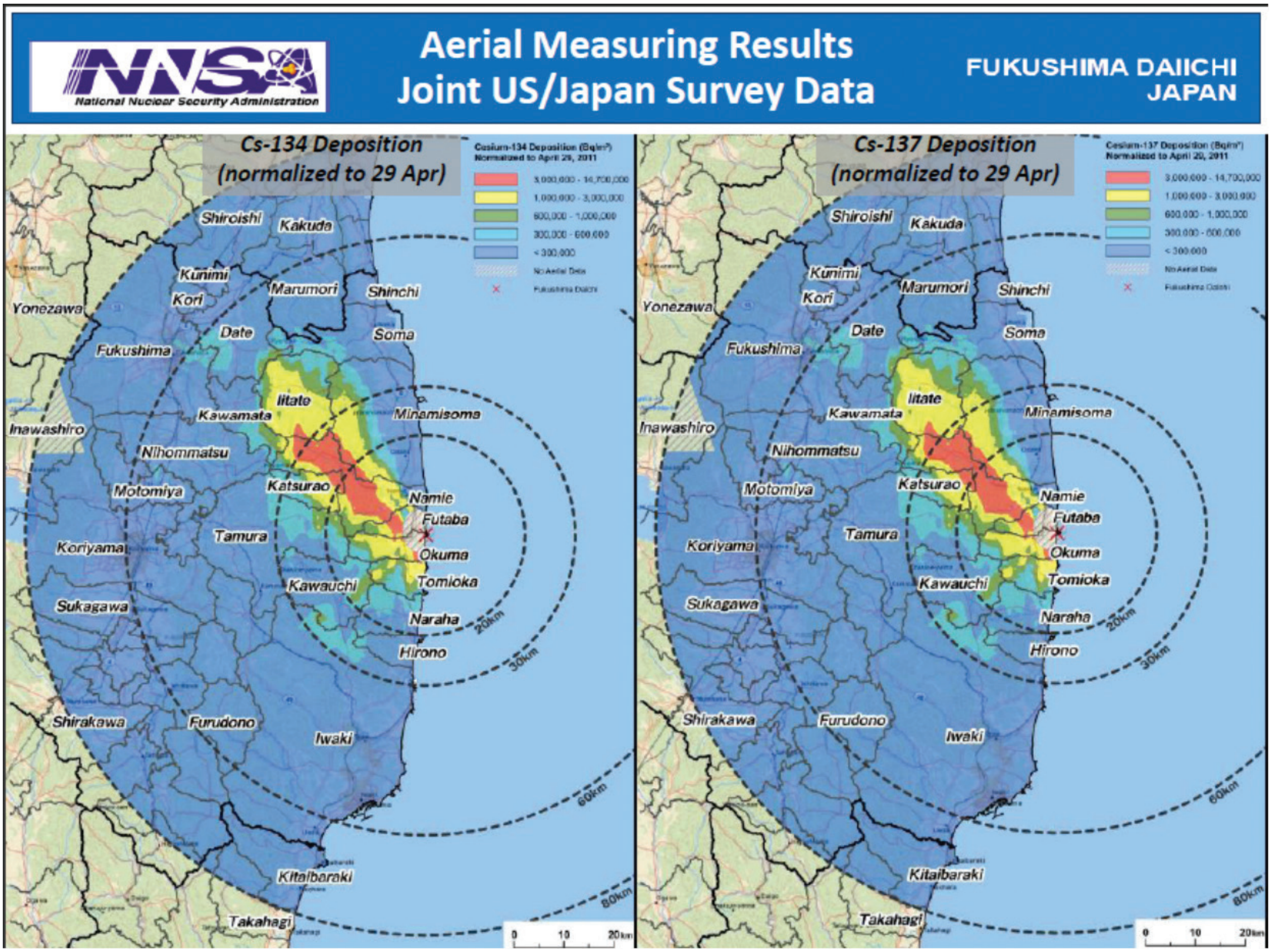
CONTENTS

1 Introduction

This study focuses mainly on the Fukushima nuclear disaster; however, it also addresses the consequences of the tsunami, as both of them influenced the impacts and emergency management.

The great east Japan earthquake (GEJE), with a magnitude of 9.0, occurred off the north-east coast of Japan at 14.46 local time on 11 March 2011. It caused a tsunami that resulted in the deaths of approximately 18 500 people and initiated the nuclear disaster at the Fukushima Daiichi nuclear power plant (FD NPP), with approximately 150 000 people receiving evacuation orders (NAIIC, 2012; IAEA, 2015a; Callen and Homma, 2017).

Figure 1. *The area affected by radiation.* ***Source****: US Department of Energy, 2011.*



At the FD NPP, with six reactors, units 1–3 were in operation whereas units 4–6 were shut down because of maintenance or refuelling works. The reactors of units 1–3 were shut down automatically by the reactor protection systems when the ground motion was detected, in accordance with the design. However, the earthquake damaged the external electric power supply lines, and then the tsunami wave, with a height of more than 14 m, flooded most of the emergency diesel generators, causing a complete station blackout. This severely affected the cooling function of the operating reactors as well as of the spent-fuel-cooling pools. Cooling of the residual power of the reactors was maintained thanks to systems regulated by batteries that stopped after some hours. As cooling could not be restored from external sources, severe damage from fuel melting occurred to the reactor cores of units 1–3. Oxidation of metal parts of fuel by steam at high temperature generated large amounts of hydrogen, and the containment vessels were breached because of an increase of pressure far beyond what they were designed to cope with. Hydrogen explosions were produced in the reactor buildings of units 1, 3 and 4, damaging structures and equipment and injuring personnel. In unit 2, an explosion in the containment building was produced. This resulted in large amounts of radionuclides, although less than 10 % of the amount from Chernobyl (Steinhauser et al., 2014), being released into the atmosphere and deposited on land in the following days, causing severe contamination in the area to the north-west of the FD NPP (Figure 1) and on the ocean. Large and direct releases of highly radioactive water into the sea were also produced from a trench at unit 2, with a peak at the beginning of April 2011. An assessment of different published estimates made by the International Atomic Energy Agency (IAEA, 2015b) indicates ranges between 7 and 50 PBq and between 90 and 700 PBq for the atmospheric releases of the key radionuclides ^{137}Cs and ^{131}I, respectively (excluding uncertain early estimates).

2 Description of the main consequences of the event

The combined effects of natural and man-made disasters had severe consequences that were not recognised in the preparedness phase. Cascading and lasting effects have been observed.

2.1 Main consequences for the environment

The releases resulted in the contamination of the surrounding terrestrial (and freshwater) environment through deposition processes and interception by vegetation (IAEA, 2015c). Soil deposition density maps of gamma-ray-emitting radioactive nuclides are supplied by Yoshida and Takahashi (2012), Saito et al. (2015) and the IAEA (2015b), and on the dedicated website of Japan Map Center (JMC, 2019), with values of several MBq/m^2 for ^{137}Cs and ^{134}Cs within the restricted area of 20 km around the FD NPP. The resulting dose rates in the areas around the FD NPP led the Japanese Government to define a deliberate evacuation area extending up to 55 km in the north-west direction, in addition to the restricted area (IAEA, 2015a). Eight years after the accident, the areas where it is expected that the residents will have difficulties in returning for a long time cover 337 km^2 extending to about 40 km in the north-west direction with a width of about 10 km (Reconstruction Agency, 2019; JMC, 2019).

The possible biological effects of radiation and its ecological impacts over time among non-human species following the FD NPP accident have been intensively studied (e.g. Steen and Mousseau, 2014). However, no impact on populations or ecosystems have been reported (IAEA, 2015b), i.e. the releases from the Fukushima Daiichi accident are unlikely to have caused any substantial harm to animals and plants. Special attention was paid to characterising the radioactive contamination in north-eastern Japan (e.g. Imamura et al., 2017), which is mostly covered by forest (c. 70 %). Recent studies (e.g. Manaka et al., 2019) have supported the view that contaminated forests have entered a steady-state phase of ^{137}Cs cycling. In rivers, Somboon et al. (2018) reported values up to 22 000 Bq/kg in riverbed sediments and 2 000 Bq/kg in flood plain deposits 7 years after the accident.

Radionuclides were also found in seawater and marine organisms through deposition to the sea surface and runoff of seawater used to cool the reactors, plus leakage of wastewaters from damaged containment structures (IAEA, 2015b). The Institute for Radiological Protection and Nuclear Safety (IRSN) reported that radionuclide concentrations were stable in the marine environment close to the nuclear power plant (within a 30 km radius) 5 years after the accident, and radioactive caesium concentrations had fallen to levels close to those observed prior to the accident more than 200 km from the FD NPP (IRSN, 2016).

Under prevailing weather conditions, more than 80 % of the atmospherically released radionuclides were estimated to have gone offshore from Japan, followed by deposition in the Pacific Ocean (Morino et al., 2011) and in other parts of the world. The global atmospheric transport and deposition of radionuclides released from Fukushima have been documented (e.g. Christoudias and Lelieveld, 2013). The long-term consequences of the releases on the environment are considered to be insignificant (IAEA, 2015b).

2.2 Main consequences for the population

The most disruptive consequences were the evacuation orders to the population around the FD NPP. Whereas the evacuation as a result of the earthquake and tsunami was obvious – more than 460 000 people were displaced to about 2 400 shelters throughout Japan – the one prompted by the nuclear disaster might not have been (Hasegawa et al., 2016). Evacuation orders around the FD NPP were issued on 11 March, successively increasing the radius from 2 km to 3, 10 and then 20 km (IAEA, 2015a; METI, 2017). Sixty patients from hospitals and nursing homes died from complications related to the evacuation (NAIIC, 2012). This continuous increase of distances did not foster trust in the authorities. Moreover, iodine thyroid-blocking tablets were not distributed within the 10 km emergency zone despite the available stocks (Callen and Homma, 2017).

Evacuated people received compensation and support for establishing their lives outside their home towns. Similarly to Chernobyl, psychiatric problems as well as psychosocial issues such as stigma or discrimination from the public emerged (Maeda et al., 2018). Radiological consequences were limited; e.g. there were no early radiation-induced health effects on humans (workers or the public). The radiological consequences in countries other than Japan appeared negligible (Masson et al., 2011; Behrens et al., 2012).

As a long-term consequence, disaster-related deaths (DRDs) were reported. A DRD is defined as 'a death caused by the deterioration of underlying medical problems due to poor medical access or illnesses arising from poor living environments, such as temporary shelters, in a disaster' (Ichiseki, 2013). By 31 March 2013, 2 688 people died in shelters or temporary houses (Ichiseki, 2013). By the end of 2018, this number had increased to 3 701 deaths (Nippon.com, 2019). The figures do not distinguish whether the DRD is a direct effect of the tsunami or the evacuation from the nuclear power plant accident. However, they clearly demonstrate the importance of long-term medical care after such a disaster.

Consequences were also investigated by a study called Fukushima Health Management Survey coordinated by the Fukushima Medical University (Yasumura and Abe, 2017) that reports the following information. The basic survey aims to estimate the external radiation dose exposure of 2 050 000 inhabitants. At 31 March 2018, 567 810 persons had answered the questionnaire. Results based on estimates show that 62.2 % had received doses below 1 mSv and only 15 persons were exposed to values above 15 mSv, with a maximum of 25 mSv.

Several specific studies were launched as well. One focused on thyroid cancer occurrence in 360 000 children who were under 18 years old when the accident occurred. The preliminary baseline screening campaign conducted from 2011 to 2014 showed 116 and 71 thyroid cancer cases in the first and second rounds for children. However, the frequency of occurrence of thyroid cancer is similar to that in non-exposed children (Yamashita et al., 2018). From 2017 onwards, evacuation orders were lifted in several villages, allowing the population to return to their homes. The official number of people throughout Japan still living in temporary housing is about 54 000 (Nippon.com, 2019). It was reported that, by January 2019, approximately 32 000 of Fukushima's roughly 42 000 evacuees still lived in other prefectures. This shows that many of the evacuees still have not returned. Indeed, the choice of returning or not is dependent on several factors: some are linked to the post-accident policy with financial incentives and constraints; others can be linked to age, family status, professional status (Fassert and Hasegawa, 2019).

The population's trust in authorities is indeed a key for success in emergency management and long-term rehabilitation (see for example IAEA, 2015a). In Fukushima, however, the local population was faced with 'chaotic mishandling of the Fukushima crisis', as reported by Abe (2015). The delayed information about release and statements such as 'The radioactive fallout does not have any immediate health effects' worried the public (Tateno and Yokoyama, 2013, p.2). To build trust, risk communication may play an important role. It helps in explaining the consequences of the accident and enhances the capability of local actors to make informed decisions and, finally, understand the authorities (Perko, 2015).

2.3 Main consequences for critical infrastructures

Several types of critical infrastructure (CI) were affected by the disaster. Among them, the sudden loss of about 10 % of power generation capacity on 11 March and the eventual shutdown of all 50 nuclear power plant units in Japan by 2012 caused a deficit of 30 % of the electricity supply that could not be closed immediately (Komiyama, 2017). This initially caused shortages in the supply to citizens, resulting in rolling blackouts that were implemented in March to April 2011 in the Tokyo and Kanto area, followed by mandatory reductions in power usage from July 2011 onwards to avoid unplanned blackouts during summer months (Komiyama, 2017)
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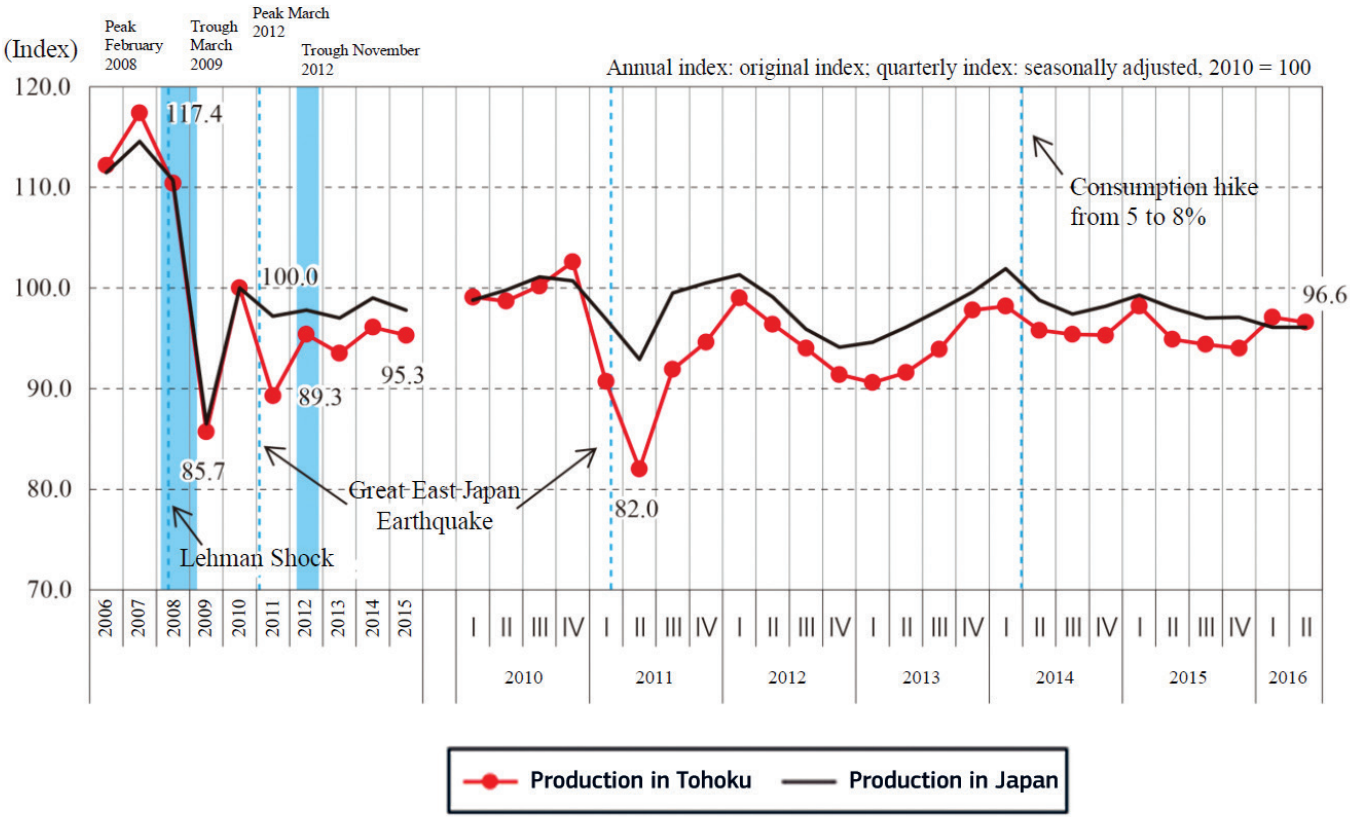
Immediate consequences to CI were caused by the earthquake and tsunami. They affected, for example, regional airports, seaports, many motorways, the Tohoku Shinkansen (high-speed railway) and nuclear plants. The Sendai airport north of Fukushima was closed for 6 days and not available to bring in rescue personnel directly after the earthquake (Kadri et al., 2014; Holguín-Veras et al., 2014). The problems at the airports resulted in the need for more intensive ground transport to deliver goods, and in particular food, to the affected areas. However, owing to shortages at local petrol stations, delivery of needed products was delayed or even impossible (Shimizu and Clark, 2015). Besides the shortage of petrol, impacts on the logistics sector also reduced the capacity for fast response (Holguín-Veras et al., 2014). Communication lines were disrupted, by either damage or loss of power, thus affecting critical communication between the national and local governments, as well as between governments and first responders (Shimizu and Clark, 2015). The medical sector, one of the most important sectors in case of a crisis, was heavily affected by the disaster. Six hospitals that were assigned as primary radiation emergency hospitals were nearly unable to function owing to physical damage, location in an area where evacuation was proposed or lack of personnel (Hasegawa et al., 2016).

2.4 Main consequences for the economic sector

The GEJE and tsunami event caused severe and long-lasting damage to the physical capital stock, infrastructure and supply chains in the affected regions and far beyond. The Japanese Cabinet Office estimated the total damage at USD 210 billion (4 % of Japan's gross domestic product), of which USD 129 billion was direct damage to buildings and facilities such as housing, offices and plants and USD 43.5 billion was for transport infrastructure, lifeline utilities and critical infrastructure such as electricity, water and communication (Ranghieri and Ishiwatari, 2014). The energy sector was one of the most severely affected by the disaster. With respect to agriculture, fisheries and forestry, in 2011 the capital stock was affected by about USD 29 billion and the total cultivated area for agricultural crops in the affected Tohoku region declined significantly (TBETI, 2016).

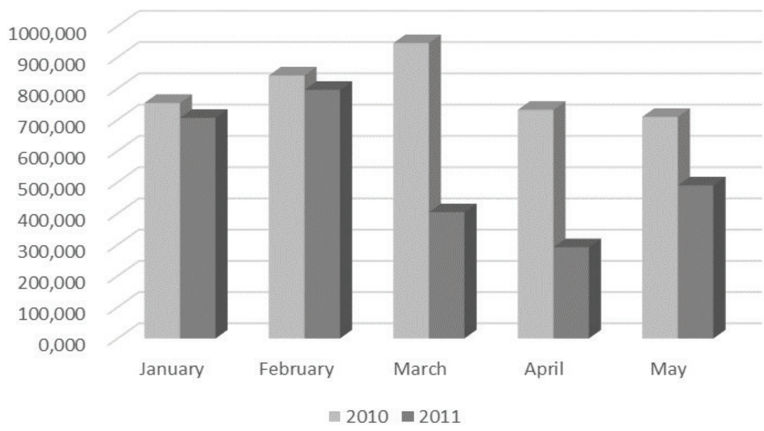
***Figure 2** shows how the GEJE-event affected industrial production of the Tohoku region compared to the level of industrial production from all over Japan. **Source**: TBETI, 2016.*



The damage to the tourism industry amounted to USD 8.7 billion (IBRD, 2012). On the financial markets, the Nikkei Index (Tokyo Stock Exchange) fell by almost 5 % for a brief period while the yen depreciated based on the expectation that Japanese investors would repatriate cash to cover the costs of the disaster (Ranghieri and Ishiwatari, 2014).

Japan is the second largest manufacturer in the world and is known for key materials (e.g. Japan provides 60 % of the world's supply of silicon, which is used as raw material for semiconductor chips) and for its high technical precision and quality in key industries such as the automotive and electronics industries (Park et al., 2013). Such key primary industries are also located in the affected region of Tohoku. Compared with the whole industrial output of Japan, the region of Tohoku is especially strong for information and communications equipment (15.2 % of the national total), and electronic devices and circuits (13.8 %), which makes this region an important manufactural hub (TBETI, 2016). Figure 2 shows how the GEJE event affected industrial production in the Tohoku region compared with the level of industrial production from all over Japan.

***Figure 3**. Motor Vehicles Production in Japan (year-on-year-comparison),*
***Source**: De Souza, 2011.*



The disruptions in the industries of the Tohoku region led to severe and prolonged interruptions in the national and global automotive supply chain, mainly caused by the lack of energy and the unavailability of a transport network as first-order effects, and the short supply of preliminary parts as a second-order effect (Ono et al., 2015). First and foremost, in March 2011, there was an immediate and strong decline of 57 % in the production of motor vehicles in Japan, as illustrated by Figure 3 (De Souza, 2011, based on data from the Japanese Automobile Manufacturers' Association). The drop in production reached 60 % in April 2011 and it recovered slightly in May 2011.

The business interruptions caused the bankruptcy of more than 650 private companies within one year, and 88 % of these Japanese firms were located outside the Tohoku region, i.e. they were indirectly affected by supply chain problems (IBRD, 2012). A large proportion of highly specialised Japanese small and medium-sized enterprises produce goods overseas, which led to notable ripple effects through supply chains around the world. Taking Toyota as an example, the GEJE caused the shutdown of domestic factories in March 2011 and they slowly recovered to an operational level of 50 % in April and May. Toyota's overseas factories were initially unaffected but dropped to an operational level of 20 % for lack of parts between mid-April and May. Both domestic and overseas factories reached an operational level of 70 % in June 2011 (Ono et al., 2015). The disruptions spilled over to other countries in the region. Farther away, GM, Ford and Chrysler closed their plants in the USA (Park et al., 2013). Opel in Germany and Renault in France saw interruptions in production, too (De Souza, 2011). One reason for the high vulnerability of the supply chain for motor vehicles, but also for electronic equipment, was the highly specialised single-source strategy of major Japanese car makers such as Nissan and Toyota (Abe and Ye, 2013). In addition to this, there was a very low level of inventory and operational flexibility because of just in time production .

2.5 Main consequences for the cultural heritage

The 2011 earthquake and tsunami had severe impacts on the cultural heritage sector. Immediately after these events, the Agency for Cultural Affairs launched two programmes to rescue/recover the affected cultural heritage and prevent the occurrence of further damage (e.g. demolition, theft, abandonment): the Cultural Property Rescue Programme, which focused on movable heritage assets; and the Cultural Properties Doctor Dispatch Project, which focused on immovable heritage assets (ICOMOS, 2014). Besides the normal difficulties involved in cultural heritage stabilisation and rescue operations during post-earthquake scenarios, the damage to the FD NPP introduced additional challenges. The defined evacuation zones made it difficult to get information about the damage to cultural heritage in those areas and perform heritage recovery/rescue operations. Moreover, the seriousness of the situation was further intensified because Japanese cultural institutions did not have, at the time, cultural heritage protection procedures or guidelines for scenarios involving radiation-contaminated areas. According to the maps provided by the Institute of Disaster Mitigation for Urban Cultural Heritage (R-DMUCH, 2012), of the many immovable assets of the Fukushima prefecture that were affected by the earthquake (which include 127 buildings and 65 historic sites; Kikuchi, 2015) only three appear to be located in the original evacuation zone (the Kannondo stone Buddhas, the Daihizanjitoku Temple and the Idagawa memorial (stone) monument in Minamisōma). Accordingly, conservation and repair measures for these heritage assets could not be implemented right after the event. In terms of the consequences to movable heritage assets, the available data provide a more detailed description of how the post-disaster situation was addressed. The areas that were evacuated because of the radiation levels have four public museums as well as several storage facilities housing archaeological artefacts excavated by local governments. Although these facilities did not sustain major damage due to the earthquake, it was critical to undertake actions to rescue the heritage assets they housed to avoid further damage or thefts. However, these actions were unable to start before August 2012.

By October 2013, close to 4 000 boxes (60 × 44 × 15 cm) of heritage assets were rescued from the evacuated areas. By then, the Shirakawa storage facility was already nearly full, even though a large number of heritage assets remained in the evacuated areas (Kikuchi, 2015). Furthermore, at the time, the whereabouts of heritage assets that were privately stored or owned remained mostly unknown, thus precluding the ability to get a clear picture about the amount of work that still had to be done. Finally, it is noted that, since the Shirakawa facility provides only (temporary) storage, heritage assets formerly in museums were no longer on display. However, Sano and Yamamoto (2013) state that a selection of the rescued heritage assets is displayed in annual exhibitions to keep the memories of these events alive and to reconnect the people who were evacuated from Fukushima with their home towns.

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3 Lessons learning and learned

Public investigations and hearings were launched in many countries, as were stress tests for more realistic and severe worst case scenarios, beyond design basis. Risk regulation and governance have been revised. Preparedness remains of utmost importance

Following the FD NPP accident, the status of existing plants was reviewed in many countries around the world, and particular stress tests initiated (OECD/NEA, 2017; European Union, 2012, 2013). In the European Union, 132 units in 17 countries were considered targets for stress tests. Positive and negative issues were identified and solutions proposed for problems, which had to be implemented by national authorities. In France, for example, stress tests are called complementary safety assessments (évaluations complémentaires de sûreté), as their purpose is to challenge NPP design assumptions with more extreme natural hazard threats. It is a complementary approach to the usual safety demonstration approach required for the licence of design and operation, in the sense that it should address 'beyond design basis' scenarios. Those beyond design basis scenarios could lead to cliff-edge effects in critical equipment and safety functions (especially loss of cooling and electricity) and would then lead to a severe accident and radiological release to the environment.

In the USA, studies were carried out to investigate the current status of safety regulations for NPP. Among them, a comprehensive study on Lessons learned from the Fukushima nuclear accident for improving safety of U.S. nuclear plants was performed by an independent Committee on Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants (2014). It provided recommendations for improvements in both plant status and emergency management.

In Japan, the national system of nuclear regulation and competent authorities was changed. On 15 August 2011 and on 11 December 2011, a cabinet decision and a recommendation from the Advisory Committee for the Prevention of a Nuclear Accident, respectively, proposed to separate regulatory functions with respect to nuclear safety, security, safeguards, radiation monitoring and radioisotope regulation from promotional functions (IAEA, 2015a,d). This decision is in line with the objective of establishing and improving safety culture worldwide (IAEA, 1998).

In Europe in particular, the need for decision-making with limited information was recognised. Response in the very early phase in Japan was dominated by missing information on potential radioactive releases and their consequences. In this respect, the available predictions from the national System for Prediction of Environmental Emergency Dose Information (Chino et al., 1993) were not used by decision-makers owing to the lack of source term estimates due to the loss of power on site at the FD NPP (IAEA, 2015e). In Europe, the ongoing discussion about cross-border harmonisation and advice in the very early phase of the emergency resulted in concerted action by the Heads of the European Radiological Protection Competent Authorities and the Western European Nuclear Regulators' Association, proposing a concept to deal with cross-border emergency management in the early phase (HERCA-WENRA, 2014). To deal with missing and uncertain information in the early stages of an accident, they proposed to characterise the need for early countermeasures, such as evacuation, sheltering and iodine thyroid blocking, by four key parameters. They selected risk of core melt, containment integrity, wind direction and time of release as factors that are sufficient to initiate countermeasures. Thus, depending on the plant status, weather and start of release, areas for early phase countermeasures are proposed and are applicable all over Europe and worldwide.

As trust and communication were considered essential, work on this topic is ongoing. Practical recommendations on risk communication can be found from Perko (2015) and Tateno and Yokoyama (2013). They conclude that timely and clear information is key for success. The public should feel that authorities care about them in the best possible way.

Provisions related to failure in CI, e.g. power or medical supplies, were addressed in many countries. Providing uninterruptible power supplies to services such as hospitals, first response centres, internet and phone services, and data centres (exempting them from rolling blackout schedules is recommended) was identified as important (National Academies of Sciences, Engineering and Medicine, 2016). It was also recognised that a response centre for a disaster should not be built in a location that is likely to be affected by a disaster: the designated off-site centre by Fukushima Daiichi had to be abandoned, as air filters were not installed by design and it lacked a reliable power supply (JNES, 2013).

The catastrophic natural disaster in Japan clearly highlighted the vulnerability of global supply chains. There are a couple of lessons learned that can be drawn from this event and are integrated in current supply chain risk management practices. A first measure relates to the preparedness of a business, which requires a business impact analysis and a business continuity plan. To this end, risk managers should work with realistic worst case and multi-hazard scenarios and establish a response plan that includes preparation, training and permanent communication with key decision-makers. Risk and crisis managers should be always aware of the fact that even the worst case can be an overly optimistic scenario if boundary conditions are wrongly considered (IBRD, 2012).

With respect to the supply networks of a company, suppliers should be part of the contingency plans and also prepare for the unexpected, especially in generic skills and organisational capabilities. As the case studies of Park et al. (2013) highlight, firms that were heavily affected by the disaster now regularly visit their suppliers to develop strategies for emergencies together with them. In addition, the need to become less dependent on energy provision and availability of critical parts was recognised. As the study of Ono et al. (2015) illustrates, Japanese supply chain managers (in manufacturing businesses) see a need for an increase in the decentralisation of domestic procurement, a need for further expansion of their overseas procurement and the importance of multiple sourcing. Finally, the application of network risk management procedures is also of high importance.

4 Consequences for emergency management

In addition to preplanning of all possible actions – including communication – in the preparedness phase, training should enhance skills for adaptation to the unexpected. Continuity plans should widen their scope with regard to cascading and lasting effects, to foster resilience within territorial and supply chain perspectives.

Many authors have addressed the need to better prepare for such an emergency; in particular, to prepare evacuation routes well in advance, to define how to deal, for example, with hospitals, elderly care homes, prisons or members of the general public with disabilities (physically impaired/deaf/blind) in the area at risk. Furthermore, there is a clear need to inform the population well in advance about the risk and the proposed management plan in case of an emergency. In the long term, healthcare services and measures to prevent social disruption have to be strengthened.

Initiated in the frame of the European stress test on nuclear power plants, the European Commission launched a study to review, in particular, cross-border emergency management arrangements in Europe (ENCO, 2014). The study highlighted several gaps in existing arrangements and provided recommendations for all EU Member States. Among them, harmonisation of criteria, cross-border communication and integration of nuclear emergency management into civil protection mechanisms are some aspects that still are not fully implemented.

Several countries in Europe initiated reflections on their emergency management preparedness. Among them, the German Radiation Protection Commission issued a catalogue with many considerations for improvement based on lessons learned after Fukushima (Strahlenschutzkommission, 2015). One demanding part of this was realised in 2014 with the new definition of preparedness-planning zones for evacuation, sheltering and iodine thyroid blocking. Planning distances were generally increased as, in the new assessments, International Nuclear and Radiological Event Scale (INES) 7 source terms (IAEA, 2008) were considered, unlike what had been done before (Strahlenschutzkommission, 2014). Similar work was performed in Sweden, where the Swedish Radiation Safety Authority (SSM), together with other agencies and stakeholders, reviewed emergency-planning zones and emergency-planning distances for early-phase countermeasures, which led to a revision of the planning zones (SSM, 2017). In France, several changes to emergency management were conducted at several levels. The government established a new national plan to respond to a nuclear crisis. Local emergency response plans were updated to integrate the effects of severe natural hazards on response. Strategies to improve robustness include strengthening on-site safety equipment to resist extreme hazard impacts, such as electricity backup with diesel generators or new emergency centres, and are complemented by resilience strategies to rely on more flexible capabilities to face unexpected situations.

Besides operational consequences, at least in Europe, several research projects started to address gaps from Fukushima. Among them, the Prepare (Innovative integrated tools and platforms for radiological emergency preparedness and post-accident response in Europe) (Raskob, 2017) project, completed in 2016, and the Confidence (COping with uNcertainties For Improved modelling and DEcision making in Nuclear emergenCiEs) project (Confidence, 2019), completed in 2019, supported the development of methods and tools that will be used operationally in Europe and worldwide, e.g. as part of the JRODOS (Java based Real-time On-line Decision Support) system (Ehrhardt and Weis, 2000; Ievdin et al., 2010). The resilience of society was also addressed as important for emergency management preparedness.

5 Conclusions

The cascading chain of events in Fukushima demonstrated the need for preparedness for compound events, beyond design basis, that are extremely unlikely but with high impact. The station blackout of the Fukushima Daiichi nuclear power plant could not be managed by the means foreseen in the preparedness phase. Decision-making with high levels of uncertainty resulted in decisions that are regarded as questionable in hindsight, but were probably inevitable given the exceptional chain of events with the earthquake, tsunami and meltdown of reactor cores.

The high number of deaths caused by the earthquake and tsunami is extremely unfortunate; however, more than 3 000 disaster-related deaths might be the result of a lack of preparedness for the long-term effects of such a combined disaster. The social disruption resulting from evacuation, and stigma resulting from fear of consequences of radiation, are key impacts on evacuees in the provinces around the power plant.

The most affected CI in Japan was the energy sector, with the stepwise shutdown of all nuclear power plants following the accident. Economic consequences were numerous and affected not only Japan but the global economy.

Gaps identified and lessons learned were manifold, particularly in the areas of nuclear safety and emergency management. Among them, proper preparedness at all levels even for very unlikely events can be regarded as a key driver of successful emergency management. In particular, the need was again highlighted to prepare for low-probability, high-impact events – such as Chernobyl and Fukushima, which were accidents with the highest INES rating and an extremely low probability.

ACKNOWLEDGEMENTS
The 5th contributing author would like to acknowledge the financial support from POCI-01-0145-FEDER-030469 - RIACT – Risk Indicators for the Analysis of Cultural heritage under Threat, by FEDER through COMPETE2020 - Programa Operacional Competitividade e Internacionalização (POCI) and by national funds through FCT - Fundação para a Ciência e a Tecnologia, and the financial support from Base Funding - UIDB/04708/2020 of CONSTRUCT - Instituto de I&D em Estruturas e Construções, by national funds through FCT/MCTES (PIDDAC).

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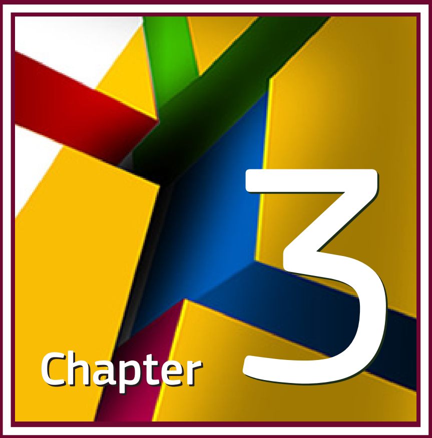

Assets at risk and potential impacts

3.3

Economic sectors

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Mysiak, J., Molinari, D., Tsionis, G., Toreti, A., Okuyama, Y., 'Economic sectors', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

3.3 Economic sectors

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3.3 Economic sectors

Introduction

Natural hazards are a major threat to sustainable development, economic stability and growth, territorial cohesion, and community resilience. According to the estimates of the European Environment Agency, the economic damage due to only natural hazard risks in the EU amounted to more than EUR 557 billion ([1]) in 1980–2017, mostly triggered by extreme weather and climate-related events whose frequencies and/or intensities are expected to increase as a result of human-induced climate change. The bulk of this damage was caused by relatively few low-probability, high-impact hazard events.

These estimates account only for the direct economic damages to physical assets only and omit often significant indirect economic losses generated by slow-onset hazards, spillover effects and indirect costs from the disruption of social networks, economic flows and ecosystem services. As a result of neglected attention to disaster risk impacts in the past, it is not easy to portray the spatial and temporal patterns of disaster damage and losses with reasonable precision.

The Sendai framework for disaster risk reduction 2015–2030 (UN, 2015) emphasised multi-hazard, inclusive, science-based and risk-informed decision-making, and laid down priorities for action and policy targets. The policy targets include a commitment to substantial reduction of economic damage. A sound understanding of risk does not only imply accounting for past damage and losses. Model-based economic risk assessment has been propelled by high-performance computing, large-scale hazard and disaster loss/impact models, and high-resolution exposure datasets of the Copernicus Earth observation programme.

A better understanding of natural hazard risk and ensuing economic losses is important for coordinating responses to shocks and crises within the European Economic and Monetary Union (Aizenman et al., 2013; Ureche-Rangau and Burietz, 2013). In the absence of financial protection tools for coping with disasters, the incidence of major disasters in several EU Member States may exacerbate economic imbalances and deteriorate credit ratings (Mysiak and Perez-Blanco, 2015).

This subchapter reviews the methods and models used, recent advances, and challenges in analysing disaster damage and losses in residential, agricultural and industrial sectors. Gross fixed capital formation in residential housing sector amounts to 5 % of gross domestic product (GDP) in the EU-27 (Eurostat, 2020). Housing statistics and prices are important indicators of living conditions and therefore regularly collected by national statistical offices and Eurostat. The characteristics of residential building stocks are surveyed by statistical censuses, and those of residential built-up areas can also be obtained from very high-resolution remote sensing data (e.g. European Settlement Map (Sabo et al, 2019; European Commission, 2020). Housing prices are sensitive to past experiences of risk and availability of insurance coverage. Insurance premiums determined at actuarial risk pricing, on the other hand, are a function of a property's hazard exposure.

The agricultural sector contributes around 1.1 % of the EU's GDP but manages almost 40 % of the EU's total land area and represents an important employment opportunity for the rural population. Agriculture is heavily exposed to weather- and climate-related hazards (storms, droughts, floods, heat and hail), other risks such as pests and diseases, and market volatility. Assessments of economic impacts of water scarcity or droughts may be based on statistical, crop growth and/or Ricardian land price models. The econometric models exploit the historical covariation between yields and weather on an annual or more frequent basis to infer the effect of climate variability and change (e.g. Schlenker and Roberts, 2011). The Ricardian method assumes that agricultural land rents reflect the expected productivity of agriculture (Moore and Lobell, 2014; Van Passel et al., 2017).

Hazard-induced disruptions of energy supply or industrial production set off supply and demand shocks that affect regional economies in and beyond the areas directly affected by the disasters. The damage to tangible productive assets is equivalent to losses caused by disruption of production networks (Rose, 2004). The demand for liquid capital may increase its price; the level of fiscal consolidation and perceived trustworthiness play a role. Efforts to restore productive and non-productive capital losses generate new demand and change consumption patterns, which may lead to changes in prices, trade levels and fiscal revenues. These effects can be modelled by input–output, computable general equilibrium, social accounting matrix and econometric models.

(1) EU-28 Member States as in 2018 (including the United Kingdom), European Free Trade Association countries and Turkey, based on the NatCatService of Munich Re, estimated for the European Environmental Agency and Eurostat climate change indicators.

3.3.1 Residential sector

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1 Importance of the residential sector

Residential buildings constitute one of the main types of assets exposed to natural hazards, with a relatively high economic value. Residential construction contributed to 4.4 % of EU gross domestic product (GDP) in 2018. The total built-up residential area in the EU is more than 200 000 km^2. Natural hazards may result in damage to buildings and reduction in their market value. For instance, the price of houses in the north of the Netherlands dropped by almost 4 % for every percentage point increase in peak ground velocity due to induced seismic activity (Duran, 2017), while the price of houses within a 100-year floodplain is reduced by 4.6 % after a flood, and requires 5 to 7 years to recover (Beltrán et al., 2018).

Residential buildings are also important for the safety and quality of life of citizens; therefore, they are essential for achieving the Sustainable Development Goal 11 for inclusive, safe, resilient and sustainable cities as well as the targets of the Sendai framework for disaster risk reduction (UNISDR, 2015a) to reduce the number of affected people by disasters and direct economic losses. Residential buildings are the target of EU policies for risk prevention and mitigation. The Union Civil Protection Mechanism encourages measures to promote resilience at building level, whereas Directive 2007/60/EC on the assessment and management of flood risks (Floods Directive) requires the assessment of the risk to assets and humans, as the basis for risk mitigation.

This section examines the impact of floods, landslides, earthquakes, tsunamis and volcanic eruptions on the residential sector. Other hazards, e.g. technological and human-made ones, are excluded, while the impact on people is discussed in subchapter 3.2.

2 Assessment of the potential damage and losses

Similar models and methodologies are used to assess damage to buildings due to different natural hazards. Harmonised and high-quality data on building features and damage, available at different geographical levels, are key to calibrate models in a multi-hazard perspective.

2.1 Methodologies for impact assessment

Models of hazard, vulnerability and the distribution of exposed buildings are used to estimate damage and losses (e.g. Casagli et al., 2017; Cloke et al., 2017; Loughlin et al., 2017; Papadopoulos et al., 2017; Silva et al., 2017). Scenario-driven approaches estimate the impact of specific events, while probabilistic ones consider the probability of occurrence of all possible events that may affect a site, and a probabilistic estimation of damage and losses, including relevant uncertainties. Depending on the purpose, there are different methodologies; there is no single one that is fit for all purposes.

'Hazard' refers to processes and phenomena that have the potential to cause damage. It is characterised by its temporal likelihood (i.e. return period), spatial likelihood and magnitude or intensity, such as extent of affected area, depth and duration of floods, peak ground acceleration and displacement for earthquakes, velocity and mass for landslides, or density and thickness of volcanic deposits. Hazard scenario can be defined as the maximum probable/credible or historical event or an event with a given return period and magnitude.

2.2 Taxonomies

A taxonomy is used to categorise buildings into classes, taking into account the characteristics relevant to assessing the impact of hazards (e.g. Fotopoulou et al., 2013; Zuccaro and De Gregorio, 2013; Du et al., 2014; Pitilakis et al., 2014a; Zhang et al., 2016; Silva et al., 2018). As Table 1 illustrates, the technical literature indicates that the same building attributes, such as year of construction, number of floors, construction material and system, are important to characterise the vulnerability of buildings exposed to different hazards. There is a clear need to better understand the response of structural and non-structural elements to different hazards (see for example Mavrouli and Corominas, 2010). Taxonomies may be expanded to include additional information and define more detailed typologies. However, the data for all attributes are not easy to collect (if available at all) at the local, regional or national level.

***Table 1**. Building characteristics that are used to assess the vulnerability to natural hazards **Source**: Authors.*

Characteristic	Earthquake	Flood	Landslide	Tsunami	Volcanic eruption
Number of floors	X	X	X	X	X
Construction material	X	X	X	X	X
Year of construction or design code level	X	X	X	X	X
Load-bearing structural system	X	X	X	X	X
Level of maintenance	X	X	X		X
Height above ground	X	X		X	X
Irregularity in geometry and resistance	X		X	X	X
Presence and type of claddings	X	X		X	X
Number and type of openings	X	X	X	X	X
Presence of domestic plants		X			
Geometry and structure of roof					X

2.3 Exposure data

'Exposure' refers to the buildings present in hazard-prone areas. The most basic sources of information on building exposure, albeit not fully harmonised across countries, are the cadastres and national housing censuses that are performed regularly and may furnish an exhaustive picture of the housing stock. Open community-based web geographical information systems (GISs), such as OpenStreetMap, are becoming available and used to identify exposed buildings. Such information, however, often does not include important attributes, e.g. roof pitch or openings as a percentage of wall area, for studying risk under natural hazards. Cadastral and census data could be integrated with spatial information from the geodatabases that are becoming freely available from local authorities and contain such attributes as location, use, year of construction, level of maintenance and number of floors. Improved exposure data may be obtained by combining census data and data collected on site (e.g. Cacace et al., 2018).

Exposure data for buildings located in earthquake-prone regions were collected initially for a few European cities, often at a high level of geographic disaggregation. Later, inventories providing the population or fractions of building types at national, regional or local level were developed (Jaiswal et al., 2010; Crowley et al., 2012, 2018; Gamba, 2014; Zuccaro et al., 2015). However, these datasets typically exclude some of the attributes that affect buildings' response to other hazards. Exposure to floods and landslides relates to the number (or total surface/volume) of buildings present in the affected areas and their monetary value. Real estate market value or reconstruction costs are used and values can be depreciated to take into account the age of the assets (Merz et al., 2010). Very few studies have collected specific exposure data for tsunami hazards. Census, land cover or socioeconomic data are mainly adopted to quantify the number of people and assets within potential tsunami inundation areas (e.g. Grezio et al., 2012; Løvholt et al., 2014). For volcanic risk analysis at local level, e.g. Vesuvius, Campi Flegrei and Ischia in Italy and Santorini in Greece, exposure data for ordinary buildings are collected by in situ surveys and combined with census information (Zuccaro et al., 2018a; Zuccaro and De Gregorio, 2019).

2.4 Vulnerability models

Vulnerability represents the susceptibility of an element at risk of being adversely affected by a hazardous event. The vulnerability of buildings is commonly modelled using fragility functions, which give the probability that, for a given hazard intensity, structures of a certain typology will exceed various damage levels. Empirical fragility functions are based on observed damage data from past events, numerical ones are based on numerical simulations of varying degrees of sophistication and hybrid ones combine numerical analyses with observed and/or experimental data (e.g. Spence et al. 2004a,b, 2005; Quan Luna et al., 2011; Mavrouli and Corominas, 2010; Pitilakis et al., 2014a; Yepes-Estrada et al., 2016; Charvet et al., 2017; Park et al., 2017). Uncertainties in damage estimates originate from the variability of the hazard characteristics, geometric and material parameters of the buildings, type of structural model and analysis, resistance models, definition of damage states, etc.

Fewer than a handful of numerical tsunami fragility functions exist in the literature. This is due to a general lack of understanding of tsunami inundation processes and flow interaction with the built environment, and of how to implement tsunami loads into structural analysis software (Rossetto et al., 2018). The past few years have seen an increase in research activity with laboratory experiments (e.g. Foster et al., 2017) and structural analysis approaches (e.g. Petrone et al., 2017).

When insufficient data are available or the scope of the study requires it, vulnerability indices and matrices may be employed (e.g. Papathoma and Dominey-Howes, 2003; Vicente et al., 2011; Hu et al., 2012; Jakob et al., 2012; Kappes et al., 2012; Dall'Osso et al., 2016; Kang and Kim, 2016). Vulnerability indices are composed of a weighted combination of indicators that represent aspects of the building, the site or socioeconomic features that contribute to the vulnerability of an asset or area. Comparison of vulnerability index values across geographical areas allows the ranking of their relative vulnerability.

While most studies estimate vulnerability of buildings as separate entities, in reality they represent elements within a highly interconnected territorial system. Systemic vulnerability is assessed by characterising the physical vulnerability and functional interdependencies between buildings with different occupancy, lifelines and transport infrastructure (Pascale et al., 2010; Pitilakis et al., 2014b; Mota de Sá et al., 2016; Zuccaro and De Gregorio, 2019). Such an approach can identify areas of greater risk, and support better emergency and spatial planning. Adaptive simulation, data mining and artificial intelligence techniques of surrogate modelling or meta-modelling, combined with health monitoring of buildings, offer possibilities of improving models (Zio, 2018).

The approach depends on the scope, context and temporal and spatial scales of analysis (Sterlacchini et al., 2014; Schneiderbauer et al., 2017). As housing characteristics vary between countries, transferability of vulnerability models is a challenge; integrating multiple methods may help a better understanding of vulnerability (Papathoma-Köhle et al., 2017) and estimation of uncertainty.

2.5 Loss modelling

Damage-to-loss models are obtained by correlating observed damage with repair costs, or are based on expert judgement or analytical models (Martins et al., 2016; De Martino et al., 2017; FEMA, 2018). The economic impact of disasters includes the costs of reconstruction, evacuation, clean-up, loss of contents, etc., and requires complex modelling (Zuccaro et al., 2013). A new generation of models based on statistical approaches, machine learning algorithms and in-depth description of damage mechanisms has emerged in the last decade (e.g. Dottori et al., 2016; Zio, 2018). They account for a large number of hazard and vulnerability parameters, and outperform simple data-driven models. All types of models need sufficiently large and detailed loss datasets to be calibrated. Data-driven models also need to be validated for different contexts.

2.6 Risk metrics

Direct losses in residential buildings mean the monetary value of physical damage and costs for cleaning, repair, demolition, etc. Indirect loss includes costs occurring as a consequence of direct loss, e.g. decrease in market value or evacuation costs. These metrics may be expressed as loss exceedance curves (probability that various levels of loss will be exceeded), average annualised losses or average annualised loss ratios (FEMA, 2017). This last is useful to compare the relative risk across different regions, since it is normalised by the replacement or market value. 'Intangible damage' refers to consequences that cannot be evaluated in monetary terms, such as loss of memorabilia

3 Assessment of the impact after an event

Knowledge from ex post damage assessment may improve the efficiency of preparedness, response, recovery and mitigation measures, at both the individual and community levels. Standardisation of methods and procedures for ex post damage collection and recording would benefit from being set at the EU level.

3.1 Post-event collection of damage and loss data

Data collected in the aftermath of disasters are the basis for tailoring risk mitigation strategies, both after an event (e.g. for identifying priorities for intervention and guiding compensation) and before an event (e.g. to support preventative measures) (Ballio et al., 2015). For instance, the extensive review of flood impacts done by Pitt (2008) after the 2007 floods in England served to improve policies and techniques of flood risk management in the United Kingdom in the following years (United Kingdom, Government, n.d.).

The standardising of disaster damage data collection has been constantly advocated so that consistent and reliable data can be provided to public administrations, scientists and practitioners. Promoting improvements in the knowledge base for disaster loss management, including loss databases, is a key priority at both international and EU levels (e.g. Sendai framework for disaster risk reduction, EU disaster prevention framework, EU Solidarity Fund, green paper on insurance of natural and man-made disasters, and Floods Directive). Accordingly, an EU working group was created to support and encourage Member States to build a process for loss data collection and recording. According to the guidelines it provided (De Groeve et al., 2013, 2014, 2015), in order to optimise required efforts, the process should guarantee the multi-usability of collected data; in detail, it should consider all exposed sectors, and data must be collected at relevant time intervals to capture direct and indirect losses, regarding both observed damage and its explicative variables, and in the finest possible detail. In fact, most of the available procedures for ex post damage assessment are still sector- and hazard-specific, hampering the harmonisation process desired at international level.

Concerning the residential sector, procedures for the post-earthquake survey of damage are the most developed (Khazai et al., 2014; FEMA, 2018). Several countries have established inspection forms, primarily to assess the safety of buildings in the aftermath of a disaster, but also to support the implementation of short-term countermeasures, and estimate compensation and reconstruction costs (García and Cardona, 2003; ATC, 2005a,b; Anagnostopoulos and Moretti, 2006a,b; Baggio, et al., 2007; NZSEE, 2009; Santos, 2011; Roldán et al., 2013; Cruz et al., 2014). It must be stressed, however, that, whereas detailed damage data are collected, losses are usually reported as total economic losses, limiting the possibility of understanding damage mechanisms, improving risk models, etc.

Figure 1*. Destroyed (red) and highly damaged (orange) buildings in Amatrice, 25 August 2016.*
Source: *extracted from Copernicus Emergency Management Service, 2016. ©EU, 2016*

Tsunami damage survey procedures are traditionally focused on the evaluation of tsunami intensity rather than impacts (e.g. Rossetto et al., 2007). Still, new approaches are emerging. For example, on the occasion of the 2010 Chile earthquake and tsunami, the International Tsunami Information Centre developed a questionnaire to collect information on structural performance as well as general tsunami impacts (UNESCO, 2010), although aggregated over an area.

More recently, following the 2011 great east Japan tsunami, Japan's Ministry of Land, Infrastructure and Transportation developed a damage scale for the evaluation of tsunami damage to residential buildings (MLIT, n.d.). An unprecedented amount of detailed disaggregated damage data was collected (Tohoku Earthquake Tsunami Joint Survey Group, 2011) and then adopted for numerous empirical fragility studies (e.g. Suppasri et al., 2012; Macabuag et al., 2016). A particular complication arises in the assessment of damage in areas affected first by earthquake and then by tsunami inundation. Unless there is evidence of the damage due to the earthquake before the tsunami hit, it is almost impossible to attribute the final damage state to one of the two hazards. To adopt a consistent evaluation of damage, the UK Earthquake Engineering Field Investigation Team and Indonesian Tsunami and Disaster Mitigation Research Centre proposed a damage scale capable of capturing damage mechanisms under both earthquakes and tsunami (EEFIT-TDMRC, 2019).

Numerous databases and digital catalogues on landslides and their consequences have been compiled at regional, national and multinational scales in recent years and used for disaster relief, research and economic purposes (e.g. CNR, n.d.). Procedures for collecting building damage data after landslides have been proposed by Papathoma-Köhle et al. (2017) and Del Soldato et al. (2017). The "LANDslides and Floods National Database (LAND-deFeND)" (Napolitano et al., 2018) allows the storing of physical, geographical and socioeconomic data on geohydrological hazards and their consequences with different levels of detail (from local to regional events). There are not many procedures for post-flood damage assessment, basically owing to the limited need to evaluate the safety of buildings after such events.

A questionnaire developed after the 2002 Elbe flood in Germany (Thieken et al., 2005) addressed several topics: flood warning, precautionary and emergency measures, flood impact, contamination and cleaning up, characteristics of the affected households and related losses, flood experience and recovery, and socioeconomic characteristics of residents. Still, the survey was conceived mainly with research objectives, to capture information to improve capabilities to forecast damage. Collected data are stored in the German flood damage database (Kreibich et al., 2017) and have been used for empirical studies on flood damage to residential buildings (e.g. Thieken et al., 2007, 2008; Merz et al., 2013). In Italy, the Reliable Instruments for Post-event Damage Assessment (RISPOSTA) procedure (Berni et al., 2017) was developed to survey flood damage to buildings, and more generally to all exposed elements, in a multi-usability perspective (see the case study on the Umbria floods below).

Disaster loss data are available from a number of sources (e.g. CRED, n.d.; Munich Re, n.d.; Swiss Re, n.d.; UNDRR, n.d.), including the Copernicus Emergency service (European Commission, 2016), which uses satellite and aerial images to map damage after disasters, as shown in Figure 1 for the 2016 Amatrice earthquake. A comprehensive picture of available tools for disaster data collection, storing and reporting can be found at the Risk Data Hub (DRMKC, n.d.), developed by the European Commission Disaster Risk Management Knowledge Centre. The Risk Data Hub is a web-based GIS tool to access and share curated risk data, tools and methodologies at local, regional, national and European levels and covers a variety of natural hazards that may affect the residential sector, namely flood, forest fire, earthquake, volcano, landslide, subsidence and cyclone.

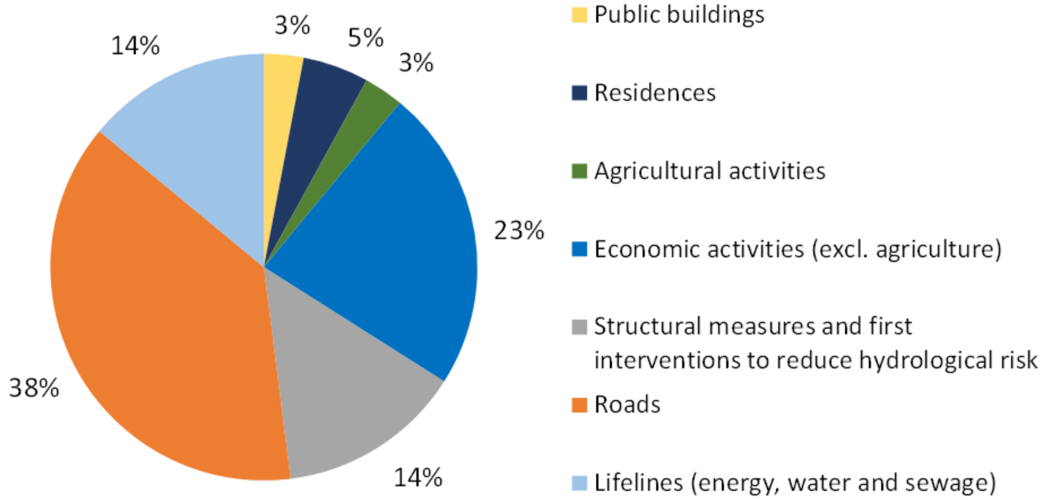
3.2 Case study: the Umbria flood in 2012

Context

In November 2012, a severe flood occurred in the Umbria region (central Italy) after a widespread, high-intensity storm. Flooding occurred with different features throughout the region, assuming the typical characteristics of riverine or flash floods. Out of 92 municipalities, 58 were affected. The total losses amounted to EUR 115 million, corresponding to 0.6 % of the regional GDP. After the event, a data collection campaign was performed by Politecnico di Milano, with the support of the regional civil protection, the main objective being to understand the damage and its causes, to identify criticalities and priorities for intervention. Data for the post-damage assessment were mostly acquired from local authorities and utility companies, which collect such information for the purpose of compensation. Damage to the residential and industrial/commercial sectors was surveyed in the field (Menoni et al., 2016).

Figure 2 shows the distribution of losses among the different sectors. As regards physical damage to the residential sector, collected data were analysed in terms of both damage and its explicative variables, as key information for the understanding of damage mechanisms and causes. In particular, the following aspects were investigated: structural and non-structural damage, water depth, velocity, sediment and contaminant loads at building locations, exposure/vulnerability of the buildings (materials, presence of basement, year of construction, etc.) and mitigation actions taken by owners before or during the event. The analysis highlighted that the most damaged component of buildings is plaster. Windows and doors were only damaged in long-lasting or high-velocity floods. Floors were usually not damaged, except where materials were not waterproof (e.g. wood). Domestic electrical plants were affected in most cases. Contents (furniture, appliances, etc.) were generally lost, apart from those cases in which people were able to move them to a safer place after receiving flood warnings (Menoni et al., 2016).

Figure 2: *Distribution of losses among the different sectors after the 2012 flood in Umbria.* ***Source***: *Menoni et al., 2016.*



Besides repairing damage, costs were related to cleaning up and to the civil protection assisting evacuees. As regards cleaning, the number of person-days declared by private residents varied between 1 and 30, depending on the damage suffered by the building. In total, 95 families (about 300 people) needed to be evacuated because houses were not habitable or accessible, for between 2 and 7 days, at a total cost for the civil protection of about EUR 150 000. Finally, the loss of memorabilia has been highlighted as significant intangible damage by most people living in damaged buildings (Politecnico di Milano e Regione Umbria, 2015; Menoni et al., 2016).

Lessons learned

The most important outputs of the campaign for disaster risk management were the following.The collection of very detailed data on damage and its explicative variables for 52 residential buildings and 10 industrial/commercial buildings. Data on residential buildings were used for:

- carrying out a cost-benefit analysis of flood proofing and construction of flood barriers versus relocation, leading to important recommendations on how to reduce the vulnerability of buildings (IDEA Project – Deliverable D4, 2016), a procedure that can be easily applied to other areas;

- analysing damage mechanisms in support of the development of In-depth Synthetic Model for Flood Damage Estimation (INSYDE), an expert-based model for the estimation of flood damage to residential buildings, validated for the Italian context, but transferable to other regions (Dottori et al., 2016; Molinari and Scorzini, 2017).

  - The development of the RISPOSTA procedure (Ballio et al., 2015; Berni et al., 2017) for the collection of damage/loss data to all exposed sectors after flood events. In particular, specific forms were created for field surveys of residential and industrial buildings (see Table 2), filling a gap in the current state of the art. RISPOSTA is now embedded into Umbria's emergency management regulations.

  - A model to assess event scenarios (Menoni et al., 2016) that offers a more comprehensive overview of the different types of damage that may affect communities and territories as a consequence of floods, and facilitates the understanding of causes of damage and its mitigation by reducing pre-event vulnerabilities. In particular, the model supports (a) loss accounting and damage compensation at different spatial scales, (b) forensic investigation in support of the recovery phase and (c) validation and calibration of improved damage and risk models. The model was applied to develop the complete event scenarios of the 2012 and 2013 floods in Umbria (Politecnico di Milano and Regione Umbria, 2015, 2018). The application of such a common model facilitates comparison between events, geographical regions and times.

Gaps and challenges

The experience highlights that the appropriate implementation of available risk management tools is the main challenge for the prevention of flood damage to residential buildings. A first issue regards promoting the adoption of floodproofing measures or the construction of flood barriers (both identified by the cost–benefit analysis as effective). This can be done with public financial aid (e.g. incentives, subsidies, loans), by including requirements in building codes for flood-prone areas, by reducing insurance premiums for owners adopting virtuous behaviours and by increasing public risk awareness.

A second issue relates to the use of flood damage models (such as INSYDE) for the identification of risk mitigation strategies. The limited availability of the required data, their complex formulation and the high uncertainty of their results prevent the implementation of such tools by decision-makers. The research community needs to make efforts to develop more usable but still reliable tools and to support decision-makers in dealing with uncertainty. To this end, a simplified and user-friendly version of INSYDE has been developed and validated in the Flood-IMPAT+ (an Integrated Meso & micro scale Procedure to Assess Territorial flood risk) project (Galliani et al. 2020).

The last challenge regards the prioritisation of strategies to mitigate the impact of flood events. Procedures such as RISPOSTA re-engineer the whole process to provide a standardised framework for collecting damage and loss data in the aftermath of flood events, optimise time and effort needed, improve the quality of data and produce analytical reports of damage. Wider use and reuse of damage data are permitted when they are collected in a systematic way, in line with the Sendai framework (UNISDR, 2015a). RISPOSTA proved effective in the 2012 floods in Umbria, reaching a good level of commitment by private and public stakeholders.

Table 2. *Information collected in RISPOSTA by means of the forms for damage to residential buildings* ***Source****: Molinari et al., 2014.*

Form	Section	Description
A: General information	1. General information	Building location
	2. Building features	Typology, period of construction, structure, footprint area, elevation, etc. to characterise exposure and vulnerability
	3. Flood event	Water depth and velocity, duration, sediment and contaminant loads to characterise stress on the buildings
	4. Damage description	Identification of affected parts of the building: number of housing units, attached buildings, common areas
B. Damage to housing unit (for every unit in the building)	1. General information	Identification of property, affected floors, residents
	2. Damage to affected floor X (for every affected floor in the unit)	Full characterisation of exposure, vulnerability, location and stress on floor X Direct damage, e.g. to coating, plaster, windows, doors, contents Indirect damage: loss of usability, clean-up cost Mitigation actions
C. Damage to common areas	1. General information	Description of affected floors
	2. Damage to affected floor X (for every affected floor in the common area)	Same as section B.2
D. Damage to attached building (for every attached building)	1. General information	Building location, identification of property
	2. Building features	Same as section A.2
	3. Flood event	Same as section A.3
	4. Damage description	Same as section A.4

4 From single to multi-hazard risk assessment

Multi-hazard risk assessment supports more effective disaster resilience strategies and better allocation of resources. Assessment methods should make use of harmonised models to provide results with comparable metrics, enabling the prioritisation of interventions.

Tackling natural and man-made hazards (including cascading effects) in a holistic way is essential to improve the resilience of the built environment and effectively allocate resources for risk mitigation. Such an approach allows the integration of multipurpose disaster risk reduction (DRR) and climate change adaptation (CCA) measures in the planning of new developments, urban regeneration and retrofitting buildings, to address in a coherent way the Sustainable Development Goals, the objectives of the 2015 Paris Agreement and the priorities of the Sendai Framework. The different backgrounds of the disaster risk and climate change domains have limited so far the establishment of an integrated methodological approach to DRR and CCA. Still, the recent path set by the Intergovernmental Panel on Climate Change (IPCC, 2014) reconciles climate risk assessment with the scientific framework in the field of risk science and theory of decisions (since UNDRO, 1980). Adopting this framework in a multi-hazard perspective means standardising hazard characterisation, exposure and vulnerability analysis methods (Marzocchi et al., 2009; Kappes et al., 2012; Garcia-Aristizabal et al., 2013), considering the similarities illustrated in Table 1. From this perspective, the following recommendations are derived from several past European research projects.

1. Define the time and spatial frames for the analysis. The probability of disastrous events from multiple hazard sources over the residential building's life (50–100 years, considering new design or retrofit) defines at the same time the potential expected damage and the type of DRR/CCA measures to implement to reduce losses. The spatial extension of the analysis can be hazard driven or exposure/vulnerability driven. In the first case, the multi-hazard characterisation gives information on the expected extent of the areas potentially affected (e.g. local for climate extremes, local to regional for earthquakes, supra-regional for volcanic eruptions), thus determining the areas to include in the analysis. In the second case, considerations such as administrative jurisdictions, planning domains and specific retrofitting programmes can guide the definition of spatial extent, in relation to the purpose of the assessment (e.g. assessing the multi-risk conditions of all residential buildings in a region, to determine tax incentives for DRR/CCA).

2. Hazard characterisation needs to be performed by experts in the specific field, deriving different events' probabilities of occurrence, magnitude, time and spatial extension, considering the future impact of climate change. Cascading effects analysis requires to determine the probability of hazard transitions within possible chains of events (Zuccaro et al., 2018a).

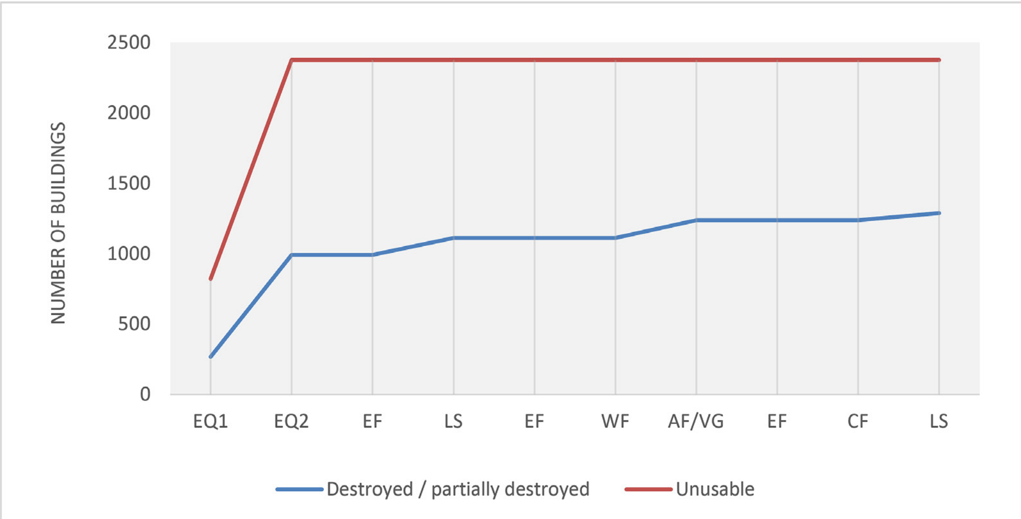
3. Exposure assessment must include the collection of all relevant (georeferenced) information in relation to the vulnerability of buildings considered in the analysis, including their geometric, typological, morphological, construction and performance features. This phase can take advantage of harmonised datasets, which must be promoted in the future, including by benefiting from significant innovations in the field of satellite surveys and big data analytics.

4. Vulnerability analysis represents the crucial step to build a reliable and flexible multi-hazard damage model. Multi-hazard vulnerability assessment for residential buildings must integrate the different characteristics that determine vulnerability to specific hazards, e.g. combining them in multi-hazard vulnerability classes or treating them as dynamic vulnerability in cases of cascading effects (Zuccaro et al., 2018a). Few studies have assessed the vulnerability of buildings in a multi-hazard context (Kappes et al., 2012) and

even fewer the changes in vulnerability due to the dynamic nature of the damaging process (El Moussaoui et al., 2017; Zschau, 2017), mainly because of the limited knowledge of process interactions and the scarcity of observed damage data, and then because of model limitations. However, there is room for improvement, as many of the vulnerability features are common to all hazards (subsection 2.2 above).

5. Risk assessment. Given the diversity of potential impacts of multiple hazards on the exposed elements, a major aspect to consider in multi-risk assessment is the need to develop common damage metrics across the different hazards considered. This allows (1) implementation of risk analyses and indexes able to provide a synthesised view of the hazards affecting a given location, (2) quantification of the expected impacts of single events, to compare the expected losses (Grünthal et al., 2006) from different hazards with the same return period, and (3) calculation of the cumulative damage from cascading effect scenarios on selected elements at risk (Junttila and Zuccaro, 2017), as shown in Figure 3. The output of such analyses enables the identification of DRR/CCA priorities, by means of multi-criteria or cost–benefit analysis tools (Garcia-Aristizabal et al., 2015; Zschau, 2017).

Figure 3. *Cumulative damage on buildings due to a Sub-Plinian eruption in Nea Kameni, Santorini island.* ***Source****: Junttila and Zuccaro (2017).*
Note*: AF, ashfall; CF, failure of the communication network; EF, failure of the energy distribution system; EQ, earthquake; LS, landslide; VG, volcanic gas emission; WF, failure of the water supply system.*



5 Disaster risk prevention

Risk prevention is key to mitigate negative consequences of natural hazards. Building codes that are effectively implemented, incorporate state-of-the-art knowledge and consider the impact of climate change are instrumental to reduce disaster losses. Insurance should be promoted to decrease the economic and social impact of disasters.

5.1 Risk insurance

Risk insurance is a means to transfer risk, provide compensation for damage, incentivise risk reduction measures and shorten recovery time (Mysiak et al., 2017). Insurance schemes for residential buildings have been introduced and redesigned in earthquake-prone countries after major disasters (Ranghieri and Ishiwatari, 2014; Başbuğ-Erkan and Yilmaz, 2015; CCS, n.d.; CEA, n.d.; EQC, n.d.) and similarly for floods (CCR, n.d.; CCS, n.d.; FEMA, n.d.; Flood Re, n.d.). Governments, private insurers and public–private partnerships offer policies that cover damage to buildings and contents, emergency repairs and reconstruction, but their potential for mitigation has not been fully exploited (Kousky, 2019). Insurance is obligatory in certain cases, e.g. for real estate sales and new homeowners in Turkey, and often risk-related premium rates are offered (i.e. depending on the hazard at the location of the building and the type of construction), with discounts for joint policies or for hazard-resistant buildings.

Despite being affordable, insurance is not widely used: the annual premium is 3 ‰ of the insured amount in Tokyo, but fewer than 40 % of households in Japan are insured for earthquake (Ranghieri and Ishiwatari, 2014). The number of policies is higher in areas of higher hazard, and it increases after major events, though many policies are not renewed (Başbuğ-Erkan and Yilmaz, 2015). Nonetheless, risk perception and damage of residential properties after disasters lower market values and increase insurance premiums (e.g. Nakagawa et al., 2009; Beltrán et al., 2018; Ortega and Taspınar, 2018).

Low-income households are less willing to purchase insurance, even after major disasters (Naoi et al., 2012), and affordable public insurance may have the detrimental effect of encouraging further development of risk-prone areas, where premiums would otherwise be very high. Moreover, middle- and high-income households abandon properties in high-risk areas without appropriate or affordable insurance, which are subsequently rented by low-income or otherwise marginalised social groups, leading to social segregation and possibly the creation of ghettos. These processes may be rather quick, and urban planning plays a pivotal role.

5.2 Building codes and standards

Over the years, developed countries have successfully implemented effective regulatory frameworks and codes for the safety of the built environment. In fact, in the last decade they have experienced 47 % of all disasters globally, but have accounted for only 7 % of disaster-related fatalities (UNISDR, 2015b). On the other hand, low- and middle-income countries have not been able to carry out such reforms, and many experience recurring human and economic losses each time a disaster hits (World Bank, 2018). There are valuable lessons that can be adapted to the needs of developing countries (see Box 1).

Risk-informed and affordable standards for the design and construction of buildings, e.g. the Eurocodes (Eurocodes, n.d.), that incorporate state-of-the-art scientific and technical knowledge have proven to be effective and cost-efficient measures to mitigate disasters and build back better after major events. Equally important is a regulatory system that is incrementally improved over time and takes into account the needs of disadvantaged segments of the population (World Bank, 2015, 2018). This is also recognised in Priority 3 of the Sendai framework (UNISDR, 2015a), which encourages the revision and development of building codes, focusing on the local context and the capacity for implementation and enforcement.

Given the long working-life and economic value of buildings, it is essential that they are resilient to the future impacts of changing climate (European Commission, 2013). In this context, adaptation of structural design to climate change is a key aspect to be considered in construction standards, at least for new structures, as intended for the second generation of the Eurocodes.

BOX 1

Building safely to avoid damages

Building codes have contributed to making Japan one of the world's most earthquake-resilient countries, as they were incrementally improved and continually incorporated lessons learned from disaster experiences (World Bank, 2018). Indeed, 97 % of buildings that collapsed during the 1995 Kobe earthquake had been built with old codes, while those that complied with the most updated ones accounted for only 3 % (World Bank, 2015). In 2003 two earthquakes were recorded in Paso Robles (California) and Bam (Iran): the death toll in Paso Robles was 2 as opposed to more than 40 000 in Bam (Kenny, 2009). Similarly, the extent of damage and collapse of buildings during the two 2017 earthquakes in Mexico confirmed that structures built in accordance with anti-seismic codes can better withstand ground-shaking events (Swiss Re, 2018)

6 Conclusions and key messages

Policymakers

Despite the significant scientific advances and the experience gained after past disasters, the application of mitigation measures is still insufficient. The implementation of building codes that incorporate state-of-the-art knowledge and consider the impact of climate change should be promoted by policymakers along with insurance schemes to decrease the economic and social impact of disasters. To this end, it is important also to promote behavioural drivers for individual protection, in order to encourage citizens in the adoption of virtuous behaviours.

Scientists

Models and methods for assessing the impact of natural hazards on residential buildings are conceptually similar but have reached different levels of sophistication. Furthermore, many of the parameters that affect the vulnerability of buildings are common to various hazards. There is therefore an opportunity for scientists to share the fragmented hazard-specific knowledge and for developing methods for multi-risk assessment to increase the efficiency of integrated mitigation actions. Such methods also require the definition of common metrics, spatial and temporal scales, and assessment thresholds across hazards.

Policymakers, practitioners and scientists

The ageing building stock and society's need for resilience – i.e. minimum disruption of activities and services, and speedy recovery after a disaster – call for new technical solutions and policy tools. The lack of harmonised, good-quality data on exposure and observed damage remains a major gap. To improve our capacity to assess and reduce losses, new developments are needed in the use of innovative and disruptive technologies (e.g. satellite and remote sensing, nature-based solutions, machine learning and artificial intelligence) for collecting data, monitoring the condition of assets, and developing dynamic models and tools for real-time decision-making (Zio, 2018; Zuccaro et al., 2018b). In this respect, shared effort by practitioners, scientists and policymakers is welcome.

3.3.2 Agriculture

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Toreti, A., Bassu, S., Perez Blanco, D., Capitanio, F., Ramos Ribeiro, R.R., Molinari, D., Webber, H., ‘Agriculture’, in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Introduction

Agriculture is a key socioeconomic sector of the EU, employing about 9.7 million people and with a regular labour force of 20.5 million (many people help on farms without being employed; Eurostat, 2019). Some 10.5 million farms manage 47 % of the total land area of the EU, most of them (96 %) being family farms and 66 % being smaller than 5 ha (Eurostat, 2019). However, 51.6 % of the total EU agricultural economic output is produced by just 2.9 % of farms (classified as agricultural enterprises). Crop and animal production contribute nearly equal shares (56.3 % versus 43.7 %) to the total agricultural economic output (European Commission, 2019). The former mainly comprises vegetables and horticulture, cereals, fruits and wine, while the animal output mainly consists of meat, milk and eggs (European Commission, 2019).

In the EU, 28 % of the population lives in rural areas, with large differences between the Member States (from 0.3 % in Malta to 56 % in Lithuania; Eurostat, 2019). The number of farms has been steadily decreasing in recent years (with estimated losses of up to 4.2 million farms since 2005; Eurostat, 2019); but the amount of land used for agriculture has remained almost unchanged. Land abandonment, however, driven by agroclimatic-environmental and socioeconomic conditions, represents a potential problem for 11 % of the EU's agricultural land (mainly arable, pasture and permanent crops) in the coming decade (Perpiña Castillo et al., 2018). The agriculture sector faces many risks associated with climate variability and extremes, pests and diseases, market volatility, socioeconomic crises and shocks. Unfavourable climate conditions, extreme weather and climate events (such as storms, droughts, floods, frost, heat and cold waves) have severe impacts on agriculture (see for example Lesk et al., 2016; Zampieri et al., 2017; Webber et al., 2018; Chavas et al., 2019), e.g. on crop yield, soil erosion, livestock production and infrastructure.

The frequency and severity of extreme events have increased, and this increase is projected to continue in the coming decades as a result of global warming (see for example Toreti et al., 2013, 2019a; Russo et al., 2014; Alfieri et al., 2015, 2017). Drought as severe as in 2018 and heatwaves as intense as in 2003 could become common occurrences by mid-century (Russo et al., 2014; Toreti et al., 2019a). Extreme precipitation events could intensify by more than 30 % in some areas of Europe (Toreti et al., 2013).

At the same time the world's population is expected to grow to 9.7 billion by 2050 (UN, 2019), increasing agricultural demand and changing nutritional patterns (e.g. Tilman et al., 2011; Davis et al., 2016; FAO, 2017; Gouel and Guimbard, 2019). Therefore, it is essential to study and better understand natural hazards and their impacts on the agriculture sector.

The impacts of climate change, variability and extremes are and will be uneven across regions and countries. Although elevated atmospheric CO_2 concentration and warmer climate conditions during the growing season may bring positive effects (especially in countries in mid-northern latitudes; Ciscar et al., 2018; FAO, 2018), concurrent and recurrent extremes may offset them and induce heavy losses as well as higher interannual variability. The 2018 drought in Europe is an example of such an event (Toreti et al., 2019a). The impacts of extreme events can be amplified (in terms of losses and damages), in particular in production systems that are not ready to cope with them. Examples are systems characterised by low levels of agro-management (Zampieri et al., 2020; Webber et al., 2014); lack of diversification (Lin, 2011); and lack of integration between production of crops, crops and forests (Altieri et al., 2015; Lin, 2011). Optimal and sustainable management practices, technological innovations and effective sectoral adaptation strategies can reduce the impacts of unfavourable climate conditions and extremes. The sensitivity of each crop and region is different, and so are the mitigation and adaptation strategies needed. Farmers represent a key component of the system for identifying and applying optimal solutions. However, there exist different levels of intervention and different actors to be taken into account. Assessing comprehensively the impacts and risks of climate change is a complex and challenging task addressed by various modelling approaches (which differ in tool availability, state of the art, open issues, etc.) involving the agriculture, climate, economic and hydrological sectors. Statistical approaches, crop growth models of varying complexity, economic partial and general equilibrium models, and agent-based models are all used.

The agriculture sector is not only affected by climate and socioeconomic conditions; it also affects the climate system and the environment. About 10 % of the EU's greenhouse gas emissions come from agriculture (EEA, 2019), and unsustainable practices can induce soil, air and water pollution as well as loss of biodiversity and habitat fragmentation (see for example EEA, 2019; Leip et al., 2015).

2 Risks and impacts

Climate extremes occurring locally and in other producing regions of the world, emerging and re-emerging diseases, and socioeconomic crisis and shocks affect agriculture, causing direct and indirect losses and damage.

The agriculture sector is exposed and vulnerable to weather and climate extremes. These events, especially when they occur during critical periods (e.g. around crop anthesis), can lead to severe losses and damages. Several studies have shown, for instance, how heat stress can affect agriculture systems, causing, for instance, yield losses (e.g. Zampieri et al., 2017; Fontana et al., 2015; Rezaei et al., 2015), and dairy and beef cattle mortality (e.g. Polsky et al., 2017; Morignat et al., 2015; Vitali et al., 2015). Drought events also severely affect the entire agriculture sector, triggering crop losses and problems for livestock (e.g. Stahl et al., 2016). Around the world, heat stress and drought have been responsible for 9–10 % reductions in national cereal production (Lesk et al., 2016) and for more than 40 % of wheat yield interannual variability (Zampieri et al., 2017). Heat waves such as those of 2003 in Europe, occurring during the crop-flowering/grain-filling period, have been shown to be associated, for instance, with durum wheat losses in the main Italian production areas, with yield reductions at the province scale reaching – 52 % (Fontana et al., 2015). The 2015 drought event also caused severe impacts on crop production and livestock farming, with, for example, production losses of potatoes reaching – 21 % in Poland and Czechia.

On the other hand, excessive wet conditions, heavy precipitation events and floods can have serious consequences by inducing crop yield and livestock losses, fatalities and injuries, damages to infrastructure and machinery (e.g. Bremond et al., 2013; Klaus et al., 2016; Mäkinen et al., 2018). Flood damage to livestock has been poorly investigated so far (Bremond et al., 2013). The limited available evidence of past events (e.g. Posthumus et al., 2009; Gaviglio et al., 2020) suggests that flood damage to livestock is mainly indirect, as animals' death and injuries can be avoided by livestock evacuation, if early warning is supplied.

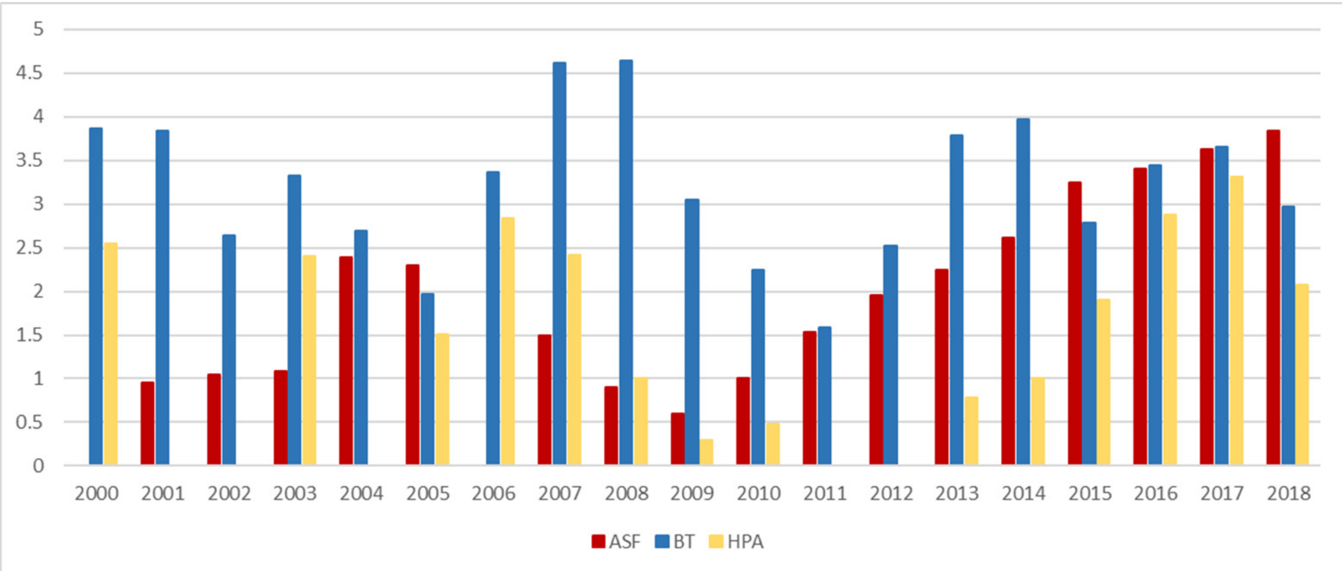
Indirect damage mostly consists in reduction in production quantity (e.g. reduction in milk production) and quality (e.g. reduction in milk quality or meat quality), due to reduction in, or change in quality of, food (due to flooding of crops and stocks); spreading of diseases and infections caused by inappropriate living conditions during the flood or the evacuation phase; and the stress suffered by the animals. Indirect damage is also linked to increased costs for farmers due to additional veterinary treatments, killing of injured or ill animals, carcass disposal and replacement of lost animals. Indirect damage to livestock can manifest even several months after the occurrence of a flood event. In the case of dairy farms, especially, the recovery time can follow the growth of the animals from the birth to the productive time, usually between 2 and 3 years.

A comprehensive assessment of losses and disasters in the entire agricultural sector attributable to weather and climate extremes does not exist, although spot assessments have been performed. This gap clearly has a negative influence on sectoral policies.

The emergence and re-emergence of livestock diseases (Figure 1), despite the better management of endemic ones, are also a serious concern, as they are influenced by evolving socioeconomic factors (e.g. ecosystem changes, agro-management practices, movement of goods, animals and people) as well as climate change (Perry et al., 2013).

Clearly not all risks and impacts are covered by this section. Other risks are, for instance, related to socioeconomic conditions, crises and shocks, e.g. input and output price volatility and spikes, economic well-being and stability, demographic structure, public infrastructure, natural resource dependence, and shocks induced by climate and weather extremes elsewhere (Chatzopoulos et al., 2020; Toreti et al., 2019b).

Figure 1. *Animal disease outbreaks (in logarithmic scale) in the EU, 2000–2018*
Source*: Data from the EU Animal Disease Notification System (European Commission, n.d.-a).*
Note*: ASF, African swine fever; BT, blue tongue; HPA, highly pathogenic avian influenza.*



3 Risk management tools

Several tools and strategies exist to manage the risk to agriculture. Damage prevention and compensation measures, ad hoc emergency aid, direct support, regulation and insurance are all available, although their use and level of implementation are not homogeneous. Farm-level specific management practices should be also better explored and encouraged.

The EU's agricultural policy is mainly driven by the common agricultural policy (CAP), which aims to support farmers, productivity and rural areas, contribute to climate change mitigation objectives, encourage environmental care, and promote sustainable development and growth. The CAP is managed and funded at the EU level and takes action on income support, market and rural development measures. Income support mainly consists of basic direct payments (based on hectares farmed), greening payments (for climate and environmental friendly practices) and young farmers' payments. Market measures are used to deal with threats posed by difficult market situations (e.g. a sudden price drop), while rural measures can be used for specific regional needs and challenges in rural areas.

In general, risk management policies and strategies in agriculture include several alternative/complementary strategies, such as hard engineering, soft engineering, information and awareness campaigns, regulations and the development of risk management tools, e.g. crop insurance, mutual funds and ex post disaster aid. Several of these policies act as a first stage of damage prevention, i.e. they aim to reduce vulnerability in exposed areas and thus limit potential damage. Supporting, for instance, the adoption and use of sectoral decision support systems integrated with targeted climate services (e.g. providing relevant climate information) contributes to significantly reducing vulnerability and increasing preparedness and awareness, thus triggering a positive feedback loop. In the context of climate change adaptation, three categories of measures have been identified (EEA, 2013): grey (relying on technology and engineering), green (based on nature) and soft (influencing human behaviour and governance).

Hard engineering solutions, such as the construction of dykes to prevent flooding, have been commonly used as an obvious way to prevent damages. Yet, despite the historical success of hard engineering solutions in harnessing the potential of the environment for economic growth, there is increasing awareness that they may not be enough to cope with growing risk. For example, water works in closed basins with inelastic supply can increase supply only marginally and at high, often disproportionate, costs, thus reducing the cost-effectiveness of the policy. Hard engineering solutions (and associated policies) may also introduce perverse incentives towards higher exposure that amplify economic damage when natural catastrophes hit. For example, flood protection infrastructures may work as an incentive for economic development in exposed areas, thus increasing the value of the assets at risk and the (economic) damage when flood events with high return periods hit. On the other hand, modernisation of irrigation infrastructure, which increases yield and profit per unit of water withdrawn, can incentivise a higher consumption rate and aggravate water depletion and related environmental problems (Grafton et al., 2018). Finally, budgetary constraints also represent a barrier to the further development of hard engineering solutions. Consequently, the cost of additional hard engineering projects often exceeds the economic benefits, constraining policy-makers to rely on other policy instruments.

Soft engineering solutions, such as rehabilitation of natural water retention measures, aim to integrate anthropic agricultural activities with natural processes and systems to enhance resilience. Under some circumstances, they may offer a low-maintenance and low-cost investment strategy compared with hard engineering (e.g. wetland restoration). However, in some other cases, their cost may be disproportionate (e.g. making room for river in highly populated areas). The EU Water Framework Directive (Directive 2000/60/EC) must be clearly considered in these evaluations. Regulations are also used to prevent risk, although they are often difficult to enforce, resulting in low compliance (e.g. restrictions for the development of new irrigated land in floodplains have often failed; EEA, 2009; OECD, 2008, 2013a; UN, 2014a). In this context, the EU contributes direct payments to stabilise and enhance farm income, and the farmers' commitment to protect natural resources and maintain the land's productive capacity, including on marginal land, prevents the risk of abandonment. In this way, the CAP aims to address a multitude of specific objectives related to the environment, food safety, animal health and welfare, although without focusing on the diverse nature of farming and natural conditions throughout the EU (Renwick et al., 2013). In this context, it is also worth pointing readers to the EU Floods Directive (Directive 2007/60/EC) and the associated ongoing activities.

Information and awareness campaigns generate intangible outcomes that are difficult to identify and quantify (OECD, 2013b; UN, 2014a) but represent an essential tool for soft adaptation (EEA, 2013). Finally, economic instruments (such as charges) can be designed and implemented with the purpose of adapting individual decisions to collectively agreed goals, including the prevention of risky attitudes or the generation of externalities that result in a higher risk for other agents (e.g. damage to valuable natural capital).

Some damages are technically difficult to predict and thus to prevent, or, even if predictable, they may not be economically efficient to prevent (Randall, 1981). This motivates the development of damage compensation policies. Damage compensation is structured around regulatory and economic instruments, notably tort law, insurance and state aid. Tort law is used where a liability is identified, e.g. where a binding regulation is not respected by an agent and this results in damage to a third party; insurance manages acts of nature – events that are no one's fault – through risk-sharing instruments; and state aid involves direct payments to compensate for non-insurable damage, and to enhance insurance uptake through greater affordability, equity and solvency in the provision of insurance policies (e.g. premium subsidisation, public reinsurance). The limits for the implementation of each instrument are often not completely set. For example, states may decide to step in to prevent disproportionate losses arising from insurable agricultural damages. Ad hoc emergency aid that compensates for damage from, for example, droughts is common in the EU Member States (Bielza et al., 2009), and may end up crowding out private insurance. This may be undesirable, as insurance schemes could offer a number of advantages compared with tort law and state aid, e.g. relieving budgetary pressures and not distorting trade, encouraging farm-level strategies to reduce risk and prevent damage, and complementing prevention policies by risk-based pricing. Finally, 'sufficiently insured events are inconsequential in terms of foregone output' (Von Peter et al., 2012). However, barriers and issues to be solved for a widespread crop insurance scheme in the EU have been identified (e.g. Cafiero et al., 2007; De Castro et al., 2011; Santeramo and Ramsey, 2017; Santeramo, 2019).

This has motivated calls for insurance policies that short-circuit the link between damage and losses (OECD, 2014; UN, 2014b). Several types of risks are insurable: yield damages; specific climatic risks (flood insurance, drought insurance, etc.); price (inputs and outputs) volatility; and climate and market risks (e.g. income insurance). The design is also varied, e.g. index-based insurance versus conventional commercial insurance based on observed damage. The conditions under which a specific insurance product is supplied are context-specific, and some insurance products may be more prevalent than others. For example, flood impacts on agriculture have received less attention so far than those on other sectors. Reasons may include the (perceived) minor importance of agricultural losses compared with other sectors, and the paucity of data for understanding damage mechanisms and deriving prediction models (Molinari et al., 2019). Although insurance schemes allow the transfer of damages from the public to the private market, damage mitigation is still the responsibility of private farmers and public authorities. The knowledge of damage mechanisms and of the main factors influencing damage/losses, as well as the possibility of simulating the effects of different risk mitigation strategies, are the key to identifying and prioritising risk mitigation solutions.

Notably, the EU and a few Member States are exploring the implementation of income insurance, a single policy that covers yield and price risks (European Commission, 2011; Meuwissen et al., 2011). The CAP 2014–2020 comprises a community income stabilisation tool 'in the form of financial contributions to mutual funds' (EU, 2013, Article 36(1)(c)), offering compensation of up to 65 % of the indemnities paid, provided that the indemnities compensate for less than 70 % of the forgone income and the income drop is above 30 % of a 3-year average based on the preceding 3 years or the preceding 5 years excluding the highest and lowest annual incomes. However, its development and implementation have been very limited (Cordier and Santeramo, 2019).

Realising the potential of subsidies to enhance insurance uptake and limit farm losses without bringing an excessive burden to the public budget necessitates efficient allocation of resources. Such welfare redistribution demands information on both producers' (insurers') and consumers' (insured's) surpluses (Dupuit, 1844; Marshall, 1879), which makes knowledge of insurance supply and demand necessary in turn (Skees et al., 1997; Martin et al., 2001; Collier et al., 2009; Mahul and Stutley, 2010; Maestro et al., 2013; Pérez-Blanco and Gómez, 2014; Santeramo et al., 2016).

Besides the aforementioned tools and policies, the EU adaptation strategy (European Commission, 2013; European Commission, 2018a; European Commission, 2018b) plays and will play a fundamental role in agricultural risk management. This policy has promoted the development of plans to increase agricultural resilience and better-informed decision support systems. An example of such a sectoral climate-oriented tool is the Italian water for irrigation information system([1]) addressing the needs of more than 12 000 farmers([2]).

At the farm scale, specific management practices can contribute to reducing the risk. As outlined and reviewed by Webber et al. (2014), these measures include, for instance, adapted sowing dates; cultivar and crop selection; reduced tillage; diversification; and integrated weed, pest and disease management. Shifting sowing dates may help to reduce the risks associated with heat stress and drought, especially under warmer climate conditions. Cultivar selection is and will be one of the key adaptation actions to deal with the interplay of climate change and climate variability, while crop selection also depends on other socioeconomic factors, such as consumer demand, market opportunities and support. Diversification of crops and of farms' investments represent an effective measure to stabilise both productivity and income. However, it is important to underline how most of these measures become effective in an integrated and optimised adaptation strategy. Efforts must be made to test combined integrated actions to respond to long-term climate change as well as to near-future changes, in which climate variability also plays a key role.

4 The 2018 drought

Heavy losses were caused by the 2018 drought in central and northern Europe. The shock did not spread, thanks to the favourable conditions in southern Europe. Derogation, advance payment and state aid were used to support the sector. This event highlights the importance of having early warning and local decision support systems and the need to develop better strategies balancing economic, financial, and adaptation multiannual tools.

Spring and summer 2018 saw unprecedented climate conditions in Europe. A combination of concurrent climate anomalies hit large regions of central and northern Europe and made this event exceptional. Extreme spring and summer temperatures associated with dry and very dry conditions were observed. As shown by Toreti et al. (2019a), the 2018 event can be considered unique in the past 500 years. Severe impacts were observed on several key socioeconomic sectors, including agriculture. Production losses were recorded in many EU Member States (Figure 2), with wheat production being the most affected (European Commission, 2018c).

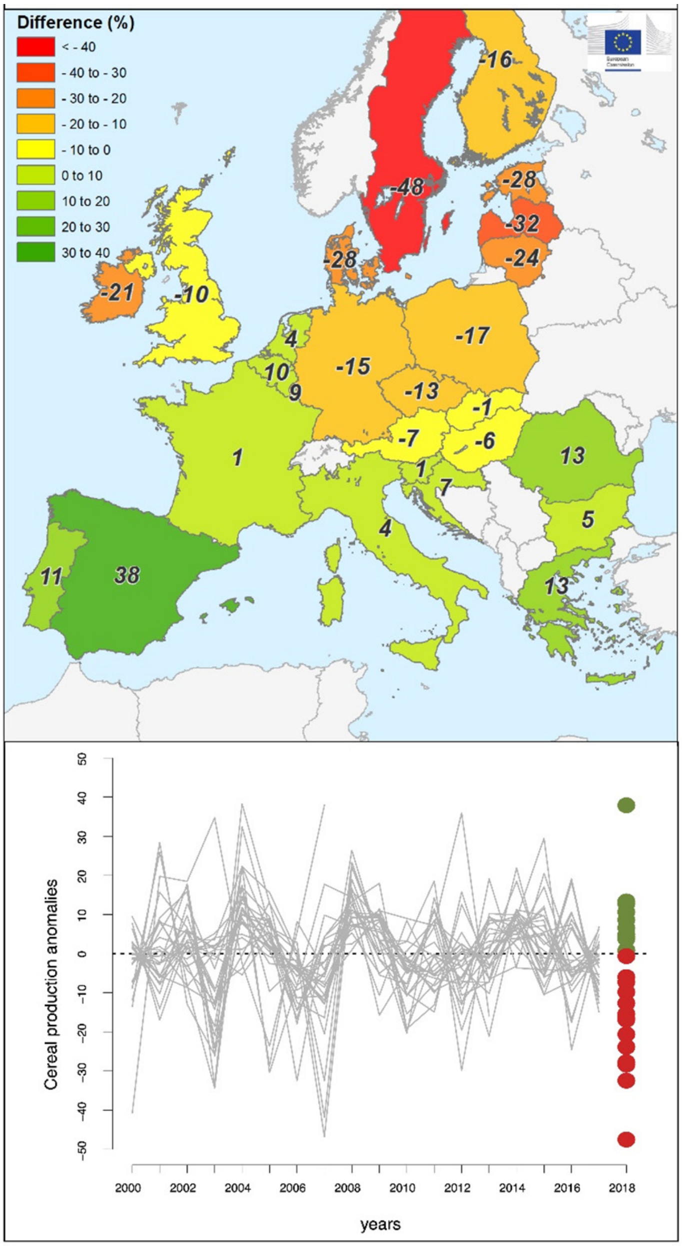
Cereal production dropped remarkably, with several Member States having negative anomalies (estimated with respect to the long-term trend based on Eurostat data) exceeding – 10 % and even reaching – 48 % (Sweden). Heavy losses were also reported in potatoes, rapeseed, turnips and sugar beet. However, thanks to the favourable conditions in southern Europe (Figure 2), the negative effects did not spread throughout Europe and beyond. The effects on market prices are shown in Figure 3. The overall losses caused by this exceptional event are estimated to be around EUR 3.3 billion, of which only around 7 % was insured (Munich Re, 2019). To support Member States and farmers dealing with the extreme drought, three strategies were put in place by the European Commission:

- higher advance payments, with farmers in the affected countries receiving up to 70 % of their direct payments and 85 % of payments under rural development by mid-October 2018;
- derogation from specific greening requirements (crop diversification and ecological focus area on land lying fallow) to allow further production of animal feed;

([1]) See https://www.irriframe.it
([2]) See https://climate-adapt.eea.europa.eu

- further derogations to use winter crops as catch crops, use sown pure crops as catch crops and shorten the defined minimum growing period of catch crops.

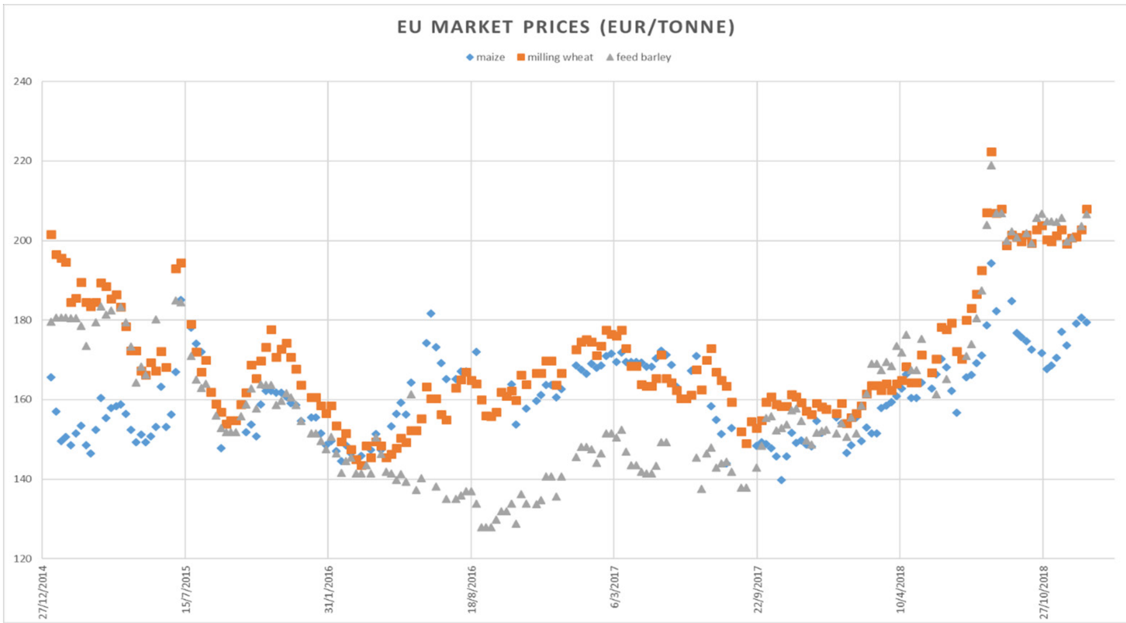
Many EU Member States recognised the emergency situation to enable farmers to request state aid as provided for by the CAP. For instance, the German federal and state governments decided on support measures amounting to EUR 340 million to support farmers hit by the extreme weather if they experienced yield losses of more than 30 %. In Poland, the government supported farmers by allowing different ad hoc payment strategies depending on the level of losses (above 70 % or between 30 % and 70 %) and on whether or not the farms were insured (50 % less without insurance).



The 2018 event points to the importance of early warning systems (monitoring and forecasting adverse conditions), associated with local targeted decision support systems to help adopt strategies to reduce negative impacts. It also highlights the need to foster the integration and use of climate services acting on time scales ranging from months to seasons and serving the farm scale. The 2018 drought reveals how developing adaptation strategies should be put in place by looking at both the near future (next 5–10 years) and longer time scales (next few decades) as well as at both the local and regional spatial scales. Adaptation measures (e.g. breeding new varieties, diversifying crops and investments within a farm) can alleviate the impacts of weather and climate extremes; however, they must be complemented with a set of policy and economic tools that balance compensation, insurance and multiannual stabilisation tools better than now, and promote climate-oriented sustainable investments.

Figure 2. *Cereal production in the EU. Upper panel: estimated cereal production anomalies in 2018 with respect to the long-term trend, estimated by using a locally estimated scatterplot smoothing (LOESS) approach on the reported values from 2000. Lower panel: time series of estimated cereal production anomalies (with respect to the LOESS-based long-term trend) in the Member States from 2000 (grey lines, one per country) and estimated anomalies in 2018 (red and green circles)*
Source*: data from Eurostat, 2019.*

Figure 3. EU market prices (EUR/tonne) for maize (blue), milling wheat (orange) and feed barley (grey).
Source: *data from the Cereal Statistics of the Crops market observatory (European Commission, n.d.-b).*
Note: *The prices refer to Rouen (France) for milling wheat and feed barley, and to Bordeaux (France) for maize. The price stage is 'delivered to port'.*



5 Projections for the coming decades

Climate extremes, such as drought, heatwaves and floods, are expected to intensify and occur more often in the future. Concurrent extremes and adverse conditions will bring new challenges for the sector. Adaptation will play a fundamental role.

Climate change projected for the coming decades poses a challenge for European agriculture (e.g. Van Passel et al., 2017; Bozzola et al., 2018; Ciscar et al., 2018; Webber et al., 2018). Despite the beneficial effects of elevated atmospheric CO2 concentrations on some crops (e.g. wheat) and the favourable mean conditions that could be induced in some regions by higher mean temperatures and/or changes in precipitation regimes, the agriculture sector will need to deal with more frequent and more intense extreme events. Extreme drought events, such as the one that occurred in 2018, could become common as soon as 2043 (Toreti et al., 2019a). On the other hand, heavy precipitation events are projected to intensify (Toreti et al., 2013), and in some regions flood events could occur more often, causing higher losses (Hirabayashi et al., 2013, Alfieri et al., 2015, 2017). Heatwaves are also expected to intensity and occur more often, and events like the 2003 one could become common (Russo et al., 2014). Therefore, there is a need to identify optimal risk reduction strategies.

Adaptation will play a fundamental role in this context, as measures such as changes in agromanagement practices (e.g. different crops and/or cultivar) or the use of tailored high-level sectoral climate services can reduce the impact of climate and weather extremes. Better farming systems, efficiently using nutrient resources, improve resilience to climate change and extremes. Depending on the projected changes and the level of global warming, stronger intervention measures (hard/soft engineering) might be needed locally and should be evaluated in terms of costs and benefit. The high degree of connectivity of the global agricultural market and the shocks that concurrent events could induce in different producing regions of the world must also be taken into account in the design of future strategies (e.g. Toreti et al., 2019b; Chatzopoulos et al., 2020). The adoption of new technologies and farmers' behaviour are key factors in assessing the impacts of climate changes and the associated risks. For instance, Koundouri et al. (2006) show that risk preferences affect the probability of adopting new irrigation technologies, and they provide evidence that farmers invest in these new technologies as a way to hedge against input-related production risk. Foudi and Erdlenbruch (2012) showed that French farmers rely on irrigation technology as a self-insurance tool against production risk, particularly the risk of droughts. Di Falco et al. (2014) investigated how financial insurance for extreme events can play an important role in hedging against the implications of climate change.

6 Conclusions and key messages

Climate and weather extremes have severely affected the agriculture sector in recent decades by causing heavy losses and damages. Specific sectoral and policy measures (e.g. within the CAP) have been taken to deal with them, often in terms of damage compensation, while the European adaptation strategy (European Commission, 2013; see also its evaluation, European Commission, 2018) has promoted, boosted and supported the development of national adaptation plans, to increase the resilience of key socioeconomic sectors such as agriculture and fill the knowledge gaps. As weather and climate extremes are projected to intensify and occur more often in the coming decades, more should be done to reduce the risks and the impact of these events. Optimised adaptation strategies acting at different spatial levels are thus needed (EEA, 2019).

At farm scale, for instance, several options can be developed and implemented, e.g. new crops and crop varieties (adapted to the changing local climate), better crop rotation schemes and diversity programmes, improved infrastructures for livestock and disease prevention. Across the spatial scales (applied locally, but enforced and developed at regional, national or EU level), the use of dedicated climate services will play a key role in limiting losses and damages. Hard and soft engineering solutions may also be needed if nothing is done to limit/stop the current rate of global warming. Crop insurance, by spreading risk, could buffer the financial implications of unexpected crop failure following local extreme events; however, broader participation can only be achieved by using targeted tools such as information campaigns (e.g. Santeramo, 2019). More should be done to promote and develop effective mutual funds and income stabilisation tools (Cordier and Santeramo, 2019). Considering the future risks and the rapid changes in the climate system, evolving adaptation strategies that combine several different options and approaches are advisable. The need for dynamic strategies, to be implemented for instance through a periodic revision mechanism, can be understood by considering the uncertainties of climate change projections as well as the role of internal climate variability on a time scale of decades. As also previously pointed out (EEA, 2019), adaptation will not take place effectively without strong engagement of all those involved in the food system (e.g. farmers, farmers' organisations, food producers). Co-design and continuous feedback in the development and implementation phases are key elements of successful adaptation to climate change.

Despite all these efforts, large-scale concurrent and recurrent events may still pose a serious threat. European farmers are and will be influenced by external events occurring in other producing regions, implying higher exposure to price volatility, spikes and market shocks. Preparedness could be achieved by including concurrent extremes in sectoral risk and impact assessments, and then testing the reaction of current trade patterns and market structure to shocks induced by these events. This may allow the development of emergency plans and measures (e.g. involving stocks, temporary changes in trade patterns, etc.) to absorb shocks, at least partially, before they propagate.

Profound changes in dietary patterns, food habits and, thus, consumer demand are usually not fully considered in risk and impact assessments. However, they may play an important role in shaping the future of agriculture and its associated risks and adaptation under changing climate conditions. Interest in novel food (as defined by EU, 2015), including for instance algae- and insect-based products as well as food engineered with nanomaterials, is growing (Caparros Megido et al., 2016; Peters et al., 2016; Menozzi et al., 2017), and public acceptance may change in the coming decades.

Disruptions in agricultural activity may have significant impacts in terms of reduced food and water security and quality, habitat and landscape protection, soil conservation, CO2 sequestration, biodiversity conservation and the economy of rural areas where agriculture is the basis (directly or indirectly) of the livelihood of most families (Pérez-Blanco and Gómez, 2013; Gómez-Limón and Riesgo, 2004; Meuwissen et al., 2003; Quiroga and Iglesias, 2009). These local/regional impacts will have consequences on critical welfare variables (e.g. negatively affecting environmental quality and amplifying income disparities between urban and rural areas). Furthermore, as observed climate trends scale up the magnitude of these disruptions, impacts will start to be felt economy-wide as well, effectively constraining the ability of the economy to create employment and income.

Policymakers

Policymakers should promote and support the implementation and use of optimal adaptation strategies (e.g. sectoral climate services) together with a periodic revision scheme. Tools such as insurance, mutual funds and income stabilisation should be better developed, as an integrated approach balancing all the available measures is needed to deal with current and future challenges. New measures to deal with global market shocks and crises, and system disruption should be discussed and developed. Emergency plans should be designed.

Practitioners

Practitioners should be heavily involved in the design, implementation and test of adaptation strategies. Innovative local risk management tools and decision support systems should be co-developed with scientists.

Scientists

Scientists should develop and test new integrated adaptation strategies and actions. Emerging risks, global shocks and system disruption should be better investigated. Behavioural patterns and changes influencing food consumption and demand should be included in impact and assessment modelling.

Citizens

Citizens should be more engaged through information and awareness campaigns, as well as periodic surveys to follow closely food consumption changes and reaction to novel food. Simplified tools that exemplify the actions taken should be made available.

3.3.3 Industry and energy

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Okuyama, Y., Girgin, S., Martínez Torre-Enciso, M.I., Šimić, Z., 'Industry and energy', In: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Introduction and background

This section focuses on the secondary sector, namely manufacturing and energy industries. These industries produce goods and services that are consumed as final or intermediate goods and services, and that are necessary for activities in a society, while they also employ labour and provide wages to households. Physical damage to these industries not only leads to a shortage of goods and services that they produce, but also causes declines in income to their labour forces. In addition, because of the globalised production networks as well as the lean production system employed in various manufacturing industries, the damage and business interruptions brought about in one region could spread to other regions in the same countries and potentially across the world. Some recent empirical observations, for example the declines in production of car-manufacturing companies at various countries in the aftermath of the 2011 east Japan earthquake and tsunami, proved that the modern manufacturing network appears vulnerable to such catastrophic disasters (Reuters, 2016). In this context, the production networks, such as intra- and interindustry linkages, should be encompassed to understand a comprehensive picture of disaster effects.

In this section, damage to physical facilities, resulting from internal causes or external forces, is called 'damage', while the decline in production level caused by the damage is called '(first-order) losses' of production (Okuyama, 2007). While the terminology used in the United Nations (2016) refers to damage and losses as 'direct economic losses' and 'indirect economic losses' respectively, the use of the words 'direct' and 'indirect' creates some confusion, such as adding these two different measures together, which is theoretically incorrect and potentially leads to the double counting of impacts. In addition, the methodologies to measure higher-order effects use the term 'indirect' with a different definition (Rose, 2004). The most up-to-date Handbook for Disaster Assessment by the Economic Commission for Latin American and the Caribbean (ECLAC, 2014), known as the ECLAC methodology, also employs definitions of damage and loss similar to Rose's. Therefore, in this section, 'damage', 'losses' and 'higher-order effects' are utilised, instead. These two numbers of damage and losses should be clearly distinguished, because adding them together would double-count the impacts, and Rose (2004) suggested listing both of them separately to paint an inclusive picture. A few methodologies are available for the quantification of damage and losses, and their details are discussed below.

2 Risks in industry and energy industries

Manufacturing and energy industries inherently involve risks that can be classified into internal and external, and/or can lead to broader effects on the macroeconomy and the natural environment.

Manufacturing and energy industries inherently involve risks that could lead to accidents that might result in a disaster, or could experience a catastrophic natural hazard, such as earthquake, flooding, severe weather, or drought, that would bring about damage or losses to the production facilities. These risks can be classified into internal (within the industry) and external (from other industries), and/or can lead to broader effects on the macroeconomy and natural environment. For example, internal risks include the malfunctioning of production equipment, software bugs, faulty operation of production systems by humans, financial risks, reputational risks if the company does not address climate change and so on. External risks can be threats of catastrophic natural (and man-made) hazards, which can cause physical damage to production facilities and/or networks, and increased climate variability leading to hazards. Internal risks can be dealt with by technological and behavioural means, while external risks may be responded to by prevention and preparedness, such as a business continuity plan (BCP).

In particular, modern manufacturing and energy industries rely heavily on supply chains (value chains) because of the increasing globalisation of production processes, through which a company purchases parts (intermediate inputs) provided by other companies (upstream industries) for its products and sells its products to other companies (downstream industries) or to consumers as final products. Specifically, upstream industries are mainly mining, material production (chemical, steel, etc.) and energy industries, and downstream industries include product-assembling industries (automobile, electrical and electronic products, etc.) and service industries. In this way, manufacturing and energy industries form complex and interwoven interindustry networks. Given this, one company's stoppage of production due to damage to its production facility resulting from internal or external causes would create a negative ripple effect on a wide range of industries and on the economy, as well as positive opportunities to other companies that can provide substitutable products. The impacts of such an event can be classified into the following five types: (1) production (supply) disruptions due to damage to production facilities; (2) forward effects of the supply disruptions to the downstream industries; (3) technical and/or spatial substitution effects for replaceable goods and services; (4) decline in both intermediate and final demands due to the decreased production and earnings; and (5) backward and positive effects from intensive demand injection of reconstruction activities (Oosterhaven, 2017). It is expected that the interindustry

2.1 Risks within industries

Manufacturing and energy industries inherently involve risks within their operations, and the realisation of such risks may cause damage to their facilities. These risks include faulty design of production processes, malfunction of the production facility and/or equipment, software problems, mismanagement of the company, or other human errors. Each company in these industries tries to minimise these risks using redundancy, backup facilities, periodical maintenance and so on. Because all the production systems, facilities, and equipment are designed and installed by humans, it is inevitable by our nature that they will contain some major or minor errors or drawbacks. While these risks originate internally in the production system in question, the systems are also exposed to external risks. Some natural hazards, for example earthquakes, flooding, severe storms, and drought, can damage or even destroy part or all of the production facilities, creating the similar impacts to the internal risks above. This risk will create production disruptions, as in type 1, and would trigger a ripple effect on the economy and society as described above.

2.2 Risks among industries

Modern manufacturing and energy industries require a set of intermediate inputs for producing their products, creating interwoven interindustry linkages. For example, car manufacturers require thousands of intermediate inputs, such as tyres, glass, seats, plastic materials, paints, electrical parts, electronic circuits and, water, from their suppliers. Even though a car-manufacturing company did not have any physical damage to its production facility, it would eventually halt or delay its operations if one of the suppliers that produces critical intermediate input were damaged and could not supply its products. This type of cascading impact on an undamaged company is called 'higher-order effects' (Rose, 2004), which can potentially produce the ripple effect of impacts through interindustry linkages (supply chains) to many other industries, described as types 2, 3, and 4 above.

This ripple effect would propagate not only to the downstream industries through the supply chain but also to the upstream industries. If one company (A) needs to pause its production because of severe damage to one of its critical suppliers (B), this is called the impact on downstream industry. Meanwhile, another company (C), which provides its product as an intermediate input to B, will need to decrease its production because B cannot produce its product therefore does not need intermediate inputs from C. This is an upstream propagation of the impact. Moreover, company A uses other intermediate inputs from another company (D) as well as from B. When company A halts production as a result of damage to B, it influences the production of company D, since A also stops purchasing D's product. This is also an upstream propagation of impact. Company A's production stoppage can also potentially lead to a downstream propagation of the impacts, if other companies purchase company A's product as their intermediate inputs. The ripple effect of impacts spreads through the web of supply chains that modern manufacturing industries have formulated and utilised. Some industries, such as car manufacturing and construction, require a wide range of intermediate inputs; if even a small supplier that provides a critical input to major companies is damaged by a disaster, it can create extensive ripple effects on many other industries.

Higher-order effects are quite entangled and complex to measure empirically by using usual macroeconomic indices, such as changes in gross domestic product, due to other macroeconomic disturbances and so on. Therefore, the quantification of higher-order effects requires economic models, such as input–output (IO), computable general equilibrium (CGE) or econometric models. Some of these models are briefly discussed below.

2.3 Effects on macroeconomy and environment

Since the higher-order effects can propagate across a broad range of industries, there is a concern that a catastrophic disaster, such as the 2005 Hurricane Katrina in the United States and the 2011 east Japan earthquake and tsunami, could affect negatively the regional or national economy. While a disaster caused by internal or external risk to manufacturing or energy industry would lead to localised damage and losses and could spread the higher-order effects further to other industries elsewhere, the economic impact of such a disaster, even a catastrophic one, may not affect the national economy of developed countries negatively in both the short and longer terms (Albala-Bertrand, 2007). This is because developed countries should have sufficient financial, technological, and other resources to better manage disaster risk through the implementation of countermeasures against the adverse impacts of disasters. In other words, if they did not prepare thoroughly against such events, there would be substantial and long-lasting negative effects in and around the country, such as after the 1986 Chernobyl nuclear accident and the 2011 Fukushima nuclear accident.

The timing of a disaster occurrence could influence the overall impact of a disaster in a macroeconomic context. When economies exhibit higher growth during a boom period, they may be more vulnerable to disasters than those with slower or declining growth in a bust period. This is because during a bust period idle and unused production capacity can serve to absorb the production shortage induced by the disaster, whereas during a boom period production capacity in economies is fully utilised and hence cannot deal with the production shortage (Hallegatte and Ghil, 2008). Having an inventory of intermediate inputs and final products can also serve as a buffer against the forward (downstream) effect of supply shortage, whereas modern manufacturing industry has been exercising the lean production system, under which it minimises or eliminates such inventories, embedding increased vulnerability to the forward effects. However, many manufacturing companies consider that such risk would last for a short period so they maintain the lean production system, even after experiencing prolonged production stoppage due to forward effects created by a catastrophic disaster (Reuters, 2016).

It is a somewhat common misconception that disasters might cause renewal or update of assets and facilities, leading to upward macroeconomic trends in the long term, which is sometimes referred to as the Schumpeterian creative destruction or fertilisation effect. Empirical investigations of the relationship between disasters and economic growth/trends indicate otherwise (Okuyama, 2019). The studies using socioeconomic disaster indicators, such as those by Noy (2009), Cavallo et al. (2013), and Fomby et al. (2013), provide somewhat mixed results for such a relationship, whereas the studies employing physical intensity indicators of disasters, for example those of Hsiang and Jina (2014), Felbermayr and Gröshcl (2014), and Berlemann and Wenzel (2016), found clear negative effects between them. Hallegatte and Dumas (2009) analysed this relationship that damage caused by hazards and subsequent reconstruction with renewed assets only increase production levels but cannot lead to overall technological progress, therefore they may not boost long-term economic growth.

Some industries, especially upstream industries (mining and energy industries), characteristically contain risks with the potential to trigger environmental damage due to their use of hazardous resources and materials. Some accident in such a company, with a natural or human cause, may result in a leakage of hazardous materials into the surrounding area, which contaminates the natural environment of the area. This may lead to an environmental disaster, such as the Exxon Valdez oil spill in 1989 in Alaska, the United States. While downstream industries (assembling products) also hold the similar risks to a lesser degree, they are not immune to causing environmental damage by fire in factories and/or inventory facilities, leading to temporary air pollution from the burning of their intermediate and final products.

3 Risks from climate change

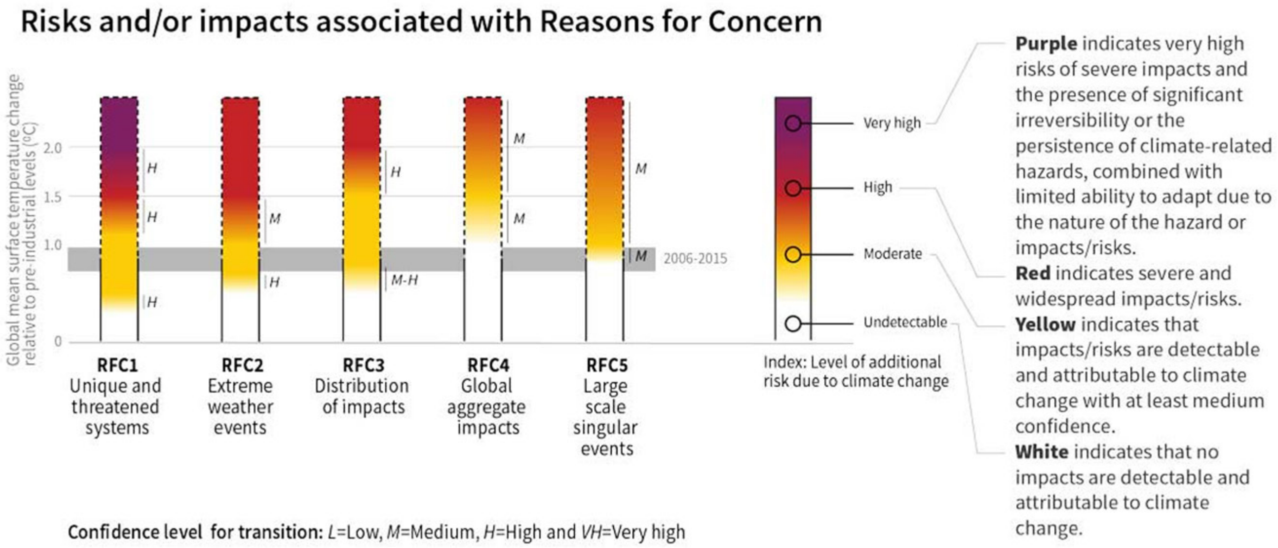
Uncertainties related to climate change risks (e.g. time of occurrence and level of increase in risk) prevent industry from organising optimal (timely and measured) and proactive preparedness.

Climate change is expected to increase both the frequency of occurrence and the magnitude of natural hazards, and this will increase the risks (exposure and consequences) to manufacturing and energy industries. The similarity of these hazards to already existing threats (i.e. extreme weather events) makes it easier for the industry to assess, prepare for and mitigate the risks. However, the uncertainties related to the issues, such as the time of occurrence and level of increase in the risk, prevent industry from organising optimal (timely and measured) proactive preparedness.

Premature and/or excessive adaptation presents risk itself. Additional uncertainty is related to regional impacts. A special report from the Intergovernmental Panel on Climate Change (IPCC) analyses the risks from various climate change scenarios between 2 °C and 1.5 °C warming above pre-industrial levels and related global greenhouse gas emission pathways (Hoegh-Guldberg et al., 2018). That report estimates the impacts and risks as high from extreme weather events, and moderate from large-scale singular events at 1.5 °C warming, with a moderate level of confidence, as shown in Figure 1.

However, the estimates of coastal flooding risk are very high, with a high level of confidence. The following two subsections discuss industry and government actions related to climate change risk assessment, adaptation and mitigation measures.

Figure 1. *Estimated impacts and risks from different levels of global warming associated with reasons for concern (RFCs)*
Source*: Figure 3.21 in Hoegh-Guldberg et al., 2018.*



3.1 Climate change risk management for the manufacturing and energy industries

The manufacturing and energy industries have been facing climate change risks to their market ratings and regulation requirements. Dealing with these risks is essential because the government regulations, financial market, and insurance companies force and/or expect them to implement timely reactions to such risks.

Goldstein et al. (2018) reviewed more than 16 000 corporate adaptation strategies and significant blind spots found in the assessments of climate change impacts and their management. CDP (2019) summarises the following findings from the companies reporting about climate change risks and opportunities: significant risks are identified as needing expanded analysis; the largest companies report major financial implications; the risks are smaller than the opportunities; some striking regional differences exist; many industries expect to experience fewer implications than the financial industry; management costs outweigh the benefits; the energy industry is a source of lessons to be learned because of early and wide-ranging impacts.

Industry could prepare better for climate change risks by incorporating its assessment into an overall risk management (RM) strategy. Continuous updating with the best available data and methodology is necessary for tackling all the related uncertainties.

3.2 Governance for reduction of climate change risk

Regulators and investors had already motivated the industry to transition towards a sustainable and low-carbon economy, even before climate-change-related risks were considered transitional risks and became highly publicised. All these various governance measures are imperative because they are designed to prepare for increased climate change risks in a socially optimal way. However, there are ongoing debates about what regulations should be imposed and which best practices should be encouraged. Considering the extensive uncertainties related to climate change risks, finding the best approaches is a daunting task. In this context, research and development to reduce uncertainties, and to improve risk assessment for efficient industry applications and effective regulations, are indispensable to tackle the climate change risks. Without the knowledge and insights from the best available sciences, all those involved would be more likely to underestimate or overestimate the future climate change risks. Either way, this would result in significant waste of resources.

4 Estimation methods

It is imperative to understand what assessment models/methods can or cannot cover based on their assumptions.

As argued in the 2017 report (Poljanšek et al., 2017), more consistent and systematically gathered data for the damage and losses to manufacturing and energy industries, and other industries, are needed for assessing the impacts of events. While the OECD governance of critical risks initiative has compiled the data([1]) for the policies, processes and practices through which OECD Member countries govern critical risks, the data for damage and losses, as well as higher-order effects, have not been collected consistently or systematically. Because the definitions of damage and loss in a disaster situation, such as the spatial and temporal extent and the valuation methodology, have not been set, nor is there any consensus among stakeholders (Okuyama, 2007), it is a good idea to start with the definitions proposed in the widely used ECLAC assessment methodology (UN ECLAC, 2014), which has been employed to assess damage and losses in recent major disaster cases in developing countries. Terminology used in this subsection – damage, losses and higher-order effects – follows the definitions in the introduction above.

4.1 Assessment of damage

In the ECLAC methodology, damage is defined as the effects that a disaster has on the assets of each industry, expressed in monetary terms. The assets here include physical assets such as buildings, machinery, equipment, furnishing, roads and ports, land, and inventory of final goods and intermediate inputs. Two pieces of information are required to evaluate damage: the level of destruction of each asset and their monetary value (UN ECLAC, 2014). While the ECLAC methodology uses the replacement cost of damaged assets for the conversion from physical quantity to monetary value, it becomes occasionally problematic, especially in a disaster situation (Rose, 2004). When a machine is partly damaged in a disaster, it does not have to be replaced but can be repaired; in this case, the cost should be the repair cost. In addition, even in a case of replacing the damaged equipment, it would not be replaced with the same machine; rather, newer equipment can be installed to replace the damaged old one. In this case, the replacement cost (the cost of new equipment) is not equal to the value of the

([1]) See https://qdd.oecd.org/subject.aspx?Subject=GOV_RISK

old one before the disaster. In an extreme case, if a company's factory were damaged by a disaster and it went bankrupt, there would be no replacement cost. Information on estimated damage is indispensable for industries to evaluate their preparedness and mitigation measures and to respond to the damage. Recent increased data collection capabilities and advanced information and communication technologies in many developed countries make it possible to estimate property damage immediately after a natural hazard hit. One such method has been proposed by Heatwole and Rose (2013); it can estimate property damage, including the damage to land, livestock, buildings, equipment, etc., from major US earthquakes based on a regression model. This model consists of 'exposure-related predictors', such as population, income, and land area of hazard-affected region, and 'hazard-related predictors', such as earthquake magnitude, distance from epicentre and so forth, to derive a set of property damage estimates (lower bound, average, and upper bound) in monetary value. While this model is only for earthquakes in the United States, this framework can be applied to other types of hazard and to other countries. This type of method can be useful to assess the damage that a natural hazard has caused and to assist timely disaster response and recovery activities.

4.2 Assessment of losses

Production or business interruptions caused by damage to production facilities lead to declines in production flows of goods and services. Losses are defined as goods and services that go unproduced during a period running from the time the hazard occurs until full recovery of the damaged assets is achieved.

By and large, different methods have been employed for the estimation of business interruption costs. The popular approaches are (1) applying an industry-specific reference value per unit affected or per day of interruption to estimate the production losses; (2) comparing production output between years with and without hazard; and (3) calculating production losses as a proportion of damaged production capital (Meyer et al., 2013). Furthermore, loss estimates can be obtained by fitting statistical models to available historical data (e.g. originating from the insurance industry) (Hogg and Klugman, 1984) by using methods such as parametric curve fitting based on extreme value theory, and generalised Pareto distribution due to the heavy-tailed and skewed nature of the data (McNeil, 1997; Jindrová and Pacáková, 2016). It is cautioned, however, that the hypothetical baseline (without disaster) case must be projected from the best information available, in order to avoid losses being over- or underestimated (UN ECLAC, 2014). Losses here are sometimes called first-order losses, to distinguish them clearly from higher-order effects, discussed below.

Like the frameworks to estimate damage discussed above, a few models have been proposed to estimate losses from hazard intensity index and socioeconomic data that are readily available. One such model is the estimation model for 'production capacity loss rate' by Kajitani and Tatano (2014).

Conventional approaches to production loss estimate require damage data on production facilities and equipment, whereas this model evaluates the production capacity loss rate through functional fragility curves and lifeline resilience factors. While their methodology is tailored to earthquakes and Japanese cases, the framework can be applied to other types of hazards and to other countries where similar data are available. One of the advantages in this methodology is that, once the ground motions of a particular earthquake are given, the estimated changes in the production capacity rate can be derived in the damaged area. This type of rapid assessment method for evaluating production loss is advantageous to timely decision-making in industry for managing response and recovery strategies as well as analysing the higher-order effects.

4.3 Assessment of higher-order effects [2]

As discussed in the introduction, the first-order losses stemming from the business disruptions caused by the damage to production facilities set off a chain reaction, or ripple effect, through interindustry linkages (supply chains). For instance, if a power station were damaged by an accident, electric power would not be available to some or all of the power grids that the power station covered, and manufacturing industries in the affected power grids would have to halt their production until power was restored, even if they were not damaged at all. Moreover, due to the lost production of those industries without power, the suppliers to and the customers of those industries would need to either decrease or pause their production, too. How the ripples of such effect spread across other industries in economies is rather complex, because of intertwined supply chains across industries and over space and even across countries.

In order to assess such higher-order effects of a disaster, one needs to use economic models, such as input-output (IO), computable general equilibrium (CGE), econometric, non-linear optimisation or some other macroeconomic models. These models are highly sophisticated and need some lengthy descriptions. In short, IO models highlight interindustry transactions to derive ripple effects from changes in demand to one or more industries, while CGE models simulate changes in demand and/or supply in various markets to replicate how an economy responds (or economies respond) to a shock. Econometric models are regression models based on historical data about an economy. Readers interested in this topic are encouraged to consult the relevant literature, such as Rose (2004), Okuyama (2007), Okuyama and Santos (2014) and Okuyama and Rose (2019). While these models have been popular and employed for numerous recent cases, they are not without criticisms (e.g. Albala-Bertrand, 2013). Because economic models are representations of specific aspects of the real world, they intrinsically neglect some other aspects, such as psychological impacts on the labour force. It is imperative to understand what assessment models/methods can or cannot cover. At the same time, there are also considerable ambiguities in the estimates, especially for higher-order effects from the cascading impacts, due to uncertainties in a disaster situation that might be amplified by these methods. Further studies on this topic are essential, given the importance of unbiased estimates of the economic impacts (Girgin et al., 2019).

5 Countermeasures against risks

Prevention, preparedness, mitigation, response and recovery measures are the most common countermeasure strategies.

In order to avoid an incident becoming a disaster, strategies for dealing with existing and emerging risks are necessary. These strategies, also known as countermeasures against risks, include prevention, preparedness, mitigation, and recovery measures. Particularly in manufacturing and energy industries, their production activities establish a complex system, which covers production, logistics networks, and budget constraints, and this complexity and the internal and external risks that they face burden their management decisions about how to formulate and implement countermeasures. For example, a company's production process relies heavily on the use of electric power, which is produced by a power company. If the power company could not produce and/or transmit power, causing a blackout, this company's production would be suspended as a higher-order effect of the power shutdown. If the accident were caused internally within the power company, the loss of revenue of

[2] The 2017 report (Disaster Risk Management Knowledge Centre, 2017) discussed the methodologies assessing higher-order effects ('indirect economic damage') to some extent, such as simultaneous equation econometric models, input–output models, and computable general equilibrium models. The issues with these models raised in the 2017 report, for example dynamic adjustment features such as recovery, resilience, interregional substitution, inventory adjustments, and changes in labour supply, have been dealt with by the recent models. In particular, Okuyama and Rose (2019) provide state-of-the-art modelling practices and examples of the recent advances.

this company could be contractually divided between the two companies and potentially compensated for by the power company. On the other hand, if the accident were caused by an external source, such as a natural hazard, it would often be out of the scope of contractual matters. As one of the preparedness measures, this company would want to install backup generators for such a case; however, the cost of generators and fuels is added to the production cost (the larger the backup generators become, the more they cost the company), whereas the occurrence of such blackouts is quite infrequent.

The countermeasure strategies against risks try not only to avoid an incident becoming a disaster but also to limit the impacts of such an event once it occurs. Usually, prevention, preparedness, and mitigation measures are identified during the pre-disaster phase, and the response and recovery measures are set up in the post-disaster phase. Measures to reduce or limit the impact of a risk are not arranged in isolation but are put in place along with strategic medium- and long-term plans, and always within the enterprise-wide RM, i.e. the overall management of the risks that organisations take, to make decisions about how to formulate and implement countermeasures and how to achieve their strategic objectives.

5.1 Risk management

Risk management is a 'combination of organisational systems, processes and procedures that identify, assess, evaluate and mitigate risks in order to protect the organisation, its strategies and objectives (Martínez Torre-Enciso, 2007). An effective RM system plays a significant role in reducing exposure to potentially unfavourable events. Many organisations follow RM frameworks([3]) and models for enterprise risk management (ERM), business continuity (BC), disaster management (DM) or crisis and emergency management (CEM), among others. Each of these models establishes its own processes and procedures; however, in certain respects they overlap regarding the identification and evaluation of risks and the control and financing of both the risks and the measures established to limit their effects. Moreover, these overlaps among different strategies (ERM, BC, DM, CEM) are allowed in many cases – and especially in regard to operational risks, which are the most important in manufacturing and energy industries – in order to obtain important synergies (Laye and Martinez Torre-Enciso, 2001). For example, a company that aims to develop ERM and BC plans should carry out the identification, assessment and evaluation of risks for both. If the same team deals with ERM and BC plans, significant savings in personnel costs and time are achieved, as processes will only be carried out once.

The Committee of Sponsoring Organisations of the Treadway Commission (COSO) ERM model and other risk management frameworks, such as International Organization for Standardization (ISO) 31.000, develop comprehensive identification, assessment and evaluation of risks through risk mapping, matrix, etc.(ISO, 2018). Once risks are determined by the company's risk tolerance levels, the ERM model and frameworks allow it to decide how the risks are treated: control, finance and transfer them. If the risk has been identified, there are several ways to deal with it, including acceptance, transference, and mitigation. To transfer the risk, the company may purchase insurance or outsource the activity to a third party. Mitigating the risk might mean that it is reduced in some way. By applying these processes, it is possible to reduce the inherent risk until only residual risk remains. ERM not only calls for corporations to identify all risks they face, so that they can decide which risks to manage actively, which helps companies in the complex decision-making process on establishing countermeasures against risks; it also involves making that plan of action available to all stakeholders, shareholders and potential investors, as part of their annual reports (e.g. figure 2).

([3]) Around the world, a number of risk management standards have been published in order to guide the application of risk management. These standards include (but are not limited to) Enterprise risk management – Integrated framework (Committee of Sponsoring Organisations of the Treadway Commission [COSO]–USA, 2017); ISO 31000:2009 Risk management – Principles and guidelines (International Organization for Standardization, 2009); BS 6079-3:2000 Project management – Guide to the management of business related project risk (British Standards Institute, 2000); King IV report on governance (Institute of Directors in Southern Africa, 2016).

Figure 2. Enterprise risk management process ***Source***: *© COSO, 2017.*

For manufacturing and energy industries, these risks may entail consideration of supply chain delays/ disruption, third-party vendors, information technology (IT), staffing and succession planning, emerging markets, and productivity and quality issues, among others. Controls can be directed to all exposures to risk (hazard, operational, strategic and financial) and can be achieved by implementing policies, standards, procedures and physical changes to a workplace. For example, when there is an identified risk of fire, organisations may employ physical control measures such as good housekeeping, fireproof materials, sprinkler systems or a no-smoking policy. For security risks, control measures may include physical barriers and locks. For IT breaches, there are measures such as firewalls, increasing password complexity or moving to two-factor authentication. For fraud risks, control measures could include background checks on staff members, segregation of incompatible duties or implementing system security to limit access.

5.2 Business continuity management

Each company has a number of critical business functions that must not be interrupted and, if they are, must be recovered as quickly and at the lowest possible cost. For such situations, companies develop BC plans whose countermeasures against risks are planned in the pre-disaster phase, but have their full development in the post-disaster phases. Business continuity management (BCM) is a 'holistic management process that is used to ensure that operations continue and that products and services are delivered at predefined levels, that brands and value-creating activities are protected, and that the reputations and interests of key stakeholders are safeguarded whenever disruptive incidents occur' (ISO, 2012).

Implementing the business continuity plan (BCP) of a company can help sort out this complex decision-making and can direct it to establish sufficient countermeasures against risks as a result. A BCP is a 'document that describes how a firm intends to continue carrying out critical business processes in the event of disasters (American Bar Association, 2011: page 1). BC planning is also the process of creating systems of prevention and recovery to deal with a disaster situation (Elliott et al., 1999). It consists of three stages: (1) risk assessment, including 'risk evaluation' and 'business impact analysis'; (2) developing and documenting BCP, including 'develop recovery strategy' and 'document plan'; and (3) testing, approving, and implementing BCP, including 'test plan', 'approve and implement plan', and 'maintain plan' (AIG, 2013: Page 3). BC planning appears closer to preparation for how to recover from and/or respond during a disaster (including impact from higher-order effects); however, business impact analysis at the first stage can highlight weakness in production processes that are vulnerable to disaster scenarios. Therefore, constructing and implementing a BCP is not only critical for minimising the impacts during recovery from a disaster but also imperative for determining prevention, preparedness and mitigation strategies before such a disaster occur'

Two notes on BCP components (Martínez Torre-Enciso and Casares, 2011) are worth discussing here. Crisis and disaster situations usually result in the loss or temporary disruption of one or more of the following necessary key business resources: facilities, infrastructure, IT applications/systems, people and supply chain. Developing a correct and deep business impact analysis is a key element for a BCP's success, as it identifies the impact of a sudden loss of business functions, and evaluates which are the core and critical business activities that must not be disrupted. On other hand, some people think a disaster recovery plan is the same as a BCP, but a disaster recovery plan focuses mainly on restoring IT infrastructure and operations after a crisis. It is actually just one part of a complete BCP, as a BCP looks at the continuity of the entire organisation. In this way, BCP documentation may include (1) a disaster recovery plan, including the loss prevention and control measures and the emergency plan; (2) a crisis management plan; and (3) contingency plans.

Manufacturing and energy industries need to have strategic plans in place to ensure that disruptions are avoided in the areas of staffing, supplies and machinery; the aim is to recover plant operations. They focus their BCPs on recovery strategies and mitigation measures, given the difficulty in finding continuity solutions. On the one hand, setting aside alternative sites for them is usually avoided because of the costs involved. In the absence of alternative production sites, there are few recovery strategies available to manufacturers. When custom construction equipment and assembly lines used cannot be easily replaced, recovery options available are (1) slowing down when they feel the impact, by using inventory/buffer storage; (2) selective recovery of production lines; and (3) ensuring that the recovery/repair operations are performed quickly. Alternatively, if some equipment in their production lines is similar to that of their suppliers, manufacturers that assemble semi-finished products may try to resume limited production capacities at their suppliers' premises.

On the other hand, the ability of having redundancies of production process as a backup for efficiency is a key objective for manufacturers, and mitigation strategies are often prioritised. Those measures should focus on either preventing or limiting the impact of a disruption, taking into account the production of goods or energy. For instance, if there is a fire, the sprinkler system might be activated as a whole, and could damage production equipment that were otherwise unaffected by the fire. This can be avoided through the use of localised sprinkler discharges so that each sprinkler needs to be independently activated, or the use of a dry delivery sprinkler system so that, upon activation, fluids are directed to only the discharge point.

Healy and Malhotra (2009) studied public spending on disaster relief measures and countermeasures, and found that every USD 1 spent on preparedness saves the equivalent of USD 15 on relief measures for all future disasters. While their study concerns only government spending and its consequences, this tendency for pre-disaster preparedness to be less costly than post-disaster recovery applies to the private sector, especially the manufacturing and energy industries, considering the amount and extent of the higher-order effects on a society. At the same time, as discussed above, because the lean production system inherently comprises the risk of supply chain disruptions, careful preparation in the BCP for alternative suppliers or supply chain, instead of having and/or increasing inventory, should be seriously considered.

6 Case studies

The impacts related to industries and energy production systems are not limited to direct physical damage, but also include business interruptions and cascading events hazardous to human life and the environment. This is especially the case for the aftermath of natural disasters that affect multiple industries at once.

6.1 The 2013 floods of the Danube and Elbe rivers in Germany

The June 2013 flood was the severest large-scale flood in Germany for the last six decades for which a hydrological flood severity had been estimated (Merz et al., 2014). In May 2013, rainfall above the long-term average in many parts of central Europe caused severe flooding. In that month, 178 % of the long-term monthly precipitation fell across the whole of Germany. The flood began after some areas of Germany experienced a total of over 400 mm of rain within a few days. While there was only moderate flooding in the south-west of Germany, the authorities in parts of southern Bavaria and Austria declared a full-scale emergency.

In Upper Bavaria, some areas had to be evacuated after embankments were breached. Eastern Germany, such as the states of Saxony, Saxony-Anhalt and Thuringia, was also severely affected, and some rivers flooded towns and villages, causing damage to houses and vehicles and forcing the evacuation of almost 100 000 people (Munich Re, 2014) (Figure 3).

The floods caused damage to a railway bridge, and the important high-speed rail connection between Berlin and the western part of Germany was cut off for several months (Schulte in den Bäumen et al., 2015). Manufacturing companies were severely affected: Krones, a global market leader in manufacturing bottling machines, shut down production in two plants in Upper Bavaria, because its workers were unable to commute to work on inundated roads. Volkswagen in Zwickau had to stop its vehicle production, since its suppliers were unable to deliver the parts in time owing to the damage to the transport infrastructure (Wenkel, 2013). Thieken et al. (2013) interviewed 557 flood-affected companies in order to investigate impacts on economic activities.

Of those companies, 88 % answered that they were affected by ‘interruption of operations’ by flooding, followed by ‘building and/or equipment damage’ and ‘turnover losses’. Manufacturing companies reported more frequently than other industries that ‘their own delivery problems’ and ‘delivery problems by suppliers’ affected their operations. Because manufacturing companies rely heavily on supply chains for intermediate inputs (parts and products), also known as vertical specialisation, once any transportation links and/or nodes are disrupted, suppliers cannot reach their customers to deliver their products. This leads to business interruptions to the downstream companies/industries, propagating higher-order impacts.

The economic cost of the flooding was estimated at EUR 10 billion in Germany alone (EUR 11.7 billion in the entire affected area), while the insured amount was EUR 1.8 billion in Germany (Munich Re, 2014). These numbers are estimates of damage, not losses, nor do they include higher-order effects over the surrounding regions. For a more comprehensive and broader assessment of the socioeconomic impacts of river floods, Alferi et al. (2016) proposed an integrated framework to estimate the economic damage and population affected by river floods at a continental scale, in which pan-European river flow simulations are linked with a high-resolution impact assessment framework.

Figure 3. *Wust-Fischbeck (Saxony-Anhalt) submerged by the river flood in June 2013.*
Photographer: *Jens Wolf. © European Union, 2020*

They applied this framework to the 2013 central Europe floods and derived aggregated estimates of (direct) damage in Czechia, Germany, and Austria amounting to EUR 10.9 billion and 360 000 people affected by this event. Their framework focuses mainly on simulating physical events (floods) and assessing physical damage, but not losses or higher-order effects. Nevertheless, this framework is quite useful to simulate events and monitor floods in severe weather conditions. For a more comprehensive evaluation of the event, especially covering a larger area, the losses and higher-order effects of the event need to be evaluated.

Employing a multi-regional IO model of Germany (including the 16 Länder of Germany and the rest of the world, with 41 types of industry) to simulate the supply chain disruptions, Schulte in den Bäumen et al. (2015) estimated that the higher-order effects of this event in Germany, which affected not only the motor vehicle and food industries in Germany but also foreign production, amounted to EUR 6.2 billion. The higher-order effects on regions and industries outside the flooded areas were around EUR 400 million. Their estimates suggest that losses of production in the damaged Länder were EUR 3.1 billion in Bavaria, EUR 750 million in Saxony, EUR 423 million in Saxony-Anhalt, EUR 398 million in Brandenburg and EUR 394 million in Thüringen. Outside the damaged Länder, it is estimated that other economies suffered production losses (higher-order effects) through supply-chain interruptions: for example, EUR 171 million in North Rhine-Westphalia, EUR 151 million in Lower Saxony, EUR 80.2 million in Baden-Württemberg and EUR 42.2 million in Hessen. In addition, economies outside Germany lost EUR 33.8 million in forgone production as the higher-order effects through supply-chain interruptions. The industries in Bavaria most severely affected by production losses were estimated to be real estate services (EUR 218 million), transport equipment production (EUR 181 million), 'other business services' (EUR 154 million) and motor vehicle production (EUR 80.2 million). On the other hand, the industries suffering the largest higher-order effects were motor vehicle production in Baden-Württemberg (EUR 85.7 million), and food industries in North Rhine-Westphalia (EUR 84.3 million) and Lower Saxony (EUR 34 million). As their results suggest, the impacts (higher-order effects) of the event spread geographically and across industries, especially among manufacturing industries, through interindustry supply chain networks.

As the globalised production system and the integrated economy, such as in EU Member States and regions, expand, it is essential to consider and evaluate the economic values not only of damage and losses but also of higher-order effects, which are becoming more extensive and crucial than before. As discussed in the previous subsections, standardising the definition and establishing the extent of higher-order effects are essential for implementing effective strategies and countermeasures to minimise such broad impacts. At the same time, because of the interconnected production systems of these industries, cooperative measures among related firms and with the public sector need to be promoted on a wider geographical scale.

6.2 Industrial accidents triggered by natural hazards

The impacts of natural catastrophes on the industries and energy production systems are not limited to direct physical damage and business interruption, but may also involve cascading events hazardous to human life and the environment, such as fires, explosions, and toxic or radioactive spills. Such cascading events may amplify the overall economic loss with further physical damage, injuries, fatalities, medium- or long-term health problems, environmental damage, loss of ecosystem services, business interruption, public unrest and social costs. These consequences can be quite substantial, and cost even more than the damage directly caused by the natural hazard. For example, the earthquakes of 5 March 1987 in Ecuador (Ms 6.9) caused the destruction of more than 40 km of the Trans-Ecuadorian Oil Pipeline in massive landslides triggered by the seismic activity. Approximately 100 000 barrels of oil spilled into the environment and the loss of revenue during the 5 months required for repair was USD 800 million, equal to 80 % of the total earthquake losses (NRC, 1991). Furthermore, if persistent or radioactive hazardous materials are also involved, environmental clean-up and restoration activities may require an exceptionally long time and enormous resources, as seen at the Fukushima nuclear power plant accident caused by the 2011 east Japan earthquake and tsunami.

Known as natural-hazard-triggered technological (natech) accidents, such cascading events are a recurring feature in many natural disasters, which affect industries and energy systems that store, handle, or transport hazardous substances. One noteworthy example in Europe is the 17 August 1999 Kocaeli earthquake (Mw 7.4), which resulted in many natech accidents with significant economic and environmental consequences. The earthquake, which was one of the most devastating natural disasters in the modern history of Turkey, caused about 17 500 fatalities, injured about 44 000 people, affected 15 million people and resulted in property damage totalling over USD 15 billion.

The affected area is one of the industrial heartlands of the country and is densely populated and heavily industrialised, accounting for 35 % of the gross national product (Özmen, 2000; Durukal and Erdik, 2008). The earthquake caused significant damage at numerous industrial facilities (Johnson et al., 2000; Rahnama and Morrow, 2000; Suzuki, 2002; Sezen and Whittaker, 2006; Durukal and Erdik, 2008), which led to many natech accidents ranging from small hazardous substance releases to enormous fires (Steinberg et al., 2001; Steinberg and Cruz, 2004). Among these events, two were especially noteworthy owing to their consequences: the huge fire at the Tüpraş İzmit Refinery in Korfez, Kocaeli, and the acrylonitrile spill at the Aksa acrylic fibre production plant in Ciftlikkoy, Yalova (Girgin, 2011).

Founded in 1961, the Tüpraş İzmit Refinery had 40 % of the refining capacity in Turkey and was one of the most advanced refineries in the Mediterranean region (Tüpraş, 2010). The fire at the refinery lasted for 5 days and could only be extinguished with international support (Danış and Görgün, 2005).

The Aksa plant, which was constructed in 1971 with a capacity of 5 000 tons per year, had a production capacity of 230 000 tons per year in 1999. Currently, it is the only acrylic fibre producer in Turkey and it is also the largest in the world, with a global market share of 18 % and an annual production capacity of 315 000 tons (Aksa, 2019). The spill of 6 500 tons of acrylonitrile, a highly flammable, toxic and carcinogenic substance, harmed domestic animals, affected agricultural activities, endangered public health and resulted in environmental pollution that required 5 years of continuous treatment for reclamation (Bayer, 1999; Zanbak, 2008).

Both events required the evacuation of the nearby settlements and hampered earthquake search and rescue operations. There were also considerable economic losses. In the case of the Tüpraş İzmit Refinery, the majority of the units were put back into operation within 3 months after the earthquake, but it required 1 year for all units to be functional. The total cost of restoration, including the oil spill cleanup, was about USD 58 million. However, the refinery also lost roughly 6 months of its crude oil processing capacity (4.6 million tons) during this period as operational losses (Girgin, 2011).

The Tüpraş and Aksa incidents showed that preparedness for large external events, considering the extraordinary and highly resource-limited conditions they cause, is critical to prevent and reduce the impacts on industries and energy production systems. Existing risk should be assessed taking into account temporal change due to factors such as climate change and ageing of the equipment; structural (e.g. strengthening of buildings) and organisational (e.g. training of personnel) measures should be implemented properly; and response and recovery plans should be prepared, periodically reviewed and practised. Sharing of information and involvement of public and other stakeholders in decision-making process are also crucial to limit consequences and increase resilience.

As for the lessons learned from the past natech incidents, analysis of historical incident data for selected industries shows that, although natech accidents occur less frequently than accidents from other causes, their economic consequences are more severe (Girgin and Krausmann, 2016). In fact, owing to synergistic and cascading effects among natural and technological hazards, natech accidents may result in complex consequences involving numerous hazardous events over large areas, damaging safety systems and barriers, and destroying lifelines needed for emergency management purposes. Therefore, it is essential to quantify the losses not only considering the direct damage, but also considering the cascading impacts. This can be challenging even for a single facility; hence, dealing with multiple facilities and mutual dependencies is a difficult task.

The main economic damage potential is attributable to fires and explosions, as they cause direct physical property damage. However, depending on the market dynamics, serious losses may also occur through business interruption even if the property damage is relatively minor. Occasionally, even the proximity of a hazard without any direct impact may lead to losses. For example, wildfires in British Columbia, Canada, in 2017 led the operators to temporarily shut down natural gas wells, pipelines and other facilities as a precautionary measure where wildfires came dangerously close to operations, leading to costly business interruptions (Marsh, 2018). The industry can transfer these risks to third parties using financial tools, such as insurance that covers the losses related to natural hazard impacts or business interruptions. But the coverage is usually limited and varies with estimated risk and existing RM practices (Olson and Wu, 2010). Safety expenditures are often not self-financing for low-probability high-impact risks such as natech risk. Therefore, in order to fill the existing gaps, some legislative or financial support might be necessary from the public authorities for the required prevention and mitigation measures (Girgin et al., 2019).

7 Conclusions and key messages

Disaster risks that manufacturing and energy industries face are rather wide-ranging. They can potentially trigger a disaster from internal causes, such as an industrial accident leading to air or water pollution, while they are also threatened by external risks, such as natural hazards and/or other companies' and/or industries' accidents. Furthermore, in some cases these industries can exacerbate disaster processes, resulting in natech events as discussed in the case studies above. Internal risks can be mostly treated through management strategies and technological means, whereas external risks are often difficult to predict. Integrating RM and BCM with their business operations can potentially reduce and/or mitigate risks, but it is still difficult and costly to prepare practically for infrequent but catastrophic events and their consequences. This type of event should be dealt with and prepared for by the public sector, i.e. various levels of government, through several means, such as regulations, subsidies, taxation, and so forth.

Some risk transfer mechanisms, for instance disaster insurance, should be considered together with RM and BCM. In the EU, disaster finance has been increasingly linked with insurance regulations (Botzen, 2013), climate change adaptation strategies (van Renssen, 2013) and a joint compensation scheme between Member States (Hochrainer et al., 2010). For developing such insurance mechanisms and joint compensation schemes for future disaster situations, detailed information on the probabilities of natural hazard occurrence and estimates of potential damage are essential (Jongman et al., 2014).

Because manufacturing and energy industries are a vital part of economies and because of the intersections of broad production factors (resources, intermediate inputs, labour, land, and money) across industries and over space, the implementation of RM and BCM requires a multidisciplinary perspective, involving engineers, management, finance, economists, and environmentalists. Since the higher-order effects could spread over an entire economic system in different ways, and in case environmental damage also results, it is vital to define, and potentially legislate about, to what extent these companies should be responsible in a disaster situation.

Policymakers

Policymakers should legislate and implement the countermeasures against disaster risks that these industries face both in the pre-event phase (regulations for handling hazardous material, pre-arrangement of compensation schemes, mandatory insurance, mandatory RM and BCM, etc.) and in the post-event phase (disaster relief, macroeconomic stabilisation, evacuation strategy, etc.), based on the findings and insights from scientific findings of disaster research.

Practitioners

Practitioners of risk management should support the efforts of these industries to install and maintain RM and BCM in each firm, encourage and help drills in the pre-event phase, and assist the operation of RM and BCM in .the post-event phase

Scientists

Scientists should work together in a multidisciplinary way to understand and anticipate the risks in these industries and provide perspectives and/or devise countermeasures that mitigate the risks and the consequences. More importantly, these four groups of stakeholders should work together to achieve the creation of a sustainable society and economy.

Citizens

Citizens need to be aware of the risks that these industries face and their impacts on society, and to understand how they can be affected both as workers (supply side) and as consumers (demand side).

In conclusion, each stakeholder has the following roles for dealing with the disaster risks that manufacturing and energy industries face.

More importantly, these four groups of stakeholders should work together to achieve the creation of a sustainable society and economy.

Conclusions

Every year, natural and human-made hazards cause sizeable damage and losses, the exact magnitude of which we do not know. Improving our understanding of the economic impacts of various hazard risks is fundamental for sound and evidence-based disaster risk management. This subchapter has reviewed the state-of-the-art knowledge, methodologies and practice of assessing damage and losses caused to residential building stock, agriculture, and industrial and energy assets.

Hazard risks are stochastic processes, which often are not stationary but respond to environmental changes, including climate change. Hazard manifestations of similar intensity and magnitude may result in different damage and losses, depending on circumstantial factors. The vulnerability and susceptibility to harm are also time-dependent, changing and evolving as our societies transform in demography, wealth, cohesion and use of technology.

Over the past few decades, disaster risk assessment has improved thanks to the advancements in high-performance computing, high-resolution topographic and other spatial data, a new generation of large-scale hazard and disaster loss/impact models, and high-resolution exposure datasets. An accurate spatial representation of exposure features such as residential and industrial facilities and assets, infrastructure, population density and gross domestic product make it possible to improve the estimates and spatial distribution of disaster impacts. Advanced quality and accessibility of Earth observation products, including from the EU's Copernicus programme, have led the way to coherent exposure and vulnerability data at continental and global scales.

Models and methods for assessing the economic damage to physical assets caused by various hazards are similar and rely on some relationship between the intensity of hazards – measured for example as floodwater depth, macro-seismic intensity, wave height or near-surface wind speed – and the vulnerability or fragility of the physical assets that is determined by their material and structural conditions (Huizinga et al., 2017; De Moel and Aerts, 2011). While the parameters of physical fragility are similar across the various hazards, their responses to various hazard intensities are different and need further study. The damage models typically rely on a monotonic function linking hazard intensity to damage in material and financial terms.

Recent analysis of a large empirical dataset of flood losses has revealed that this monotonic form may not always apply, and a beta function with bimodal distributions for different water depths may better explain the observed losses (Wing et al., 2020). Moreover, most damage models and studies fail to account for the functional interdependencies between various buildings, lifelines and transport infrastructure.

Models and methods used to assess the hazards' impacts on crop and livestock production have to deal with more complex and articulated relationships between hazard intensity and impact. The fragility of crops to extreme weather and climate-related events may not be constant over the various phenological phases. The damage revealed at the time of harvest reflects the cumulative impacts of various climate extremes and biological plagues suffered over the whole season, mediated by crop resilience and agronomic risk mitigation. Better computation and storage capacity have made it possible to advance coupled climate models and simulate climate extremes with higher temporal and spatial resolution. Still, some damaging local-scale extreme atmospheric phenomena such as frost and hail cannot be measured or simulated at a resolution that would be necessary for detailed damage assessment.

Assessment of damage and losses to industrial and energy production build upon and combine the approaches to address damage to physical assets, losses due to business interruption and systematic losses caused by the propagation of the initial impacts through a web of interconnected supply and transportation chains. The financial impacts consist of value of capital lost, recovery costs and opportunity costs. These impacts may set off supply and demand shocks that affect regional economies in and beyond the disaster-affected areas. The direct damage to tangible productive assets is equivalent to indirect economic losses caused by disruption of production webs, measured by flows.

The COVID-19 pandemic has taught a lesson about how closely environmental and human health are connected. What we have lived through during the lockdown, and still will, is a mild foretaste of the systemic shocks that climate and global environmental changes may and will cause in the future. Future improvements of risk assessment need to be focused on a better understanding of indirect and spillover economic losses generated by slow-onset hazards, compound risks and cascading risks, as well as losses caused by disruption of social networks, economic flows and ecosystem services. The EU Green Deal and the unprecedented post-COVID-19 recovery package will stimulate immense investments in green technologies and innovation, and lead the way to sustainable development and climate neutrality. Only with sound, evidence-based and multi-hazard risk assessments can we reconcile short-term 'building back better' recovery and medium- to long-term climate-resilient development.

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Introduction

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3.3.2 Agriculture

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Super Case Study

3

Eyjafjallajökull eruption in 2010

Online Version

Super Case Study 3:

Eyjafjallajökull eruption in 2010

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Petursdottir, G., Reichardt, U., Bird, D., Donovan, A., Gísladóttir, G. Hauksdottir A., Johannesdottir, G., Sigmundsson, F., Thordardottir, E.B., Ulfarsson, G.F., 'Eyjafjallajökull eruption in 2010', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

CONTENTS

1 Introduction

The effects of an eruption can depend more on the vulnerability of the man-made infrastructures and systems affected than on its geophysical size.

Iceland is a volcanic island in the North Atlantic Ocean, located on the ridge between the Eurasian and American tectonic plates. The area contains more than 30 active volcanic systems that generate relatively frequent eruptions. Many volcanoes are located under ice caps and can produce highly explosive eruptions when water interacts with magma, with plumes exceeding 12 km in height and fine-grained ash that can traverse great distances in the atmosphere. Eruptions have occurred in Iceland on average once every 3–5 years over the last four centuries (Thordarson and Larsen, 2007). These eruptions are usually moderate in size (VEI 1–3) ([1]) and have generally not caused significant harm beyond the island's borders. The most notable exception was the Laki eruption in 1783, which emitted vast amounts of SO2, which caused a drop in mean temperatures north of the equator, and besides its devastating effects in Iceland is believed to have markedly increased mortality in the United Kingdom and on the European continent (Grattan et al., 2003).

In comparison, the Eyjafjallajökull eruption in 2010 was small but its effects were large. The effects of an eruption can depend more on the vulnerability of the man-made infrastructures, systems and services affected than on the event's geophysical size. While no direct fatalities were attributed to the 2010 eruption, the travels of millions of people were disrupted as well as the transport of goods. Recent research links global warming and deglaciation with the possibility of increased generation of magma under Iceland (Compton et al., 2015), which could mean that an eruption similar, or larger, in size and impact could possibly occur on average once in every 7 years in the future, if all the magma were brought to the surface (Pagli and Sigmundsson, 2008). This super case study discusses local and international effects of the 2010 eruption, the measures taken to mitigate its effects, and recommendations on how to improve responses to future eruptions.

2 The Eyjafjallajökull eruption April – May 2010

Westerly and northerly winds prevailed, carrying ash towards mainland Europe.

Eyjafjallajökull, with its peak at approximately 1 660 m above sea level, is a moderately active ice-capped volcano with eruptive periods separated by hundreds of years of dormancy (Thordarson and Larsen, 2007). After an 18-year period of intermittent volcanic unrest, two eruptions occurred in 2010: first, an effusive lava-producing eruption from 20 March until 12 April 2010 on the eastern, ice-free, flank of the volcano, and, second, an explosive summit eruption taking place from 14 April until 22 May 2010 (Gudmundsson et al., 2012) (Figure 1).

The summit eruption had an initial phase of subglacial activity for a few hours during which cauldrons were melted into the ice by the eruption, creating floods of meltwater, known as *jökulhlaup*, rushing down the slopes of the volcano. *Jökulhlaup* is an Icelandic term that has been adopted in other languages to describe the glaciological phenomenon of a glacial outburst flood, triggered by a subglacial volcanic eruption or geothermal heating.

([1]) The volcanic explosivity index (VEI) is a logarithmic scale from 0 to 8 to describe the magnitude of explosive volcanic eruptions, including observations of volume of products and eruption cloud height (Newhall and Self, 1982). VEI 6 eruptions occur once or twice per millennium (Gudmundsson et al., 2008).

A catastrophic explosive eruption began when the magma had melted its way through the overlying ice cap. The VEI 3 eruption emitted a 5–10 km-high eruption plume of unusually fine-grained ash. The amount of erupted material has been estimated as the equivalent of 0.18 ± 0.05 km^3 of dense rock (Gudmundsson et al., 2012). Intense ash fallout occurred in inhabited areas in south Iceland, leading to total darkness during the periods of most intense tephra fall. Westerly and northerly winds prevailed during most of the eruption, carrying ash towards mainland Europe (Stohl et al., 2011; Woodhouse et al., 2013).

Figure 1. *Eyjafjallajökull volcano erupting on April 18, 2010.* ***Source****: photos courtesy of Gunnar Gestur.*

3 Local crisis

3.1 Crisis management

A trustful relationship has been built between scientists, officials, and the public.

An important factor in the management of natural hazards in Iceland is that one agency, the Icelandic Meteorological Office (IMO), leads the monitoring of all natural hazards, be it weather, floods, landslides and avalanches, earthquakes or volcanic eruptions. The IMO takes part in Iceland's emergency management both by giving advice to the Icelandic Department of Civil Protection and Emergency Management (ICP), which manages the response to all natural hazards, and by participating in the Civil Protection Scientific Advisory Board, which meets twice a year when no eruption is occurring but more often during eruptions. The board communicates its findings in a transparent and open way, reaching out to the public through the media. A trustful relationship has been built between scientists, officials, and the public (Bird et al., 2018).

Following signs of renewed activity in the beginning of 2010, authorities had been preparing for a potential eruption of the Eyjafjallajökull volcano. The National Commissioner of the Icelandic Police along with the ICP are responsible for disaster risk management at the national level and operate a National Crisis and Coordination Centre for emergency situations (Act on Civil Protection 82, 2008). In collaboration with local civil protection authorities the ICP had prepared contingency plans based on a hazard assessment for Eyjafjallajökull (Gudmundsson and Gylfason, 2005). These had been tested in a full-scale live evacuation exercise in 2006 (Almannavarnir, 2006)
.

When the summit eruption of Eyjafjallajökull started, the ICP had only just finished responding to a relatively ash-free eruption in a mountain pass on the eastern flank of Eyjafjallajökull. The ICP system had been fully activated from March 20th until April 12th, 2010, but mainly remaining on the *Alert Phase* ([2]). The response involved support and protection of thousands of travellers, who wanted to witness the small but spectacular eruption. The sudden and much larger explosive eruption in the Eyjafjallajökull summit crater on April 14th, 2010 called for an immediate activation of the ICP system only a day and a half after the flank eruption ended. An Emergency Phase was declared shortly after midnight and the ICP issued the highest priority evacuation orders for the immediate surroundings of Eyjafjallajökull. The Red Cross opened emergency shelters for evacuees in nearby villages. In the early morning, a glacial outburst flood started on the slopes of Eyjafjallajökull, roads were closed and access restrictions enforced around the eruption site. The dense ash made things difficult and the use of protection masks and safety goggles when outdoors was strongly recommended.

The ICP opened temporary service centres that served as one stop shops for locals that needed assistance. In the coming spring and early summer weeks, the local communities required much assistance due to copious amounts of ash and lack of pasture and hay for the livestock. It was vital to offer psychological, social, and economic support to those suffering, in an effort to secure their wellbeing. The National Crisis and Coordination Centre coordinated the disaster response dealing with not only national, but also global crisis communication, allocating resources and assisting the various stakeholders and government institutions (Bird et al., 2018). Even though the ICP was well prepared for the eruption, the large amount of airborne ash caused challenging international pressures that called for an exceptional disaster response. Because of the flight restrictions, the eruption developed into an international crisis that needed reactions that had not been anticipated in the contingency plans.

([2]) The levels, or phases, of the Icelandic Civil Protection activation are uncertainty, alert and emergency/distress (Regulation No 650/2009).

3.2 Community effects

Access roads and tracks should have been closed to all traffic to prevent sightseers risking their own lives and those of first responders..

At the time of the eruption, approximately 2 700 people were registered as living in the municipalities potentially affected by an eruption in Eyjafjallajökull. Sheep, cattle and horse farming were the most important livelihoods in the region, while many residents were also involved in tourism activities. When ordered to evacuate because of the potential risk from *jökulhlaup,* many residents were concerned about leaving their livestock unattended. Nevertheless, many people complied and, overall, officials considered the evacuations a success (Bird and Gísladóttir, 2018). A note is warranted here on the cooperation between locals and officials during evacuations in rural areas. When evacuating their homes, people put up a sign (coloured cardboard) in a window or other easily visible place, to be noted by their neighbours or other passers-by. The police monitor the main road junctions leaving the area and ask drivers what farms have put up the sign. This spares police the effort of having to visit every farm.

There were no fatalities or serious injuries caused by the jökulhlaup or the eruption. From a tourism perspective, many residents and rescue workers believed access roads and tracks should have been closed to all traffic to prevent sightseers risking their own lives and those of first responders, because many sightseers were ill prepared for the conditions. In fact, two people lost their lives to hypothermia after getting lost during a trip to view the earlier flank eruption.

It should be noted that, while the majority of residents evacuated, Bird and Gísladóttir (2018) found that almost half (47 %) did not, many because they needed to care for elderly family members or livestock or because they felt it was safer to shelter within their own homes. Some considered the evacuation orders irrelevant to them. Despite these issues, the community trusted those responsible for public safety. This trust stemmed from the ongoing and perceived honest communication between officials and residents well before the eruption commenced, during the initial small eruption in the mountain's flank, as well as during the more severe summit eruption. Officials also earned community trust by relaxing evacuation protocols and allowing farmers to re-enter the hazard zone for 2-hour periods each day so they could attend to their livestock.

While many people coped well with the eruption, their farming and tourism businesses did not fare as well. Farmland and livestock of roughly 120 farms were affected by the volcanic ashfall and glacial outburst floods (Thorvaldsdottir and Sigbjörnsson, 2015). A sharp drop in the number of inbound tourists to Iceland was observed in April and May 2010, which affected the local hospitality sector during that period. In the following years, however, the publicity received through the infamous eruption seems to have contributed to the start of an unprecedented tourism rise in Iceland, with a yearly increase of 16 % in 2011 and with the growth peaking at a 39 % year-on-year increase in 2016 (Icelandic Tourism Board, 2011, 2019).

3.3 Health effects

Residents who had been exposed to the eruption, and to the ongoing resuspension of ash in the period that followed, reported worsening of several health impacts

Natural-hazard-related disasters can have serious consequences at both individual and community levels, damaging the infrastructure of societies and causing suffering or death among those affected (Hansell et al., 2006). Previous research shows that individuals exposed to volcanic eruptions are at a greater risk of psychological (Araki et al., 1998; Warsini et al., 2014) and physical (Higuchi et al., 2012) morbidity than unexposed individuals in the short term, particularly those living in close proximity to the eruption. Studies assessing the long-term health effects of volcanic eruptions have been rare and the results inconclusive (Horwell et al., 2006, 2015). A series of studies were undertaken following the Eyjafjallajökull eruption to add to the understanding of the short- and long-term effects of a volcanic eruption on the local population.

A few weeks after the onset of the Eyjafjallajökull eruption, findings from a cross-sectional study, including 207 individuals living close to the volcano, indicated that short-term exposure was associated with upper airway irritation symptoms and exacerbation of pre-existing asthma, but it did not seem to contribute to serious physical health problems (Carlsen et al., 2012a). However, 39 % of individuals showed symptoms of mental distress, and parents reported respiratory symptoms and increased worry and anxiety among their children. Six to nine months following the eruption, a larger population-based questionnaire study, sent to 1 615 residents exposed to the eruption and a matching sample of 697 unexposed individuals, indicated that those living in the exposed area had markedly increased prevalence of physical symptoms, such as tightness in the chest, cough, phlegm and eye irritation, as well as psychological morbidity symptoms, compared with those unexposed (Carlsen et al., 2012b). This was more evident among those living closer to the eruption than further away. Another part of the study revealed that having suffered material damages or intense insecurity, having had a view of the eruption from their home or having had to stay outside during ashfall was highly associated with increased likelihood of adverse mental health outcomes, such as post-traumatic stress disorder (PTSD) or stress symptoms (Gissurardottir et al., 2018). A quarter of the inhabitants (26 %) reported having used the psychosocial support offered, and the vast majority (82 %) were satisfied with the support received (Thordardottir et al., 2018).

Three years after the Eyjafjallajökull eruption, the same individuals took part in a follow-up study. At this time, residents who had been exposed to the eruption, and to the ongoing resuspension of ash in the period that followed, reported worsening of several symptoms such as morning phlegm in winter, skin rash/eczema, back pain and insomnia. PTSD symptoms decreased during the 3-year follow-up, while levels of psychological distress and perceived stress remained similar (Hlodversdottir et al., 2016). In both surveys, in 2010 and 2013, parents were asked to answer questions about their children's health. According to their answers, children exposed to the eruption were more likely than non-exposed children to experience respiratory symptoms and anxiety/worries 6 to 9 months after the eruption (Hlodversdottir et al., 2018). Children whose homes were damaged in the eruption were more likely to be reported as having psychological symptoms, such as anxiety/worry and depressed mood, than children whose homes were not damaged. Alarmingly, parents did not report a significant decrease in their children's symptoms between 2010 and 2013.

3.4 Lessons learned

There is a need for an all-hazards approach to disaster risk reduction of volcanic eruptions, incorporating plans for medium to long-term recovery.

Locally, the 2010 Eyjafjallajökull eruption showed that, although physical and psychological effects of an eruption may seem relatively benign, health symptoms may still be prevalent years after the event. The Eyjafjallajökull eruption highlighted the need for an all-hazards approach to disaster risk reduction, incorporating plans for medium- to long-term recovery as well as the immediate response and early recovery phases (Bird et al., 2018). The findings on adverse health effects in the aftermath of the Eyjafjallajökull eruption in 2010 emphasise the importance of future research on the long-term health of those who are exposed to volcanic eruptions. This includes long-term studies, health monitoring, and development of efficient and accessible psychosocial treatment and support, especially for children and other vulnerable groups.

Furthermore, the event showed the importance of systematic and interdisciplinary preparations by civil protection and other responders such as the ICP. Open and transparent communication with multiple stakeholders is of prime importance. This needs to be organised and prepared, not least when the natural hazard turns out to gain international attention, as was the case with the Eyjafjallajökull eruption in 2010.

4. International aviation disruption

4.1 Regulation of volcanic ash and air traffic in europe prior to 2010

Volcanic ash risk was known and met with precautionary approach that did not match current air traffic and economic developments.

The 2010 Eyjafjallajökull eruption aroused international attention not because of its size as such, but because of an interplay of ash volume, winds and regulations that did not match air traffic developments and the interconnectedness of global supply chains. Although scientific findings indicating the risk posed to European airspace were available (IAVWOPSG, 2008), they were not used for risk characterisation in Europe. The European risk management approach to aviation and volcanic ash was not updated despite increasing air traffic volume, which turned the 2010 eruption of Eyjafjallajökull into an emerging systemic risk (Castellano, 2011). The lack of preparedness was further reflected in the lack of a coordinated approach between different transport sectors to absorb the shock caused to one mode of transport.

The impact of volcanic ash on jet engines has been recognised since the 1980s (Smith, 1983). The threat that volcanic ash poses to aircraft jet engines was brought home to the public and the aviation community when a British Airways B747 lost power on all four engines while flying through the volcanic ash cloud of Mount Galunggung, Indonesia, in the summer of 1982 (Smith, 1983; Tootell, 1985; Miller, 1994). Numerous encounters followed, including ones with engine damage (for an overview of known encounters until 2009, see Guffanti et al., 2010), some showing the still-potent effect of ash clouds that had travelled great distances from the eruption (Casadevall, 1994). After examining the threat from ash to aircraft, especially the observed immediate harmful impact of ash on jet engines, with resulting high maintenance costs and shortened lifespan of the engines, Casadevall (1993) states that the only way to manage the risk is a precautionary approach whereby aeroplanes avoid clouds of volcanic ash completely

Until 2010 the general guidance in Europe was, as it still is today in most parts of the world, to completely avoid airspace contaminated with volcanic ash (ICAO, 2007). It is assumed that potential personal, societal and economic losses of ash encounters (USGS, 2004) always outweigh the costs of rerouting or cancelling flights. In fact, little is yet known about the effects of different ash compositions and concentrations on aircraft. Although aircraft may manage to traverse ash-contaminated airspace, jet engines exposed to ash can suffer long-term damage that shortens their lifespan at considerable cost. Advice on the predicted ash contamination of airspace is issued by the Volcanic Ash Advisory Centres (VAACs) worldwide (Met Office, 2017). At present, VAAC forecast graphics indicate airspace with ash at selected densities or no ash, so that air traffic can be diverted to avoid encountering ash.

According to the regulations prior to the eruption in 2010, airspace in Europe could be closed by national authorities individually if conditions were deemed unsafe. At the onset of the Eyjafjallajökull eruption, the instructions of the International Civil Aviation Organization (ICAO) were zero ash tolerance (ash volumes < 0.2 mg/m^3). The decisions for air traffic are based on the ash dispersal modelling by the VAAC, which is further informed by ground-based monitoring measurements. When the London VAAC forecast the ash being blown towards Ireland and the United Kingdom, Irish and British aviation authorities started reducing air traffic and closing airspace, followed by similar actions by aviation authorities on the European continent (CAA, 2010).

4.2 Eruption impact on international air traffic and decision-making

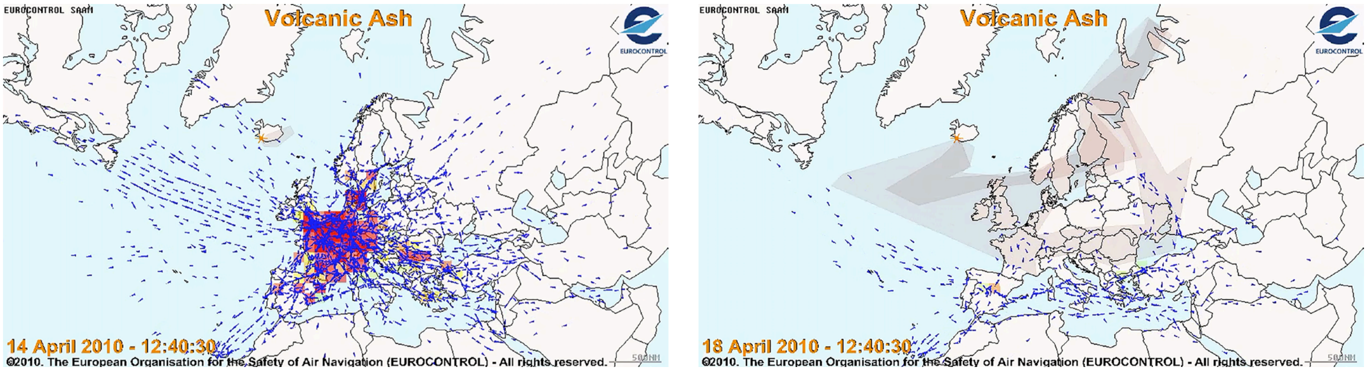
Amid individual national efforts, the crisis called for a coordinated European approach.

In April 2010, about 48 % of Europe's total air traffic was grounded during an 8-day period (Bye, 2011). In its cascading effects, the 'eruption of disruption', as it was called by Birtchell and Büscher (2011), affected individuals, businesses and institutions worldwide. The disruption drove African flower producers out of business, threatened lives through the delay of organ and bone marrow air transport in North America and northern Europe (CBS News, 2010; Alexander, 2013), and delayed industrial supplies between continents. From 14 to 21 April 2010 more than 100 000 flights were cancelled, with an estimated EUR 1.3 billion loss of revenue for the airlines (Bolić and Sivčev, 2011) and an 11.7 % decrease in air travel throughout the month for European air carriers (IATA, 2010). The event disrupted the travels of 10 million passengers and 40 % of cargo transport in Europe (Eurocontrol, 2010).

The amount of ash emitted by the eruption and its dispersion in the atmosphere, both actual and predicted, severely affected international aviation for weeks. The ash reached up to 10 km in the atmosphere and was carried by northerly winds towards Ireland, the United Kingdom and mainland Europe, where it impacted one of the most densely populated airspaces in the world. Airspace in Europe was closed on several additional occasions until the eruption ended in May 2010. The eruption is claimed to have caused the greatest disruption of air traffic since the Second World War, with an estimated worldwide loss of EUR 3.75 billion (Oxford Economics, 2010).

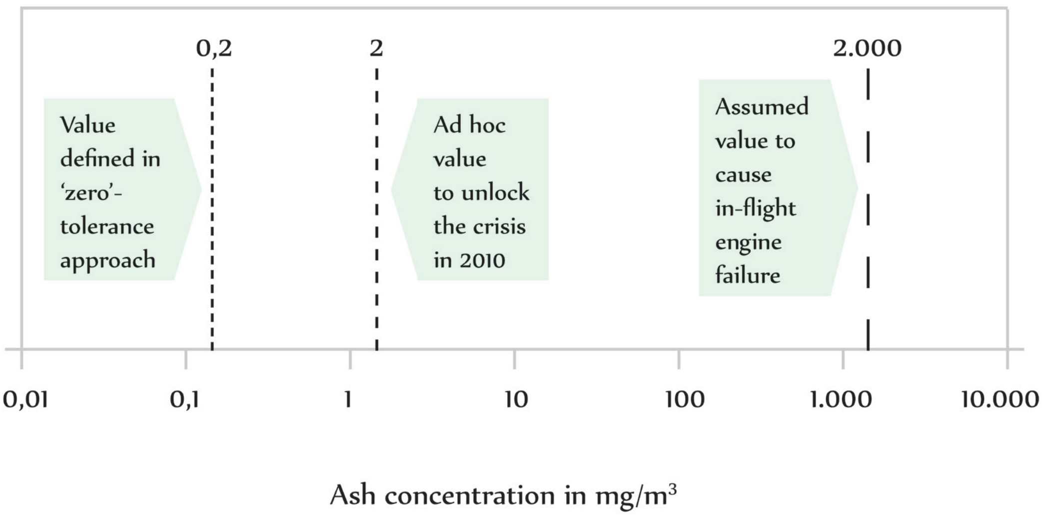
This unprecedented disruption led to a paradigm shift in European regulation and risk management regarding volcanic ash. Figure 2 illustrates the impact of the volcanic ash cloud on air traffic in Europe.

***Figure 2.** Effects of the volcanic ash cloud on aviation in Europe in April 2010: stills from a Eurocontrol video simulating air traffic in real time.*
***Source**: IVATF, 2010.*
***Notes:** The image on the left is from the onset of the eruption on 14 April, and the image on the right is from 18 April 2010. Blue dots indicate individual aeroplanes, while coloured squares represent space too densely populated with aeroplanes for individual representation. The grey area refers to the modelled ash dispersion issued by the London VAAC. Grey shades reflect different heights of the ash plume: light grey, up to 6 100 m; dark grey, up to 10 700 m.*



Three days into the airspace closures, the financial implications of the zero-tolerance response led to pressures for revision and a search for a safe solution that would allow airports to open again (Mazzocchi, 2010). In an effort to reopen British airspace, the UK Civil Aviation Authority sought to determine safe ash concentration thresholds. Scientists, air traffic managers, airlines and engine manufacturers were consulted to revise the ash thresholds while ensuring flight safety (Reichardt et al., 2017). Figure 3 presents a comparison of how the safe-to-fly threshold was changed in spring 2010 from 0.2 mg/m^3 to 2 mg/m^3. This value was later revised to 2–4 mg/m^3.

***Figure 3** Comparison of the ash threshold change during the 2010 Eyjafjallajökull eruption in Europe, in relation to ash concentration values assumed to lead to engine failure.. **Source**: Reichardt et al., 2017.*



Amid individual national efforts, the crisis called for a coordinated European approach. Without a designated regulatory body to manage such a move at an international level, committees had to be formed during the crisis. Days into the event, the European Commission asked Eurocontrol, the aviation network manager and organisation for the safety of air navigation, to provide regulators with suggestions on how to solve the crisis (Alemanno, 2010). Eurocontrol proposed to introduce areas of different ash concentration levels in which the operation of air traffic is possible, provided that specific inspection and maintenance requirements are fulfilled. The decision to fly through these designated zones was left to the aircraft operators (European Commission, 2010).

4.3 Crisis management: regulatory actions and scientific support

The event emphasised the need to build broader frameworks for scientific cooperation to coordinate knowledge and support decision making regarding ash and aviation.

The risk to aviation from volcanic eruptions in Iceland has been known by different entities within the scientific community for many years (Thorarinsson, 1981; Oppenheimer, 2010) but was not included in states' emergency plans across Europe. The Joint Research Centre (JRC) in Brussels similarly had not previously worked on the threat of volcanic ash and had little internal expertise on this issue (Donovan, 2019). An overarching structure to connect different voices in the scientific community with each other and with members of the aviation community and policy-makers was missing. Internal government exercises, such as the United Kingdom's horizon-scanning exercises to identify potential future threats, did not typically include academics (Miles, 2005). Thus, although authorities had been made aware of the threat, the event was not anticipated by the industry as a whole and this made the response reactive (Alexander, 2013).

During the crisis, scientific advice was requested on two fronts. On the one hand, modellers and experts in space- and ground-based monitoring from the fields of volcanology, meteorology and atmospheric dispersion were consulted regarding volcanological input parameters and the accuracy of the European ash dispersion model. On the other hand, engineers' advice was necessary to define how much ash jet engines could take without lasting damage or catastrophic failure. Scientific input from different fields and countries significantly helped to unlock the crisis (Reichardt et al., 2017), yet the event emphasised the need to build broader frameworks for scientific cooperation to coordinate knowledge and to support decision-making regarding ash and aviation.

The Secretary General of the ICAO formed the International Volcanic Ash Task Force (IVATF) in May 2010. The IVATF reviewed the response to the Eyjafjallajökull 2010 eruption, assessed areas of improvement regarding volcanic ash and aviation, and defined actions needed to address aviation risks (WMO, 2012). The group consisted of a multidisciplinary team of experts working in subgroups on atmospheric sciences, airworthiness, air traffic management and international airways volcano watch coordination (WMO, 2012). The aim was to establish guidance for further research, issue recommendations for risk management and deliver 'new tools to counter future volcanic ash events' (ICAO, 2012b). The group delivered a final report in 2012, and further work is being carried out by the International Airways Volcano Watch Operations Group as well as other ICAO groups (WMO, 2012). Information provisions include developments in scientific research and modelling, and inclusion in the system of decision-making, as stated in the IVATF report (ICAO, 2012b).

Following the Eyjafjallajökull 2010 eruption, the European Aviation Crisis Coordination Cell (EACCC), with Eurocontrol as chair, was created to facilitate a coordinated European approach to aviation crises in the future (Bolić and Sivčev, 2011). The function of the EACCC is to manage and coordinate actions when circumstances disturb normal aviation operations. It provides a platform to collect and distribute information, suggests solutions to support regulators and decision-makers, and implements decisions made. The coordinating body consists of a variety of European stakeholders, such as representatives from the EU Member State holding the presidency of the European Council, the European Commission, the European Union Agency for Aviation Safety, national militaries, national air traffic managers, airports and airspace users, and national agencies with connections to national crisis management as well as experts on the nature of the crisis (Eurocontrol, 2020).

Since 2010, much work has been done to improve the inclusion of science in policy-making and to strengthen links between volcanologists in key institutions across Europe. Since the Eyjafjallajökull 2010 eruption, scientists have built a new connection with operation service providers from the VAACs to join forces in advancing knowledge of ash characterisation and modelling of volcanic ash plumes (Reichardt et al., 2017).

The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and the World Meteorological Organization (WMO) organised the IAVCEI–WMO workshop in 2010, the first to bring scientists from various fields together with experts from the London VAAC. Specialists in modelling and space- and ground-based monitoring from the fields of volcanology, meteorology and atmospheric dispersion met to discuss ash grain-size distribution, volcanic mass eruption rates and plume height, uncertainties of prediction models, and the ash particle aggregation to be taken into account in models (Bonadonna et al., 2012). Whereas this first workshop initiated communication about technical aspects and spurred a number of new research projects, the second workshop, in 2013, was more political, including how to institutionalise the cooperation and strategies for operational implementation of scientific findings (Bonadonna et al., 2014). The WMO SCOPE Pilot Project 2, 'Advanced Nowcasting for Aviation', organises meetings to foster exchange between institutions to keep track of the international state-of-the-art developments in volcanic ash cloud detection and monitoring equipment (WMO, 2019).

Within a few days of the eruption in 2010, scientific advice helped revise ash thresholds that had been in effect globally for more than a decade (Bolić and Sivčev, 2011). Such cooperation between policymakers and (regulatory) scientists can, however, cause problems. It may lead to loss of credibility, as the public tends to fear that short-term political agendas may reduce the integrity and quality of experts' advice. Similarly, the shift of decision-making from aviation authorities to aircraft operators based on scientific advice during a crisis could have a negative impact on the public's trust.

A study of UK residents in 2012 showed that airlines were better trusted than the media, social networks, or friends and family concerning the risk from ash and believed to have a similar level of accuracy in their judgements to that of the UK government (Eiser et al., 2015). However, it was also found that the airlines were regarded as much more likely to underestimate the risk. This might reflect the effect of comments given by impatient airline chief executives during the crisis, as well as an awareness of the cost issues facing airlines with grounded flights (Eiser et al., 2015). It suggests that the public may not fully trust aircraft operators to be the sole decision-makers. Transparency in safety risk assessment procedures, prior to an eruption, may be necessary to ensure trust in decision-making. It may be pointed out that aircraft operators are already trusted to make similar fly or no-fly decisions regarding several other safety factors, such as inclement weather. Research has also shown that the high repair and maintenance costs of engines congested with volcanic ash can lead airlines to take a rather conservative stand when it comes to volcanic ash (Reichardt, 2018).

Although procedures have been greatly improved since 2010, much needs to be done to better understand the relationships between policy, public trust and risk management.

4.4 Lessons learned

Trust needs to be built between advisors and policymakers prior to crises.

Although the 2010 eruption in Eyjafjallajökull was geophysically moderate in size and local consequences, it had a major effect on international aviation, disrupted the travels of approximately 10 million people and delayed the transportation of goods. Yet airspace closures only lasted for a few days. Larger volcanic events, up to VEI 6, may occur, and volcanic events may possibly occur with greater frequency in the coming decades, as studies suggest (Compton et al., 2015). Thus, the most important aspect of the Eyjafjallajökull eruption may be to serve as a wake-up call.

Internationally, the Eyjafjallajökull 2010 eruption led to increased awareness of the threat of volcanic ash to air traffic in Europe. Since then, numerous advances have taken place in research, regulation, and cooperation (Bolić and Sivčev, 2011; Ulfarsson and Unger, 2011; Reichardt et al., 2016, 2017). Research cooperation was established between airlines and private businesses to test on-board measuring devices for volcanic ash, such as AVOID (Prata et al., 2016) or ZEUS (Clark, 2014), to avoid ash-contaminated airspace.

According to the updated regulations and procedures, most of the European airspace now remains open and the relevant aircraft operators decide whether to fly or not (Reichardt et al., 2017). For aircraft operators to decide whether or not to fly in ash-contaminated airspace, a safety risk assessment (SRA) must be in place, stipulating safety procedures when encountering volcanic ash in flight. The SRA must be approved by the operator's national aviation administration for the operator. As of November 2016, the majority of European nations mutually recognise the SRA.

A number of studies have been conducted to improve the understanding of ash characterisation, modelling of the volcanic ash plume and the atmospheric environment (see e.g. the special issue in the Journal of Geophysical Research: Atmospheres in JGR, 2012; Langmann et al., 2012). The cooperation within the scientific network has been expanded through workshops that facilitated exchange between neighbouring research fields (Bonadonna et al., 2012, 2014). The level of communication, e.g. between information providers in Iceland and the United Kingdom, has been elevated, and institutional staff exchange supports a trustful environment for effective interaction (Reichardt et al., 2017).

To practise and adapt volcanic ash contingency plans and procedures, an annual volcanic ash exercise has been introduced and is run by ICAO. A volcanic ash scenario is simulated to practise the emergency with the EACCC, service providers, regulators and aircraft operators during a 2-day exercise (Easa, 2011). The exercise focuses on the air traffic response to the onset of a volcanic eruption with ash emission. Since the 2010 eruption in Eyjafjallajökull, the ICP has prepared contingency plans for different types of volcanic eruptions to deal with the response to ash, toxic gas, lava and *jökulhlaup*.

Thus, the Eyjafjallajökull eruption in 2010 led to several advances in the management of volcanic ash and air traffic. While the regulatory framework has been well established formally, and exercises and coordination have improved, there is potential for further lessons to be learned (Reichardt et al., 2018).

Volcanic eruptions can affect air traffic beyond the initial phase, as the 2010 Eyjafjallajökull event demonstrated. Eruptions of greater volume and duration than in 2010 can have a severe and long-lasting impact on European air traffic, as a scenario analysis of a hypothetical VEI 6 eruption of the Öræfajökull volcano in south-east Iceland showed (Reichardt et al., 2019). Potential responses still need to be determined and practised (Alexander, 2013; Reichardt, 2018).

A smooth transfer between transportation modes benefits from preparation and coordination in advance to determine the additional resources needed. This means timely information flow to and from other transportation agencies and partners in order to enable them to plan and respond to a crisis in a coordinated fashion. Broadening the partnership and enabling a coordinated execution of the response to impactful eruptions will simultaneously strengthen trust in decision-making, because such exercises can improve preparedness and leadership (Reichardt et al., 2018, 2019).

To save time and effort, governments and academics need to become better at engaging with each other, particularly in anticipation of future potential risks. Trust needs to be built between expert advisors and policymakers prior to crises. Governments and other responders need established connections with the right experts to communicate effectively in times of crisis. A platform is necessary to enable information exchange between the different sectors involved. Multi-stakeholder workshops using worst-case scenarios of volcanic eruptions have proven to be successful in bridging the knowledge gap between information providers, operators and decision-makers and in creating connections for them to interact in a timely manner in times of crisis (Reichardt et al., 2019).

5 Conclusions

The ash from an Icelandic eruption has the potential to interfere with several intercontinental flight corridors for goods and passengers, affecting economies worldwide. In the light of a potentially much larger eruption in the future, the case study of the 2010 Eyjafjallajökull eruption emphasises the need for national and international efforts to be strengthened. Locally, the importance of trust and cooperation between the public and various sectors of civil protection cannot be overestimated. Systematic exercises, planning and consultation of different stakeholders must be maintained in times when no eruption is occurring. Long-term support and follow-up of potential health effects, both physical and psychological, need to be built into the response system. On a cross-border scale, international agreements and protocols are urgently needed to manage volcanic eruptions with widespread ashfall.
The following recommendations should be taken into consideration to better prepare for future eruptions, at both local and international scales (Reichardt et al., 2018).

- Research funding: To support informed decision-making on how to mitigate the adverse effects of volcanic eruptions, more research is needed on all fronts. Regarding aircraft operators, further research on volcanic ash and jet engines is particularly necessary to improve understanding of the limits for safe operation of jet engines in ash-contaminated air.

- Operational experience and research. Involving potential users in exercises helps when evaluating their needs, as well as the need for further research. To better accommodate user needs through research, the capacity for research work within operational work should be increased or closely linked to external research institutions.

- Long-term contingency planning: Effects of longer-lasting eruptions need to be considered and prepared for, locally and internationally, within and beyond the aviation network.

- Improved exercises. New response exercises must avoid training for a previous event. Rather, the exercises should be novel and challenging and drive the stakeholders out of their comfort zone.

- Communication. Direct communication between stakeholders should be improved to align products with end-user needs and address uncertainties in datasets and forecasts. Crisis management would benefit from a designated single point of information. It has yet to be discussed whether or not this single point of information should serve for public information as well.

- Staff funding. The staff capacity of agencies under accelerated demands creates a bottleneck for adequate responses. To mitigate work overload, the staff must be sufficiently trained, and provisions made to access additional staff if needed.

- Involve other modes of transportation. A framework is needed to coordinate information exchange between different transportation networks, i.e. air-, land-, and sea-based transportation.

- Regulatory alignment. Alignment of regulations, and not least the application of the SRA, would improve coordination between stakeholders and allow a smoother response.

The most important measure to strengthen societies' resilience to volcanic ash is to think further. This means developing contingency plans that can handle events of truly long duration, when air traffic is effectively halted for months, not merely a few days. An important part of such preparations is to expand the network of stakeholders managing the threat of volcanic ash, to include other modes of transport, on land and sea. Other transport systems can mitigate the systemic risk, economic loss and inconvenience due to delayed or cancelled flights for passengers and goods. They should be included in risk management processes.

Lastly, a key improvement is to strengthen the exercises and prepare for more unexpected events. The exercises need to be based on larger events and designed to surprise and stress-test the response systems. When time passes and the last event becomes an increasingly distant memory, it is harder to draw stakeholders to the table to participate in possibly costly exercises and contingency planning. It is crucial to maintain stakeholder interest in the topic. For that to occur, it is imperative that stakeholders see realistic benefits from taking part in exercises and planning efforts.

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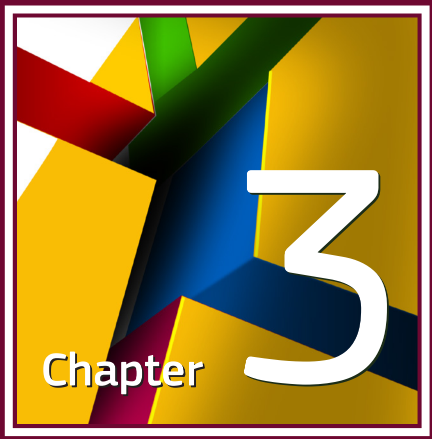

Assets at risk and potential impacts

3.4

Critical infrastructures

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Agius, J., Karagiannis, G.M., Pescaroli, G., Galbusera, L., Theocharidou, M., Krausmann, E., Chaudhari, K., 'Critical Infrastructures', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

3.4 Critical Infrastructures

CONTENTS

3.4 Critical Infrastructures

Introduction

Critical infrastructure (CI) provides the essential services that underpin modern societies and support national economies. CIs are complex, adaptive, sociotechnical and highly interdependent systems that can fail less predictably than our technological prowess allows for. Moreover, CIs are most often designed in a fragmentary manner, the design of each system considering a mere fraction of its interactions with other systems. Urban populations rely heavily on critical infrastructures, making their protection a major issue, particularly for megacities.

The strategic importance of some assets of the built environment, such as aqueducts and roads, has been known at least since Roman times. As our society evolved and developed an industrial economy including a system of production, our consumption and day-to-day activities are more reliant on technology, long-range supply lines and interconnected networks with the result that our contemporary society, is more vulnerable to the impact of potential disruptions'. Conducted pursuant to a directive by President Franklin Roosevelt, the United States Strategic Bombing Survey estimated that the Second World War air raids would have been more effective if they had targeted electricity-generating plants instead of urban and industrial areas (Air University, 1987). This chapter focuses on CI, construed as 'The physical structures, facilities, networks and other assets which provide services that are essential to the social and economic functioning of a community or society' (UNDRR Glossary, 2017, p. 12).

The national definitions of CI and related sectors have changed over time in response to the complexity of the built environment and society, and changes in strategic needs (Lazari, 2014). The definition of CI has evolved throughout history. For example, power plants were considered in this category during the Cold War, and received more attention in the late 1990s during the Clinton administration, which recognised this trend through Presidential Decision Directive PDD-63 (White House, 1998). Some key events have pushed and pulled practitioners towards a new approach to CI protection. These include the renewed attention to terrorist threats, following the attacks in New York (2001), Madrid (2004) and London (2005), as well as major disasters such as the Indian Ocean tsunami in 2004 and Hurricane Katrina in 2005 (Lazari, 2014). Resilience of CIs includes considerations of their physical, informational, cognitive and social domains, because their technological components cannot be separated from the wider implications of dealing with disruptions (Linkov et al., 2014).

In the EU, in June 2004, the European Council called for the preparation of an overall strategy to protect CIs in Europe. On 20 October 2004, the Commission adopted a communication on critical infrastructure protection (CIP). The communication put forward suggestions on how to enhance European efforts to prevent, prepare for and respond to disruptions to CIs resulting from terrorist attacks. In December 2004, the Council endorsed

the intention of the Commission to propose a European Programme for Critical Infrastructure Protection (EPCIP). In November 2005, the Commission published a Green Paper on the EPCIP. The Green Paper presented a combination of measures intended to be viewed as complementary to CI national efforts at the time. On 12 December 2006, the Commission issued a communication on the EPCIP. In its communication, the Commission set out an overall policy approach and framework, including an action plan for CIP in the EU (European Commission, 2006).
Following the creation of the programme in 2006, the Critical Infrastructure Warning Information System (CIWIN) and the CIP expert group were established. In December 2006, the Commission published a proposal for a directive of the Council on the identification and designation of European CIs and the assessment of the need to improve their protection.

Council Directive 2008/114/EC was adopted on 8 December 2008 (EU, 2008). It establishes a procedure for identifying and designating European critical infrastructures (ECIs) and a common approach for assessing the need to improve their protection. Article 3 of the directive limits its scope to the energy and transport sectors while providing for the eventuality of considering the inclusion of subsequent sectors at a later review stage.

The directive defines a critical infrastructure as 'an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions' (Article 2).
In simple terms, a CI is an asset, system or part thereof that if disrupted for any reason can bring a Member State to its knees. Hence the importance of protecting CIs. What emerges from the definition of a CI as depicted in the directive is the association of the physical disruption of a CI with the loss of functional assets in society.
Moreover, the directive identifies European critical infrastructures. The definition of an ECI introduces the cross-sectoral elements and cross-border dependencies of disruption associated with those elements whose disruption engenders consequences in two or more EU Member States. (Article 2(b)).

In its EPCIP, the European Commission encourages all Member States to include in their programmes the impact of CI disruptions in terms of scope, severity, population affected, economic losses, environmental effects, political effects, psychological effects and public health consequences (European Commission, 2006, p. 7).

No CI operates in isolation. As a result, a disruption within one CI can trigger cascading effects on related, associated and other relevant assets and/or systems. Cascading effects can be defined as 'the dynamics present in disasters, in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that result in physical, social or economic disruption. Thus, an initial impact can trigger other phenomena that lead to consequences with significant magnitudes'.

Cascading effects can result in 'cascading disasters', whereby secondary emergencies can be caused by existing vulnerabilities (Pescaroli and Alexander, 2015, p. 64). These can quickly become the centre of a crisis and can challenge the coordination of emergency relief and long-term recovery. Cascading effects raise issues of interdependencies whereby 'new and emerging threats faced by critical infrastructure assets and systems, in conjunction with the interdependencies among them at national and European level, makes it virtually impossible to keep addressing critical infrastructure safety in the traditional, hazard-based way (Agius et al., 2017, p. 387).

Experience from recent disasters, together with the scientific literature, has provided evidence of the dependencies among critical infrastructures, highlighting pathways of cross-sectoral and cross-border failures. The next sections analyse how critical infrastructures shape the disaster risk environment of communities and nations. The focus is on the vulnerabilities generated by the increasing reliance of modern economies on critical infrastructure, the challenges of interdependent systems, the options for building resilience into the design of such systems, and the need to pay particular attention to infrastructure in comprehensive emergency management, including mitigation, preparedness, response and recovery. The ultimate goal of this subchapter is to broaden the understanding of current and future risks related to critical infrastructure, thus contributing towards a more resilient and sustainable Europe.

Section 3.4.1 provides an analysis of the essential concepts and the challenges associated with organisational resilience and continuity management for emergency facilities. Emergency services are complex sociotechnical systems spanning all levels of government and include a wide range of facilities, personnel, plans, equipment and organisational arrangements. The role of emergency facilities in the disaster cycle is elaborated through their operational obligations in a European context while they also need to ensure the sustainability of mitigation and response. The procedures and practices that create operational resilience are then defined, explaining how cascading effects can affect the resilience at the organisational level and the level of individual operators. The section concludes by providing a set of examples and lessons learned, integrating them into practical advice and guidelines for continuity management and policies formulated in order to reduce vulnerability and increase flexibility during worst-case scenarios.

Section 3.4.2 discusses networked infrastructures, that is, those systems made up of interconnected assets distributed over a large geographical area, or those with numerous interacting components and functions. The centrality of these networks provides some degree of resilience by design. However, it is due to this network centrality that fragilities are not only intrinsic to each technological layer but can manifest at the boundaries among systems. Therefore, networked infrastructure systems can be channels for the propagation of disasters' consequences, mediators of mitigation actions or both. Considerations from cases in which natural hazards or human acts caused significant impacts are used to illustrate these attributes. Situations in which intrinsic network failures resulted in unprecedented consequences are also considered.

Among all critical infrastructure sectors, electric power is a cornerstone of modern economies. Electricity is ubiquitous in the daily lives of European citizens and spans all sectors of the European economy. In addition, all critical infrastructure systems depend, to a greater or lesser extent, on the reliable delivery of electricity. Long-term power outages can slow down disaster recovery efforts and severely disrupt the economy of affected communities (Karagiannis et al., 2017). On a similar note, transport networks are expansive, open, accessible and interconnected systems, the sheer size and capacity of which move, distribute and deliver billions of passengers and millions of tonnes of goods each year across Europe. Transportation becomes a critical issue when aid and resources need to be channelled quickly and efficiently in disaster-affected areas. Yet these systems are exposed and vulnerable to all types of human-made and natural hazards. The authors of Section 3.4.2 focus on exposure mitigation, with the objective of identifying gaps and describing lessons learned, which lessons may be relevant to risk analysis and the management of future crisis scenarios.

Section 3.4.3 addresses risks to society and the environment from damage to core industrial and energy facilities due to human-made and natural hazards and how these impacts can be prevented or reduced in the future. Using case studies, the authors highlight how communities can be affected by such incidents, including via cascading (also referred to as 'ripple') effects due to interdependencies between systems and sectors. Examples of solutions for improved risk and impact mitigation based on lessons learned from past events are then provided. Practices and actions for the different stakeholder groups (policymakers, practitioners and scientists) are proposed, and how the citizens can better understand and be involved in related risk reduction is also discussed.

Lastly, Section 3.4.4 discusses the role of communication systems and their varying degrees of responsibility for the transfer of information of differing levels of criticality. Establishing and sustaining interoperable communications is a critical prerequisite for emergency response. Failures in communications systems have often been blamed for several challenges in emergency response. Also discussed are considerations of information and communication systems as critical infrastructures themselves. Rapid advances in technology are noted in the context of the rapidly developing communication systems and services and the advent of fifth-generation mobile technology. Because of the potential for information isolation, the dependency of European societies on information and communication systems is an essential element of the societal impact of the digital divide. In addition, cybercrime and cyberterrorism are opening up new disaster scenarios, which could range from local to global and from minor to catastrophic. The potential failure of communication systems can easily have cascading impacts on other critical infrastructures. Two case studies are featured, with concluding remarks on what measures are essential for the appropriate operation and use of communication systems in building resilience with a view to protecting CIs.

3.4.1 Emergency infrastructure and facilities

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Pescaroli, G., Alexander, D., Murray, V., 'Emergency infrastructure and facilities', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Introduction

Emergency facilities and infrastructure are essential assets for society, but they need to maintain their resilience and operational continuity.

Emergency facilities and infrastructure (EMFIs) are essential components of society's mechanism, as they can make the difference in addressing crises. For example, fire engines, police cars or ambulances deploy from a backbone of stations and coordination centres that have the duty to respond to adverse conditions that could disrupt the functions of a community. EMFIs are part of the vital networks and assets that allow the delivery of emergency services, which are defined by the United Nations Office for Disaster Risk Reduction as 'a critical set of specialised agencies with specific responsibilities and objectives in serving and protecting people and property in emergency situations' (UNISDR, 2017). They include first responders, such as fire service personnel, police, primary healthcare operatives, civil protection responders and local authority workers.

Their structures, jurisdictions and organisation depend on national legislations and regional contexts. EMFIs are intended to be highly resilient, and they can often be seen as strongholds designed to withstand all levels of external (operational) and internal (organisational) pressure. They should have reliable emergency and operational continuity plans to help them avoid failures that could potentially compromise the delivery of relief (Lindell et al., 2007; Alexander, 2016). However, this is far from being the whole truth. If there are gaps in their preparation strategy and if some threat has been underestimated, they can be disrupted and the whole emergency sector may be affected, leading to hiccups in emergency support.

At the international level, emergency facilities have been mentioned in some major global agreements that provide guidance for policies and practices, such as the Sendai framework for disaster risk reduction (SFDRR). This has been adopted by UN Member States as a follow-up to the Hyogo framework for action, and it includes seven targets and four priorities areas intended to 'prevent new and reduce existing disaster risk' (UNISDR, 2015). The SFDRR identifies key actions on emergency facilities to be taken within multiple priority areas.

The reality in which EMFIs operate has evolved as technology has developed, and this chapter provides a basic understanding of the new challenges to their operational continuity and organisational resilience. The next subsections will identify possible guidelines for management designed to ensure that lifelines can respond to complex events. First, they introduce the operational role of lifelines in the disaster cycle. Secondly, they explain some key challenges to organisational resilience. These are clarified using case studies and examples. In conclusion, the chapter defines how to adopt practical steps to increase operational continuity and organisational resilience. For feasibility, the focus is on those facilities and infrastructure involved directly in the management of events and does not include those that can be used for emergency evacuation or shelter, such as education facilities (Lindell et al., 2007; Alexander, 2016).

2 Role in the disaster cycle

Emergency facilities and infrastructure are essential in all phases of the disaster cycle, but their operational context changes and needs to be understood.

According to both scholars and practitioners, there are phases in the process of dealing with disasters (Coetzee and Van Niekerk, 2012). These are usually considered to be mitigation, preparedness, emergency response, recovery and, in some approaches, reconstruction. The cycle has considerable utility in both planning and teaching or training. However, not all scholars and practitioners accept it.

For example, Neal (1997) observed that the phases might not be fully consecutive. Kates and Pijawka (1977) also noted the overlap between parts of the cycle. Historically, there has been an emphasis on the emergency response phase, but it is not the only element to consider in crisis management.

EMFIs are not only the hub of response activities, but they are also the natural home of various forms of planning, including those that pertain to hazard and risk mitigation, and to recovery of basic assets and infrastructures. The natural hub of operations varies from one country to another, depending on which is the lead agency and how interagency relations are organised in the national system (Alexander, 2007).

For example, in the United Kingdom the lead agency is often the police force, as emergencies have traditionally been considered to be a matter of public order. In Germany and Italy, it is the fire service, as technical rescue and scene management dominate the early stages of emergency intervention. Dynamic forces such as globalisation, urbanisation and just-in-time economics have helped change the landscape in which EMFIs operate and are maintained (Helbing, 2013; Linkov et al., 2014; Alexander, 2016).

For example, tools such as the Global Positioning System (GPS) and other global navigation satellite systems have been used intensively to improve the coordination and deployment of resources, but they have also created a network of hidden interdependencies that could compromise operation capacities if they are not mitigated (Pescaroli et al., 2018). Similarly, budget cuts have created the conditions for the development of more effective procedures but have also compromised the redundancies and buffering options that are essential safeguards in this sector.

Wherever a nation's emergency response system is placed on the continuum from command and control to cooperation and collaboration, the functionality and sustainability of the system depend on how it performs under pressure. Planning and redundancy are two of the possible solutions, but both are expensive, and EMFIs easily become a target for cuts in times of austerity.

3 Challenges for operational continuity and organisational resilience

Cascading effects and compounding dynamics can challenge the organisational resilience and operational continuity of emergency facilities.

The capacity of EMFIs to maintain the continuity of operations presents multidimensional challenges in contemporary disaster management, which is distinguished by the presence of complex scenarios (UNISDR, 2017). Indeed, organisational resilience goes beyond the functionality of buildings hosting vital assets or services, including also the interrelation between technological and societal drivers (Hellstrom, 2007; Sommer and Brown, 2011). Three main dynamics have to be considered as key emerging challenges to be integrated into policies and planning strategies in the future.

(a) Direct involvement of EMFIs at the 'epicentre' of a crisis. Increased urbanisation, diffusion of vulnerability in the urban environment and climate change make it likely that buildings are in areas that are at risk from primary threats such as flooding or heatwaves (Birkmann et al., 2014). The high degree of reliability required of structural mitigation measures and safety practices, and the changing patterns of urban vulnerabilities may lead risk to be underestimated. For example, this may be the case for command centres located in floodplains or near sites that become possible terrorism targets when the security environment changes, as happened in 2017 to the London Fire Brigade, whose headquarters are located near the site of the London Bridge attacks of that year.

(b) Impact on EMFIs of cross-sectoral cascading effects. Instead of being stabilised by the mobilisation of emergency resources, the crisis escalates as time progresses, and spreads because of the innate vulnerability of society and the disruption of interconnected infrastructure nodes (Pescaroli and Alexander, 2018).

(c) Complex scenarios and compound and interacting drivers, such as the concurrence of natural hazards. This refers to the concurrence of two or more events that are extreme either from a statistical perspective or by being associated with a specific threshold (Field et al., 2012). For example, demand on EMFIs may increase because of wildfires during a heatwave or drought. Other elements of complexity can be referred to interactions between hazards, for extreme heat triggering an avalanche, or earthquake triggering a tsunami (Pescaroli and Alexander, 2018).

The next two subsections will develop points (b) and (c) further, as their implications for organisational resilience are more complex to understand.

3.1 Impacts on EMFIs of cascading effects

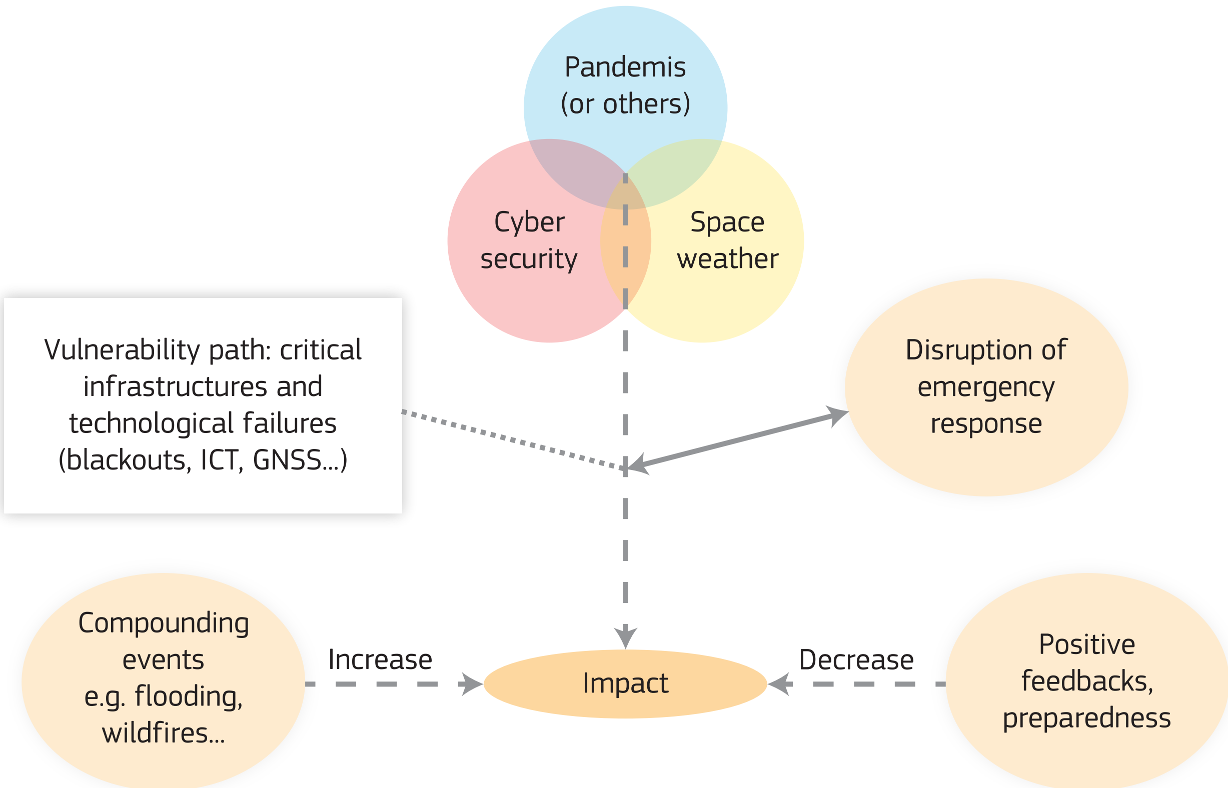
In general, when disasters and crises are triggered, increased pressure on EMFIs can be always be observed. However, their organisational resilience and operational continuity can be challenged by cascading effects that originate in other infrastructure sectors. This can arise as a result of multiple shortfalls of vital supplies, such as electricity, petrol, food, water, hygiene, drugs and personal communication systems. For example, power failures can reduce the energy available for operations, creating both communication disruptions that compromise the internet and transport disruption affecting logistics (Petermann et al., 2011; Van Eeten et al., 2011).

Preparedness for multiple failures can be underestimated or neglected owing to the complexity of the interrelationships that need to be taken into account in planning (Alexander, 2016). For example, changes in the working environment associated with flexible hours, and the evolution of the urban landscape due to inequality or gentrification, may lead to understaffing of command centres in scenarios of public transport failures. In other words, when there are extended disruptions of public transport and communication, it has to be assumed that some personnel will not be available. Therefore, emergency procedures need to be in place to ensure the presence of essential staff, and lifelines have to be reassessed. Operational continuity needs to be made sustainable and resources need to be maximised. Awareness of possible interdependencies needs to be increased by adopting new scenario-building processes that aim to understand common vulnerabilities to multiple threats (Pescaroli et al., 2018).

3.2 Complex scenarios and compound and interacting drivers

In the future, climate extremes will make it possible for cascading effects to recombine with compound drivers. This could lead to scenarios in which initial events of variable intensity, such as a local or regional flood, may coincide with a technologically driven escalation, as shown in Figure 1 (Pescaroli et al., 2018).

Figure 1. *Disruption of operations scenario associated with technological failures and compounding events.*
Source*: Adapted from Pescaroli et al., 2018.*



Primary triggers could originate in the natural domain, as when storm-force winds cause a blackout during a cold wave, or they could potentially be associated with malicious intents, as when cyberattacks aim to disrupt emergency operations. In other words, emergency management could require action to contain primary threats while at the same time being challenged in scaling up processes that are highly reliant on technological resources. Knock-out scenarios are far from implausible. In September 2017 the strongest solar flare in 12 years caused radio and GPS communications to deteriorate while, in the wake of Hurricane Harvey, Hurricane Irma was challenging emergency services on Atlantic coastlines (Crane, 2017).

While there is no evidence that the solar flare complicated the provision of relief, it affected the same hemisphere. Moreover, it has been suggested that shocks to the cyberdomain could be triggered by attacks on critical infrastructures during some other type of crisis, which could limit the capacity of technicians to activate protection measures (Sommer and Brown, 2011). An additional example can be considered by analysing the 2020 coronavirus (COVID-19) global pandemic. Just in the first half year since the emergency declarations in Europe, it become evident that the cascading effects of the primary trigger (COVID 19) could re-combine and compound with events such as heatwaves, wildfires, flooding, earthquakes, hurricanes, chemical accidents and targeted cyber-attacks (York 2020, Clark-Ginsberg et al. 2020).

4 Examples and case studies

There are different examples of how cascading effects and compounding dynamics can directly and indirectly disrupt emergency facilities, and provide complementary lessons learned.

The following subsections propose three case studies that have been chosen for their capacity to support the understanding of the points explained above. The triggering events included two cases of flooding in small to medium-sized urban areas, representing high-frequency hazards of the most common kind. Each of the case studies refers to an area of well-known risk, in which other events followed the main impact, and also involves a recent event with few precursors and active lessons to be learned. One case involves extended technological failure during hot weather. This has been chosen because of growing concerns about ageing infrastructure in Europe, and the possible concurrence with climate extremes such as the heatwaves of 2017–2019. The cases are reported in chronological order, first describing the background and then identifying the lessons learned. The principles that have been discussed apply to most of the other human-made or natural threats, such as earthquakes, forest fires, volcanic eruptions or cyberattacks. In other words, the section uses an all-hazards approach by proposing an analysis of the effects that could be common to different triggers. Practical suggestions about organisational resilience for decision-makers are given subsequently.

4.1 Power outage in Auckland, February–March 1998

With a 2018 population of approximately of 1.6 million inhabitants, Auckland is the largest city in New Zealand. It is the major economic and financial centre of the nation. It is located on North Island on a volcanic field that is potentially disruptive. During the southern hemisphere summer of 1998, the city experienced an extended power outage of 10 consecutive weeks. This directly affected the central business district, where the economic activities were concentrated. An analysis of the event and its implications for emergency management was conducted by Stern et al. (2003). The crisis was triggered by the failure of four major cables that delivered energy to the city, but it was rooted in unaddressed vulnerabilities, such as lack of adequate maintenance of the grid. In the first instance, emergency services had to deal with demands that are common to wide-area power failures (Petermann et al., 2011; Royal Academy of Engineering, 2016) such as people trapped in elevators, activation of automatic alarms, and pressure on healthcare associated with carbon monoxide poisoning, rotten food and contaminated water. Afterwards, issues of the continuity management of EMFIs came into play. Owing to the failure of telephones and computers, communication between the organisations became harder. The concurrence of the event with summer reduced the working capacity of personnel (Stern et al., 2003). Indeed, many of the buildings suffered public heath issues and failure of ventilation systems. The temperature in offices exceeded 30 °C, which required personnel to be relocated precisely when there was the maximum strain upon their operational capacity. This was particularly true of the facilities located in high-rise buildings, such as the City Council itself.

Lessons learned

Although this case study is now quite dated, it offers various kinds of lesson to learn. First, it shows that, despite high reliability, worst-case scenarios have to be taken seriously. Second, it required workers to balance short- and long-term decision-making as the crisis dragged on and resources and international logistics had to be used sparingly. Finally, it showed that crisis managers themselves can be victims of disruption. Although the event is quite long ago and society has changed since 1998, technological failures concurrent with climate extremes have to be taken seriously and integrated in actual continuity management. For example, the 2018 power network overload in Cascais, outside Lisbon, happened during one of the most severe heatwaves of the decade. In the United Kingdom, summer 2019 was marked by rail transport disruptions in July due to extreme heat, and then a month later a blackout in southern England, where Ipswich Hospital was disrupted during an extended period of severe heat. Moreover, this case study illustrates that multiple levels of cascading effects originating in the energy sector can create cross-sectoral challenges to operational capacity and organisational resilience (Petermann et al., 2011;

Royal Academy of Engineering, 2016). Emergency tools such as generators or stored fuel may be inadequate, while high reliance on contractors could imply loss of lifelines where the crisis implies competition for the same resources, for example when demand for the services of the same contractor is higher than its capacity. The loss of pressure in water mains or heating could compromise the safety of buildings, while reduced telephone capacity during periods of increased demand may overload landlines. Finally, the disruption of technological assets such as servers and data centres could imply shifting to paper-based procedures, as well as requiring tools for individual resilience such as hand-cranked battery chargers. In both cases, underestimation of risks or cuts in budgets may limit the redundancy of resources. In areas where cashless transactions are common, scenario building should consider the impacts of cross-sectoral failures on emergency personnel independently from the triggering events. Electricity failures may make simple activities, such as grocery shopping, impossibly difficult (Royal Academy of Engineering, 2016). EMFIs are operated by personnel that rely daily on the effective functioning of the same systems as everyone else.

4.2 Flooding in Carlisle, January 2005

Carlisle is an industrial town in Cumbria, northern England. It has a population of approximately 74 000 and it is known to tourists for historic heritage such as the nearby Hadrian's Wall and the Lake District National Park.

The city has several areas at risk of flooding, which happened in 1771, 1822, 1856, 1925 and 1968. In January 2005 approximately 1 600 properties were inundated in the city and three people died. Critical infrastructure disruptions were widespread, which affected emergency relief and rescue. The UK Environment Agency (2006) noted that more than 250 000 homes and business in Cumbria and north Lancashire were affected by power failures, with restoration costs of approximately GBP 4.5 million in Carlisle alone. Moreover, as a consequence of the power outage the mobile phone network was disrupted, as was part of the landline telephone system, further burdening the emergency services. Some of the key personnel were prevented by road closures from reporting for duty. Police stations in Carlisle, Penrith and Appleby were heavily damaged, as were council offices and schools. The official report (Environment Agency, 2006) emphasised that the shutting down of the police station in Carlisle was the first closure of a major station in peacetime.

The closure of the civic centre led to the relocation of the strategic ('gold') command centre, which was directly affected by the flooding. It lost its communication room but managed to remain operational despite heavy challenges. The county Fire and Rescue Service was also disrupted, as a fire station was flooded to a depth of approximately 2.5 metres. The emergency situation required the support of fire and rescue crews from across the United Kingdom.

Lessons learned

According to the UK Environment Agency and Cumbria County Council (2016), the 2005 flooding led to the development of a new flood defence scheme and presented an opportunity to define new flood-warning areas and practices. However, in December 2015, as a consequence of Storm Desmond, the city suffered another major event, with 2 128 proprieties flooded in Carlisle and approximately 60 000 homes subject to power outages across northern England. Although the lessons learned at the emergency coordination centre were implemented, further lessons were derived from critical infrastructure failures in the 2015 flood (Environment Agency and Cumbria County Council, 2016; Royal Academy of Engineering, 2016). First, household preparedness and emergency response were inadequate to face extended blackouts, as noted in the previous example in Auckland. Second, it has been shown that, during the flood, power disruption affected the whole area and a pumping station started to rely on an emergency generator until it ran out of fuel and stopped (Environment Agency and Cumbria County Council, 2016; Royal Academy of Engineering, 2016). The exact time was not recorded, but it had an impact on emergency services, as it led to flood overtopping in some affected areas. In conclusion, it can be noted that the wired telephone system continued to hold up, but mobile phone systems did fail. The need for reliable communications was highlighted as a cross-cutting issue in considering the needs of the public (Royal Academy of Engineering, 2016). To sum up, this case study highlights the need to plan carefully the location of EMFIs, and, if they lie in areas at risk, some alternatives should be identified in the preparedness phase (UNISDR, 2015). Moreover, their resilience to multiple infrastructure failures should be assessed, giving priority to increasing redundancies and buffering (UNISDR, 2015).

The last element to consider in this case study is that complex events may require the development of improved cross-border coordination for fast deployment of emergency teams under mutual aid agreements. Since 2005, the evolution of the EU civil protection machinery has provided a concrete answer to that challenge. However, further work may be needed to prepare for the cascading effects of multiple infrastructure losses, in particular to define the logistics of fast deployment during technological failures and loss of lifelines to emergency facilities.

4.3. Flooding in Parma, October 2014

Parma is a well-known centre of high-quality food production in northern Italy. In 2018 the city had approximately 200 000 inhabitants. Over the period 10–13 October 2014 three of its neighbourhoods were partially flooded, causing EUR 26.5 million of direct economic damage but no loss of life (Protezione Civile Emilia-Romagna, 2015). The majority of the economic damage was associated with the disruption of two pieces of critical infrastructure.

(a) The flooding of the Piccole Figlie hospital (Figure 2), a nearby nursing home and a health care centre for non-self-sufficient elderly people necessitated the emergency evacuation of 96 patients. Although the principal clinic of the hospital was located less than 20 metres from the riverbank, all its functions were still operational until river water entered the building. In a few minutes, flooding reached 1.5 metres and staff had to help the patients, many of whom were elderly, climb onto tables to reach safety. Moreover, the building had an oncology centre, from which 16 patients, some with terminal cancer, had to be evacuated using rudimentary methods (Petri and Ciocci, 2014). The hospital was inoperative for 2 months, which placed a burden on other health services in the city.

(b) Flooding of a telecommunications hub led to the total interruption of both landline and mobile telephone coverage supplied by Telecom Italia in the western portion of Emilia-Romagna for days, and it directly affected the operational capacity of the emergency services (Protezione Civile Emilia-Romagna, 2015). In the affected area, situational awareness was reduced because citizens were unable to communicate with the emergency services. The offices of the city hall had communications disrupted, and the personnel were only able to deliver official communications using the Facebook profile of the mayor. Similarly, general practitioners were unable to communicate with vulnerable patients in the flooded areas. Some calls to the 118 emergency medical number had to be rerouted through the regional emergency network using diverse repeaters.

Figure 2. *Parma during the flooding: the Piccole Figlie hospital*
Source*: Wikicommons, author Comune di Parma (2014), CC BY-SA 2.0*

Lessons learned

The event shows the impact on EMFIs associated with both the direct effects of primary triggers, such as flooding, and the cascading effects of disruption in other critical infrastructure sectors, such as telecommunication. There are different lessons to be learned and gaps to be addressed in the future. First, this case study highlights how hazard and critical infrastructure maps still do not connect with each other. In Parma, the location of the telecommunications hub was known only to the provider. They need to be better integrated with the development of processes, practices and scenarios (Nones and Pescaroli, 2016). As happened in the previous case study, these elements should naturally be considered in continuity management, but this is far from always being the case. The location of emergency facilities may be well known, but their vulnerability may be not be understood because changes in the urban landscape have increased the risk. Moreover, this case study points out the need to assess critical infrastructure interdependencies, and the location of nodes and hubs, but also to integrate cross-sectoral failures and cascading effects with measures to ensure the organisational resilience of the emergency services (Pescaroli and Alexander, 2018).

Coordination issues may become primary challenges to address. At the time of the disruption, the contingency plan needed further work. If information is not shared enough, communication challenges may arise within the emergency services, and between the emergency services and the public. For example, the impacts on the continuity of data of hospitals and healthcare facilities has proven to be particularly critical, affecting both routine operations and emergency management (Klinger et al., 2014). Moreover, a growing tendency for disaster management to be over-reliant on internet services has been noted (Royal Academy of Engineering, 2016; Aldea-Borruel et al., 2019). In Parma, the key factor to contain the crisis was low-tech radio capacity, which was vital to operations when more sophisticated technological solutions failed (Perri, 2014).

Practical solutions to those challenges include the development of alternative procedures and redundancies, such as increasing the sphere of operation of radios in case of extended emergencies, and constructing scenarios of emergency needs with respect to the population of vulnerable people. Finally, warning and preparedness strategies are clearly relevant to emergency facilities, as lack of action can compromise their operational capacity and exacerbate the risks for their beneficiaries. There must be further integration and standardisation across functional sectors (Birkmann et al., 2014).

5 A discussion of guidelines for operational continuity and resilience

The resilience of emergency facilities and infrastructure can be improved by considering both primary threats and cascading effects in checklists and operational standards.

The increased complexity of society requires a shift in emergency planning and management (Helbing, 2013; Linkov et al., 2014; Pescaroli and Alexander, 2018; Pescaroli et al., 2018). Indeed, despite the relatively high reliability of critical infrastructure networks that support lifelines in emergencies, the future is one of complex scenarios of reduced operational capacity. The case studies presented above represent a starting point for further discussion. There are some main elements that can be discussed in considering an all-hazards approach, to support scenario building, exercises, risk assessment and horizon scanning.

- Emergency facilities can be affected by primary threats, and consideration needs to be given to addressing investments in retrofitting and mitigation. The literature shows that emergency facilities such as healthcare facilities are dependent on physical resilience, and non-structural and organisational components such as evacuation planning, staff rotas, time of day at which the event happens and accessibility by road (Birkmann et al., 2014). The online technical guidelines of the World Health Organization (2019) have reported some specific considerations that can be used to understand the impacts of some other recurrent hazards in Europe.

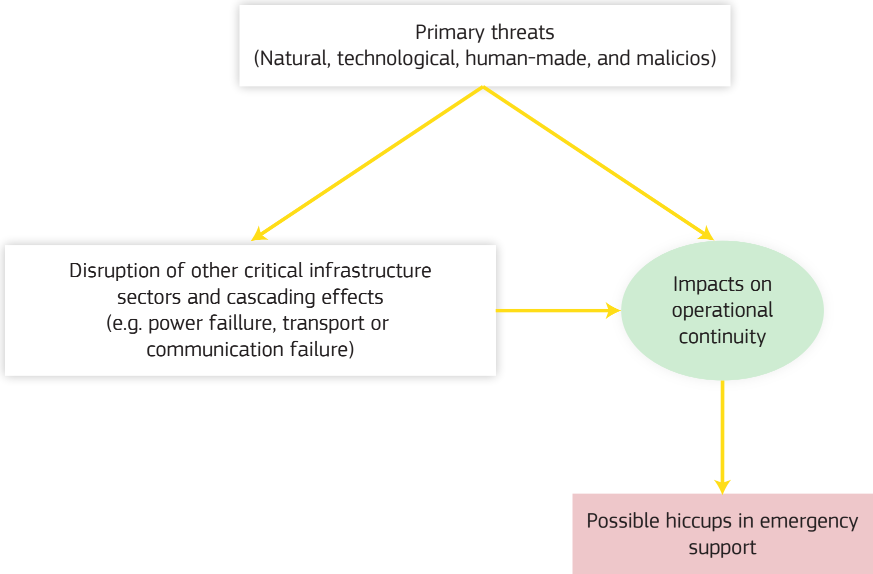
  For example, the effects of earthquakes on hospitals and healthcare facilities can be described in terms of both direct impacts, such as physical damage, and stressors associated with infrastructure failures, such as absence of workforce caused by transport disruption, or the loss of medical supply and procurement. EMFIs can represent a potential target for malicious attacks. The WannaCry ransomware attack in 2017 disrupted one third of hospital trusts, and 603 primary care and other organisations in England (Smart, 2018). The electronic flow of clinical information was compromised, causing the lack of availability of records and test results. Appointments were rescheduled, including visits for cancer patients, while ambulances were diverted and emergency departments became unable to treat patients (Smart, 2018).

- Emergency facilities are vulnerable to cascading effects, technological failures and compound dynamics. Researchers agree that emergency facilities can be widely affected by dependency on infrastructure such as energy supply or telecommunications. However, lessons have not always been adequately incorporated into effective preparedness and training. Helsloot and Beerens (2009) investigated the response to power outages in 2007 in the Netherlands that lasted approximately 3 days and coincided with particularly cold December weather. More than half of the participants in the study highlighted that local governments' response was inadequate. Other exercises highlighted that events such as power failures could hamper backup systems used by EMFIs such as satellite phones, and 'a mechanism to support widely distributed emergency communication is a fundamental need that must be addressed' (Aldea-Borruel et al., 2019, p. 25). Finally, climate extremes and technology could interact in new ways to increase pressure on EMFIs. For example, the heatwave affecting California in 2019 meant that power had to be shut down for safety, to 'prevent equipment from starting wildfires during hot, dry, and windy periods' (Jackson, 2019, p. 1). These shutdowns affected approximately 3 million people.

Figure 3 reports a synthetic overview of possible dynamics that could be exacerbated by lack of preparation. It can be noted that operational continuity can be directly affected by a primary threat, such as floodwaters, earthquakes or malicious attacks. This is the case, in particular, if emergency facilities and infrastructure lie in areas at risk or are exposed to new risks that were not assessed before, such as terrorist attacks, and find themselves at the epicentre of a crisis. However, there could be new stressors and cascading effects associated with critical infrastructure disruptions originating in other sectors during ongoing events, and they could be concurrent with the primary threat.

When the resilience of the EMFIs is not sufficient to stand the impact of a primary threat or the stressors caused by the disruptions, the capacity of emergency support may be reduced or compromised. Unfortunately, with current knowledge it is not easy to produce worst-case scenarios for the escalation of secondary emergencies such as blackouts, telecommunication failures and transport breakdowns. It is often assumed that emergency facilities are safe from primary triggers without committing to regular assessments that evaluate both technological failures and concurrent dynamics. The process could find common escalation paths and thus seek to maximise resource usage and the effectiveness of emergency responses (Pescaroli et al., 2018).

Figure 3. *Factors affecting operational continuity of EMFIs* ***Source***: *Authors*



5.1 Operational standards and checklist

Some frameworks are already available to improve operational continuity and resilience at the strategic and political levels. They will be described in the next subsections. The first element to consider is the development of international standards that can be used as reference for operational continuity and organisational resilience.

The International Organization for Standardization (ISO) and British Standards Institutions (BSI) standards on continuity management (ISO 22301:2019) and organisational resilience (BSI 65000:2014, ISO 22316:2017) provide the framework for defining a consistent process to identify potential threats, adapting and integrating the operational use of existing guidelines, and increasing flexibility to deal with unanticipated threats. These include support for assessing the integration of cascading effects and interdependencies (ISO 22301:2019) and resilience 'maturity levels' in an organisation or facility (BS 65000:2014, ISO 22316:2017).

Moreover, the US National Fire Protection Association (2019) highlights further the need to evaluate the possible cascading impacts of 'regional, national or international incidents', considering the potential combinations of frequency, severity and cascading impacts for different categories of threats. Continuity management could then inform some key questions for self-assessment derived from the existing guidelines on the subject (UNISDR, 2012; Pescaroli et al., 2017). Using that as a basis, the following checklist may be considered by practitioners and strategic trainers.

- How much has the planning and construction of the EMFIs taken into account current and future disaster risk in the area? Are there any critical nodes for command and control, or emergency relief logistics, that lie in high-risk areas?
- Is vulnerability assessment of the facility conducted and updated, and have mitigation measures been implemented considering the possibility of an escalating crisis? Has planning integrated forward-

looking tools and wider impact assessment methods that are suitable for defining cascading effects and multiple infrastructure failures? What training tools could need implementation?

- Has a gap analysis or resilience assessment been conducted in order to consider the ability of the EMFIs to remain operational during an extended energy, transportation or telecommunications failure? Is it updated and considered to be a realistic worst-case scenario with compounding dynamics (e.g. a power failure during cold weather)? Does the organisation have provisions for emergency power and communication?
- What are the technological lifelines that the organisation has to ensure to remain operational? Is there a 'plan B' for short-, medium- and long-term disruptions? Have backup solutions for essential information and communication technology tools been arranged and alternative procedures been developed?

5.2 Documentation in the European Union

Given the emphasis on Europe in this report, a short overview of the key documentation produced by the European Commission is warranted. Scenario building can be facilitated using the documents that explain and list the expected impacts of extreme climate change on critical infrastructure, and the concomitant implications for society (European Commission, 2013a). Although this approach has limitations, it can provide a practical overview of compounding dynamics upon which to develop scenarios and understand cross-sectoral disruptions. Similarly, in 2013 the European Commission (2013b) provided a roadmap for the implementation of the European programme on critical infrastructure protection, with the inclusion of cross-sectoral interdependencies that could be used as a basis for understanding cascading effects.

Although this documentation needs better integration between the legislative tools, for example between the European Floods Directive (EU, 2007) and the Council Directive 2008/114/EC (EU, 2008) — identification and designation of European critical infrastructures and assessment of the need to improve their protection (Nones and Pescaroli, 2016), the process is constantly evolving. With respect to cascading events, the capacity to communicate and coordinate efforts needs to be increased, while new strategies for vulnerability assessment need to be put in place. At the EU level it can be assumed that there are contextual differences between national capacities, local realities and organisations present in the same jurisdiction. These differences must be recognised and considered at the strategic level.

5.3. United Nations guidelines and checklists

A wider spectrum of actions can be derived from the documentation produced by international bodies. The SFDRR contains some specific references to emergency facilities. It recommends increasing the resilience of critical infrastructure such as hospitals, and introducing practices of safe design, standardisation, periodic maintenance and sociotechnological impact assessment (UNISDR, 2015). The SFDRR stems from the evolution of multidisciplinary and practice-oriented research that integrates climate change adaptation into planning and policy design, and promotes emergency planning oriented towards prevention (Aitsi- Selmi et al., 2016).

It can be noted that some of the observations on emergency facilities were based upon other practices, such as those developed by the World Health Organization and Public Health England (2013). These recommendations underline the need to build safe hospitals and to ensure that health facilities remain operational in emergencies. Planning, training, exercising and developing a surge capacity are essential activities. They highlight the need to plan for multisectoral disruption in order to assure the continuity of health services (World Health Organization and Public Health England 2013). Some complementary guidelines have been developed under the Words into Action initiative, which has been promoted by UNISDR in order to support the national implementation of the SFDRR. These provide information on the underlying drivers of risk including the different types of disasters that could occur (UNISDR, 2017). An essential asset to consider is national disaster risk assessments, which provide the means by which the vulnerability of emergency facilities is understood, and standards of preparedness are created by means of investment and exercises (UNISDR, 2017).

For example, if the risk register defines a possible event as having moderate likelihood but major impact, contingency planning will have to consider realistically possible disruption over a broad scale. At the local level, local disaster risk reduction and resilience strategies have to identify the essential aspects of risk scenarios. They must update information on critical infrastructure, the potential impacts of hazards, and possible cascading effects that could reduce local capacity (UNDRR, 2019). Further consideration has to be given to the strategic dimension of interagency coordination and protocols, which in many cases can lead to the fragmentation of preparedness and organisational standards. For example, there may be gaps in the process of informing the public and deciding what information to provide in case of technological disruption, such as power failure, and how this provision of information can be extended to other urban and rural areas.

The case studies reported in this chapter illustrate the need to plan for operational continuity and organisational resilience in order to assure that lifelines can be restored as fast as possible. Further guidance can be found in practical handbooks for local government and professional practice (UNISDR, 2012; Linkov and Fox-Lent, 2016; Pescaroli et al., 2017).

Future impacts of climate change should be considered in order to establish early warning and monitoring systems, defining, ex ante, the decision thresholds that could influence crisis management agencies and coping strategies (UNISDR, 2012, UNDRR, 2019). Finally, the location of emergency facilities should be reassessed in relation to changing vulnerability and hazards. Minimum standards of resilience should ensure that supply routes and lifelines are identified in order to prioritise the maintenance of emergency facilities and the delivery of emergency relief, for both events triggered by natural hazards and those triggered by technological scenarios (UNISDR, 2012; Pescaroli et al., 2018).

6 Conclusions and key messages

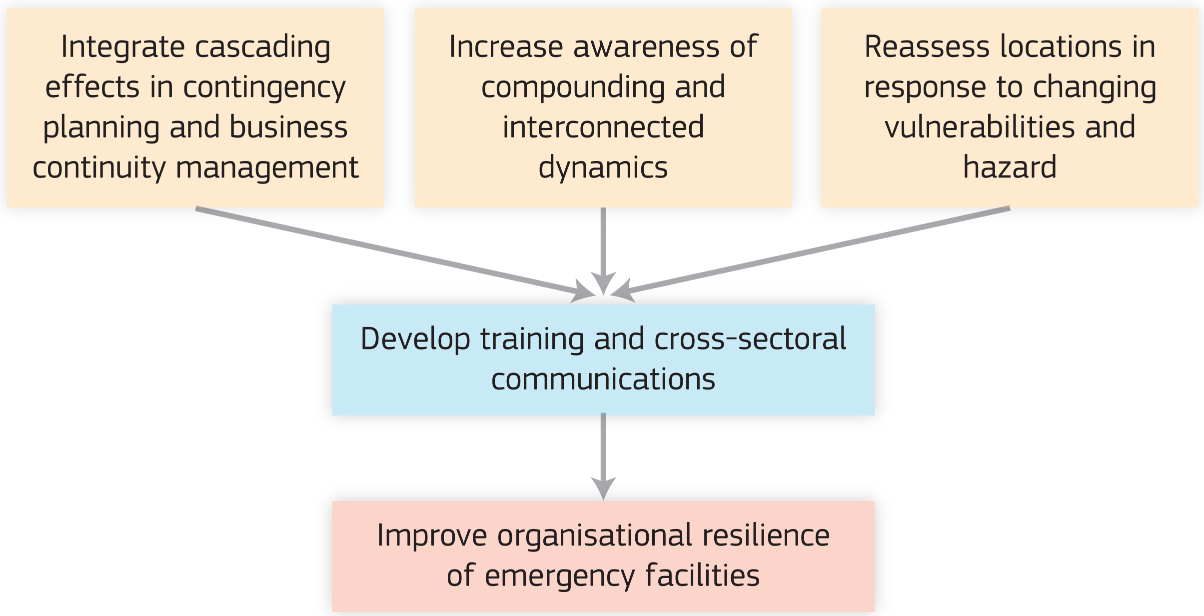
The next steps for improving the resilience and operational continuity of emergency facilities and infrastructure include efforts to improve multi-stakeholder coordination and impact assessment.

Maintaining the operational capacity of emergency facilities and infrastructure is at the centre of this subchapter. The adoption and implementation of the SFDRR and the Words into Action guidelines are essential measures designed to increase the resilience of emergency facilities while at the same time reducing future disaster risk (UNISDR, 2015, 2017;UNDRR 2019). However, the theory and the case studies provided here highlighted that many challenges for the application of these concepts still exist in practice.

First, there may be a structural issue of coordination, communication and information sharing in the management of EMFIs, and this could undermine the improvement of training and exercising for complex scenarios.

This is particularly true in the case of cross-sectoral failures, in which emergency facilities are disrupted by the cascading effects triggered in other sectors, such as electricity. The recent global crises associated with COVID-19 highlighted even further the need to see EMFIs as the nerve centre of our social functions, developing a collaborative and inclusive process to assure their operational capacity.

Figure 4. *Steps for improving organisational resilience of emergency facilities* ***Source****: Authors*



Cross-cutting challenges

Differences in the language used by academics, policymakers and practitioners could cause problems. It is realistic to believe that they could be overcome by collaboration in the medium term, so that counterparts learn to know each other's point of view, creating both trust and knowledge exchange. The existence of different timelines for policymaking, utility management and research may need the development of a focused research project and impact-oriented studies. In conclusion, it is evident that dynamics (such as budget cuts) affect both academics and practitioners by limiting the resources available.

This element can potentially disrupt emergency services and represents a situation in which positive changes, in terms of proactive collaboration, may be less limited by institutional and administrative barriers. New steps to assure the organisational resilience of emergency facilities are essential to prevent the escalation of future crises, and the collaboration of all the actors involved in emergency planning and management is necessary to mitigate complex scenarios.

Policymakers

Account must be taken of the need for further development of conventions on multi-stakeholder collaborations to support a systematic exchange of information, expertise and results. The identification of internal and external interdependencies suggested in new continuity management standards such as ISO 22301:2019 and NFPA 2019/1600 could be the first step in this process. However, new steps are needed in terms of legislation and policies to support the development of a holistic collaborative framework and introduce better accountability and compliance requirements. Some open questions remain, associated with the quantification of cascading impacts triggered by the disruptions of EMFIs. At the time of writing, it is not possible to access any quantitative information on losses and damages that could have been avoided if EMFIs had been completely efficient. These data could be used to develop some better cost–benefit analyses to support decision-makers. Clearly, this approach is merely a first step in a longer process of improvement and evolution that should involve EU legislation and policies.

Practitioners

Possible mitigation for this issue includes the adoption of standardised practices for creating organisational resilience and understand internal vulnerabilities (ISO 22316:2017, 22301:2019; NFPA 2019/1600), while increasing the adoption of measures in line with the scenarios proposed in the updated versions of national risk registers (UNDRR, 2019). Figure 4 shows the main steps needed to improve the organisational resilience of EMFIs in the near future by actively involving training and cross-sectoral communication between stakeholders. In the assessment process the functionality of vital services must involve multiple dimensions, such as operations, structure, planning and resources. These have different potentials to become useful tools in practice. They have been extensively evaluated, for example in the Intergovernmental Risk Governance Council's Resource Guide on Resilience (Linkov and Fox-Lent, 2016). Furthermore, scenario building should integrate cascading effects and interconnected dynamics in order to understand the carrying capacity of EMFIs during technological failures and complex events (NFPA 2019/1600). The integration of these aspects in practice requires the development of further collaborations with academia.

Scientists

Many aspects of this assessment process represent a fine opportunity for an active role of scientists in supporting practitioners and decision makers. For example, new collaborations can be developed in order to understand gaps in preparedness for cascading events, as well as to analyse structural and non-structural vulnerabilities to multiple threats. Moreover, scientists could actively support the development of new scenarios and strategic foresight to be used in training activities, as has already been done in the field (e.g. Alexander, 2016; Pescaroli et al., 2017).

Citizens

The role of individual citizens is another element that can be explored to improve the status quo. For example, the literature recommends defining what to communicate and how to do it (Alexander, 2016; Lindell et al., 2007), but there is a lack of understanding of what procedures would be most useful if emergency facilities were disrupted. In line with the SFDRR (UNISDR, 2015), it could be useful to develop better involvement with local communities and stakeholders. Indeed, civil society could represent an essential asset for coordinating emergency efforts, and developing basic training for the population on cascading scenarios could be one of the tools for improving societal resilience (Royal Academy of Engineering, 2016).

3.4.2 Network infrastructures

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Galbusera, L., Theocharidou, M., Monserrat, O., Novotny, P., Sansavini, G., Stojadinovic, B., 'Network infrastructures', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Introduction

Many of today's critical infrastructures (CIs) are commonly described as 'networked' because of their spatial imprint or the many interacting components and functions they are made of. Mutual linkages also come into play, sometimes subtly, when different processes and technologies interact, overlap, compete over resources or intertwine to compose services. Expressions such as 'networks of networks' and 'global supply chains' are highly meaningful in relation to a modern definition of networked CIs, and the scientific community is investigating the subject of interdependencies through several methodologies, chiefly relying on network science and related disciplines (Rinaldi, Peerenboom, and Kelly 2001; Barabási 2002; Barthélemy 2011; Ouyang 2014).

In the EU policy framework, networked critical infrastructures (NCIs) and their interconnections take on a major role in both the 2004 Communication from the Commission to the Council and the European Parliament – Critical Infrastructure Protection in the fight against terrorism (European Commission, 2004) and Council Directive 2008/114/EC on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection (Council, 2008)([1]). The energy and transport sectors, central to the latter policy instrument, are particularly relevant to the present section.

Key enablers for modern economies, NCIs require special consideration from the standpoint of risk and disaster management. Indeed, failures can be rooted in both exogenous (e.g. natural or human-made hazards) and endogenous (e.g. ageing) factors.

Moreover, interconnections can give rise to various failure propagation patterns, often hardly predictable; see for instance the categories of cascading, escalating and common cause failures from Rinaldi et al. (2001). As a result, assessing NCI risks solely as the sum of the risks associated with the individual parts may be grossly misleading and, conversely, the broader picture of risks ought to be investigated. Moving from the standard definition of risk as 'effect of uncertainty in objectives' (ISO, 2018, p. 1), Helbing (2013) discusses the concepts of systemic risk ('the risk of having not just statistically independent failures, but interdependent') and hyper-risk ('implied by networks of networks').

The same author also points out some key failings of current risk-assessment methods. These include poor estimates of probability distributions and parameters for rare events, underestimation of likelihoods of coincidence of multiple rare events, shortage of accounting for feedback loops in fault/event tree analysis, insufficient consideration of joint probabilistic analysis and complex dynamics analysis, human/social factors, lack of questioning about established ways of thinking on economic/political/personal incentives.

The spectrum of consequences can be vast, and recent studies emphasise how, for instance, a local disruption to infrastructure can result in considerable macroeconomic impacts, e.g. see Hallegatte et al. (2019). Awareness of similar aspects and the non-conventional nature of risks in NCIs is rising among researchers, practitioners, policymakers and stakeholders at large.

This can be observed, for instance, in the Sendai framework for action on disaster risk reduction 2015–2030 (UNDRR, 2015). Therein, in particular, Global Target D ('substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030') sets objectives in terms of both 'damage to critical infrastructures attributed to disasters' and 'number of disruptions to basic services attributed to disasters'.

(1) See Theocharidou et al. (2018) for a more extensive discussion of the EU policy framework on CIs.

Interdependencies and direct/indirect effects are also central to standard ISO 31000 (ISO, 2018); see for instance the comprehensive interpretation given of the term 'consequences'.

These examples and many more found in several policy documents manifest the need for a refined approach to disaster risk management, especially as far as NCIs are concerned. Broadening the landscape even further, what has been mentioned so far is only one facet of the topic from a disaster risk management perspective.

These systems are also vital and integral to the deployment of response actions during crises, providing relief to the population, channelling recovery resources and ultimately softening the consequences of adverse events. Accordingly, they should be better interpreted today as socio-technical systems, wherein different technological layers are interoperating at the boundaries between those environmental, social and organisational contexts that shape their design, operations and development (Masys, 2014). From this perspective, Vespignani (2009) observes how 'the major roadblock in defining the fundamental predictability limits for techno-social systems is their sensitivity and dependence on social adaptive behaviour'.

Social consensus is needed to ensure resilience of those assets and services that NCIs provide to society. Our discussion, therefore, has implications for the engagement of civil society, volunteers, community-based organisations, public institutions, academia, scientific and research entities, business, professional associations, the private sector and the media.

2 Case studies

In European power grids and transport systems, significant cascading consequences have been observed in the past.
The structure of networks can greatly influence direct and indirect impacts, relief and recovery from disasters.

Lessons on disaster risk management related to NCIs can be drawn from memorable failures from the recent past. As mentioned above, next we focus on some case studies from the energy and transport sectors, which are mentioned in Council Directive 2008/114/EC.

2.1. European power outages

The European Transmission System (ETS) is an evolving, highly meshed network, which entails five synchronous large area networks. According to the European Network of Transmission System Operators for Electricity (ENTSO-E, 2019a), it includes about 489 381 km of high-voltage lines and is operated by 43 transmission system operators (TSOs) from 36 countries, serving 534 million citizens with an annual electricity consumption of about 3 329 TWh (in 2017) and a peak load of 542 GW (cold wave on 18 January 2017). To ensure security of supply and reliable operation, the ETS needs protection against cascade tripping, voltage/frequency collapse and loss of synchronism. ENTSO-E (2019b) observes that 'Europe enjoys one of the world's most reliable power grid'. Kröger (2017) observes the following trends and challenges for the ETS:

- unbundled market structure replacing monopolies, with the responsibility for power supply security shifting from single industries to national authorities;
- operation modes pushed closer to limits, even beyond initial design parameters;
- fast-rising share of intermittent asynchronous renewable energy sources, which are highly dispersed,

usually abundant in sparsely populated areas and often available during low-demand periods; this requires massive power transfers over long distances, as well as peak-smoothing strategies;

- increasing volumes of cross-border power exchange and of short-term trading;
- increasing smartness and user involvement due to information and communication technology pervasiveness, self-sustaining areas and transfer of control functions from central units to decentralised private users while at the same time the coexistence of novel and legacy technologies must be managed;
- broadening spectrum of threats and hazards related to cyber- and physical attacks and extreme weather, with both frequency and severity increasing, ageing of systems and components, lack of adequate investment and decreasing redundancy/reserves.

The most serious challenges that the ETS faces are blackouts, which are increasingly rare but can have devastating consequences for people and the economy. In 2006 an incident on the north German transmission grid led to its being cut off from the interconnected power system of continental Europe, with 15 million households across 20 countries experiencing power supply disruption (UCTE, 2007).

Another example that shows how electricity supply, and the lack of it, can affect society is the Italian electric power blackout on 28 September 2003 (Sunday morning to Monday night) (UCTE, 2004; Kröger and Zio, 2011). At 03.01, one of the main north–south transit lines through Switzerland – the Lukmanier transmission line – shut down because of a tree flashover.

This resulted in the redistribution of the electricity, and another north–south transit line, namely the San Bernardino transmission line, was overloaded. The Swiss and Italian transmission operators communicated in order to relieve the overloads in Switzerland and return the system to a secure state.

Thus, Italy reduced its imports; however, this reduction was insufficient to relieve the overloads. At 03.25, the San Bernardino line tripped after another tree flashover. With two important lines down, cascading failures occurred on the remaining lines. This resulted in the Italian system becoming isolated from the European network, and several generation plants in Italy failed. A total blackout followed at 03.27 throughout Italy, with the exception of Sardinia and some load islands.

In Italy, the restoration process started immediately after the blackout. After 3 hours, energy had been restored in some regions connected to France (such as Liguria). Nine hours later, in the afternoon of 28 September, electricity was restored gradually in most places, including Turin, Milan, Venice and Rome. Rolling blackouts continued to affect about 5 % of the population over the next 2 days (29–30 September). In Italy alone, the estimated total energy not supplied amounted to 177 GWh, and it took 18 hours to complete the restoration.

According to the analysis proposed in (Kröger and Zio, 2011, p. 14), the impact on the population was strong (‘about 56 million people have been affected, five elderly persons died’; ‘hundreds of people have been trapped in elevators’), economic losses moderate (including those related to spoiled foodstuff and the interruption to continuously working industries) and the impact on dependent critical infrastructures varying.

Among the critical infrastructure sectors affected were transportation (trains and subways stopped, flights delayed or cancelled, outages of traffic lights), water supply (`in some southern regions interruptions of water supply for up to 12 h’) and ICT (`telephone and mobile networks in a critical state but operable; Internet providers shut down their servers’). Less severe was, for instance, the impact on hospitals (`due to the use of emergency power generators’).

2.2 Transport-related failures

According to the 2018 OECD Survey on Critical Infrastructure Resilience and Security, transport is very consistently designated as a CI sector by the countries surveyed (OECD, 2019). It branches into many segments; for instance, the list of European CI sectors in Council Directive 2008/114/EC includes road, rail, air and inland waterway transport, as well as ocean and short-sea shipping and ports.

A conspicuous effort has been put into determining the key stressors for each transportation category and providing quantitative indicators. For instance, Koks et al. (2019) estimate that approximately 27 % of the global road and railway assets are exposed to at least one natural hazard, while about 7.5 % of all assets are exposed to a 100-year flood event.

Common categories of transport disturbance causes include natural events, accidents, social events and malicious attacks (Khademi et al., 2015). The sensitivity of different means of transport to different kinds of events can be quite variable. Notably, the scientific community has inquired into their risk and resilience qualities as a function of specific network features (Barthélemy, 2011; Rodrigue et al., 2016). The latter reference, for instance, characterises a given transport network in terms of topology (expressing its 'arrangement and connectivity') and typology (which 'relates to its geographical setting as well as its modal and structural characteristics').

According to various studies, road infrastructures often exemplify the concept of hierarchical mesh, spanning multiple geographical scales ([2]). Setting apart large-scale events, a peculiar vulnerability is related to the failure of strategic connectors such as some bridges or tunnels. In this sense, a major event occurred in Europe on 24 March 1999, when the fire that spread from a truck severely affected the Mont Blanc tunnel (France–Italy) and led to the deaths of 39 people. Despite the triggering of security mechanisms, a critical issue was the lack of oxygen due to toxic smokes, while high temperatures were reached and cooling took days. Three years of closure followed, leading to economic losses estimated in excess of EUR 300 million. After damage assessment and evaluation of restoration and modernisation options, the French–Italian commission of investigation issued a list of recommendations including improved tunnel configuration, vehicle regulations and training aspects (Duffé et al., 1999). Further events followed soon, such as the 1999 fire in the Tauern tunnel (Austria) and the 2001 fire in the Gotthard road tunnel (Switzerland). Fires have also affected the Channel Tunnel (France–UK) more than once since its construction (Lewis et al., 2013), as well as the Alpine pass of Fréjus (France–Italy) in 2005. Bridge disasters in Europe in recent decades include the Entre-os-Rios (Portugal) tragedy in 2001, when the collapse of the Hintze Ribeiro bridge caused 59 deaths, and the 2018 collapse of the Morandi bridge in Genoa, which resulted in 43 victims.

Observing the historical evolution of air transport routing, Rodrigue et al. (2016) observe how 'geographically, a key outcome of airline deregulation has been the emergence of hub-and-spoke networks centered on a major airport where a single carrier is often dominant' ([3]). Air transport networks can be highly vulnerable to disruptions at such hubs.

A seminal paper by Guimerà et al. (2005) describes the worldwide air transport network as a scale-free small-world network with centrality anomalies due to the community structure resulting from both geographical constraints and geopolitical aspects. Among its implications, for instance, the authors observe how 'cities that connect

([2]) See also Rodrigue et al. (2016) for a discussion of the case of rail networks and their specific network layout.
([3]) According to ICAO (2004), a hub and spoke system is 'an operational system in which flights from numerous points (the spokes) arrive at and then depart from a common point (the hub) within a short time frame, so that traffic arriving from any given point can connect to flights departing to numerous other points'.

different communities play a disproportionate role in important dynamic processes such as the propagation of infections such as severe acute respiratory syndrome'. See also Colizza et al. (2006) for correlations between the properties of the air transport network and epidemic spread.

According to Eurocontrol ([4]), flight delays cost the European economy close to EUR 18 billion in 2018 (Sullivan, 2019). A recent report by the International Air Transport Association estimates that 'the terrorist attacks in Western Europe in late-2015 and early-2016 reduced European airlines' international passenger traffic by around 1.6 % in the following year, compared to what would otherwise have happened. [...] This reduced European airlines' 2016 revenues by around US$2.5 billion' (Oxley, 2017). The same report also highlights that, 'as was the case during the SARS [severe acute respiratory syndrome] pandemic in 2003 and the Icelandic ash cloud in 2010, the impact on European international passenger traffic has been only temporary. This underlines the resilience of air passenger demand to short-lived shock events'.

By contrast, events such as the terrorist attacks of 11 September 2001 and the global financial crisis had a more lasting impact. Another example of disruption to airport services can result from problems with fuel supplies, such as in a recent (April 2019) case related to the Portuguese air transport system, when strikes by drivers of hazardous materials had consequences on fuel provisioning.

The vulnerability of maritime networks and sea lanes involves different considerations depending on whether the node is a hub or a gateway (Rodrigue et al., 2016). Disruptions at a hub will mostly affect maritime shipping networks, whereas disruptions at a gateway will mostly affect the hinterland. See the latter reference for case studies, including cases of global maritime routes and chokepoints. When considering transport disruptions, tolls in terms of human lives are often accompanied by significant outbound and inbound cascading effects on and from other sectors. As an example, studies mentioned by Rozenberg et al. (2019) estimate that the total yearly costs due to extreme events on the transport system in the European Union are in the order of EUR 2.5 billion, predominantly road costs, with predicted rises for the years to come. Reliance on other sectors is critical, with energy and information and communication technology often topping the list of sources of delays and disruptions. Modes of transport, when disrupted, can severely affect each other, owing to the transfer of demand and the fact that they are often interconnected. Modern cities aim for transport intermodality, making these dependencies increasingly important. An event with major consequences from this viewpoint was the ash cloud resulting from the Eyjafjallajökull eruption of April–May 2010 (see Super Case Study 3 on the Eyjafjallajökull eruption), which resulted in the 'closure of Europe's airports and airspace which lasted for a period of over seven days with cancellation of up to 100,000 flights affecting 10 million passenger journeys. [...] The airline industry faced high costs of up to $400 million per day' (OECD 2019, p. 33). 'Stranded passengers looked for other transport modes, notably trains, the cross-channel Eurostar and ferries which were neither equipped nor flexible for such an increase in demand' (OECD 2019, p. 33).

Finally, transport nodes are key for managing disasters, as they are essential for the deployment of equipment and humanitarian goods in order to help and provide relief to victims. An efficient response helps to reduce the social, economic and environmental impacts. As an example, some recovery actions implemented during the 2016 earthquakes in Amatrice (Italy) were related to restoring access to the village, which required over-river access, after the collapse of bridges. A joint group formed by the National Civil Protection and the Italian army built two temporary bridges within 10 days of the 24 August 2016 main shock (Durante et al., 2018).

([4]) Note that Eurocontrol (jointly with Galileo, the electricity transmission grid and the gas transmission network) is one of the CIs selected to pilot the approach to CI protection and resilience proposed in (European Commission, 2013).

3 Gaps and challenges

Past events affecting network infrastructures pushed forward our awareness and response to critical events, for instance through updated legislation, technologies and crisis management solutions. Many challenges remain, due for instance to complexity and hyperconnectivity, evolving market conditions, climate change and infrastructure ageing.

A recent study in German cities (Monstadt and Schmidt, 2019) observes that the governance of critical infrastructures 'overarches different, often fragmented, policy domains and territories and institutionally unbundled utility (sub-)domains'. The authors also observe that risk mitigation and preparedness are based on catastrophic scenarios as opposed to past events, and involve considerable uncertainty. While national policies or regulations may be needed, this is often not translated to local vulnerabilities, needs and gaps. The discussion proposed so far in this section can help to shed light into some of the gaps and challenges to addressed, as far as NCIs are concerned.

In power networks, the analysis of recent major blackouts and disturbances led to the identification of some underlying causes, factors and considerations for future developments (Kundur and Taylor, 2007; Kröger and Zio, 2011), as illustrated below.

- Technical failures, external impacts and adverse behaviour of protective devices are important triggering events, when not protected by the N-1 security criterion ([5]) and/or manifesting in combination with high-load conditions. These triggering events can lead to cascading outages of lines or other equipment and, eventually, to the collapse of the entire system.

- Organisational aspects and factors, such as market liberalisation and short-term contracting, can cause the system to operate beyond its original design parameters. Stressing operating conditions such as weakening maintenance work and/or inadequate integration of intermittent power generation have proven to be outstanding causes of critical situations.

- The TSOs play a decisive role in contingency management; lack of situational awareness and short-term preparedness, as well as limited real-time monitoring beyond control areas and poorly timed cross-border coordination, can accumulate as aggravating factors.

- The inadequacy of the N-1 security criterion and, even more importantly, of its evaluation/implementation in various cases has prompted attempts to make it more stringent and legally binding.

- Power systems are increasingly being pushed harder, with higher levels of power transfers over longer distances. Transmission protection operations in the absence of any faults have played a major role in cascaded outages. This is because, as the equipment is more stressed, the boundary between functioning and faulty equipment becomes blurred, making it more difficult for the protection to discriminate.

([5]) The N-1 criterion is 'the rule according to which the elements remaining in operation within a TSO's control area after occurrence of a contingency are capable of accommodating the new operational situation without violating operational security limits' (European Commission, 2017).

Recent critical situations, not necessarily leading to continent-wide blackouts, have highlighted additional areas for improvement in the ETS. In particular, the cold spell of January 2017 (ENTSO-E, 2017) underlined the need for (1) close cooperation among energy sector operators, i.e. electric power and gas TSOs, (2) increased fidelity in the models used for system security and adequacy assessment, and (3) the conduction of stress tests at the pan-European level, also accounting for climatic trends. This becomes even more important as today's electricity systems integrate, requiring efficient interaction between the different stakeholders and levels of responsibility (ENTSO-E, 2019c).

Moreover, Europe's energy sector is shifting from a supply-centric model dominated by fossil fuel to a consumer-centric system with many distributed resources (ENTSO-E, 2019c). Such systems can operate in islanded mode. They can offer options to cope with critical conditions or emergencies in the rest of the power network and to increase the resilience of the overall system, by providing redundancy in energy paths and quick recovery options. In addition, flexibility in terms of long-term and short-term energy storage systems is a key element for enhancing the resilience of the grid and the ability to withstand unforeseen occurrences. Flexibility, however, adds operational complexity to the grid, which has to be appropriately assessed and managed.

In the case of transportation networks too, recent events have led to the identification of gaps to be filled at various levels, including the technological and policy layers. Lessons learned from the aftermath of tunnel disasters, for instance, have highlighted shortcomings in regulation and led to Directive 2004/54/EC (EU, 2004) on minimum safety requirements for road tunnels in the trans-European road network. This expresses a fundamental effort in formulating compliance requirements for tunnel infrastructure safety, and its implementation has been closely monitored throughout the years since it came into force; see for example Krausmann and Mushtaq (2010); Durante et al. (2018); ICF (2015). As a complement, the research community is also addressing tunnel safety and providing suggestions, for instance in the areas of uncertainty treatment and behavioural analysis (e.g. during evacuation); see Ntzeremes and Kirytopoulos (2019).

Transnational transport networks and corridors are increasingly central in emerging disaster risk management strategies. Notably, Directive 2008/96/EC (EU, 2008), complementing the abovementioned Directive 2004/54/EC, laid down key principles for road infrastructure safety management at the level of trans-European road transport systems. Procedures put in place include road impact safety assessments, road safety audits, road safety inspections and network safety management. The implementation of the directive led to a series of successive implementation appraisals (Schrefler and Dinu, 2018). Similar initiatives are in place to cover, more broadly, the Trans-European Transport Networks, a set of strategic land, air and water transport networks currently in the works and representing a key constituent of the EU Trans-European Networks.

A posteriori analyses of events involving aviation have produced a rich set of recommendations. Alexander (2013), discussing the case of the 2010 Icelandic ash cloud, points out criticalities such as some arbitrariness in air restriction decision-making, risk aversion, gaps in procedures and planning, and a lack of modal integration in the European transport system.

The Single European Sky (SES) initiative by the European Commission is an example of the evolving approach to the management of air transportation networks and infrastructures. In particular, the Single European Sky ATM

Research (SESAR) initiative represents the technological pillar of SES, and aims to deliver ATM innovation. The rich SESAR solutions catalogue (SESAR, 2019) includes, for instance, the notion of trajectory-based operations, 'to enable the ATM system to know and, where appropriate, modify the flight's planned and actual trajectory, before or during flight, based on accurate information that has been shared by all stakeholders.

Prospective advantages include efficiency gains both for individual aircrafts and for the network as a whole. Further solutions described therein at the network level include collaborative decision-making and performance management, demand- and capacity-balancing mechanisms, and free routing in high-complexity environments.

In general, assessing the cascade impact of disruptions such as those described above (e.g. major air transport disruptions) remains a challenge due to the complexity of these NCIs. Many approaches exist. Examples include: the cascading impact assessment methodology from (Rehak et al. 2018); the framework for modelling the robustness of the critical infrastructure network proposed in (Pinnaka, Yarlagadda, and Cetinkaya 2015); the integrated framework for hazard estimation, network estimation and infrastructure failure assessment presented in (Pant et al. 2018); the multi-agent system framework for conceptualising, modelling and analysing interdependent critical infrastructure from (Pereyra, He, and Mostafavi 2016); the approach for the analysis of geographic hotspots of critical infrastructure illustrated in (Thacker et al. 2017); various other interdependency models focusing on critical infrastructure networks, such as the ones in (Duan et al. 2016; Lin et al. 2016; Johansen and Tien 2018). While similar models can assist a policymaker in assessing the complex relationships between infrastructures and potential cascade effects, often there is a lack of the resources or expertise needed to apply such models in real-life situations or to scale their application to nationwide assessments.

Network infrastructures face changes in demand and usage due to urbanisation and population growth. The concentration of the population implies a concentration of some risks. Thus, the impacts of any disaster affecting an urban area will be compounded proportionally to the population and infrastructure density. For example, road networks may be used at the maximum of their capacity due to changes in traffic or the development of the city. Another challenge is looking for cost-efficient alternatives.

At the same time, operators of infrastructures have to deal with the ageing of their networks. Maintaining, retrofitting or updating components of infrastructures is a significant annual cost for most operators and poses challenges, as in many cases it may reduce service uptime. In many cases, there may be a lack of alternatives in terms of service provision, or another infrastructure or sector may be affected. In some types of networked infrastructures, such as water distribution systems, ageing may pose problems both to business continuity and to the health of consumers (Allen et al. 2018).

Climate change can affect NCIs, such as energy, transport or water infrastructures. Temperature changes, sea level rise, changing patterns of precipitation and storms may affect demand, reduce efficiency, cause inundation of coastal infrastructure or damage assets, such as bridges, ports and airports (OECD, 2018). Moreover, interdependencies between sectors should be taken into account when planning for climate-resilient and sustainable infrastructures. For instance, Beheshtian et al. (2019) analyse the interdependency between transport and motor fuel supply chains, and investigate how vulnerability to climatic extremes in a fuelling infrastructure hampers the resilience of a transport system.

4 Conclusions and key messsages

In this section, we have addressed NCIs from the disaster risk management perspective. Taking stock of case studies related to the power and transport sectors, we have made observations on the gaps and challenges that systems of this kind pose to our community. Enabling a fuller operationalisation of the scientific contributions still requires substantial effort, which this report contributes to. Next, we provide some conclusions and recommendations.

4.1 Risk and resilience policies

Recent policies stress the importance of resilience for better disaster risk management. For instance, many recommendations issued in recent years are about infrastructural climate resilience, which has the potential to improve the reliability of service provision, increase asset life and protect asset returns. 'Building climate resilience can involve a package of management measures (such as changing maintenance schedules and including adaptive management to account for uncertainty in the future) and structural measures (e.g. raising the height of bridges to account for sea-level rise or using natural infrastructure such as protecting or enhancing natural drainage systems)' (OECD, 2018, p. 2).

Predominantly, the CI resilience issue is faced by resorting to a comprehensive, all-hazards approach. In recent EU policies related to CIs, resilience has gained more and more importance and is connected to a number of strategic directions (Theocharidou, Galbusera, and Giannopoulos 2018). The Sendai framework considers four priority areas related to disaster risk management: (1) understanding disaster risk; (2) strengthening disaster risk governance to manage disaster risk; (3) investing in disaster risk reduction for resilience; (4) enhancing disaster preparedness for effective response and to 'build back better' in recovery, rehabilitation and reconstruction. As mentioned above in this section, the dual aspect of damages to facilities and services, as well as the links to the economic dimension, are also considered.

A key challenge for regulators and governments is to encourage investments by private companies in risk reduction and resilience, especially within the current economic and environmental context. Operators have varying technical, financial, political, reputational and legal priorities and constraints, which the policymakers need to bear continually in mind. To this end, stakeholder engagement and information sharing can be enhanced through participation in public–private partnerships and other networks (Theocharidou, Galbusera, and Giannopoulos 2018). As the OECD (2019) discusses, 'it is important for governments to find the right balance between mandatory and voluntary frameworks to enhance stakeholder engagement in the process and ensure that investments in resilience are effectively made'.

The recent OECD survey mentioned therein identified an articulated set of policy tools for this purpose; see Table 1. The same reference also contains a proposal for a structured approach to CI resilience policies, including the transboundary aspects.

Table 1. *Policy tools to foster critical infrastructure resilience.* ***Source****: © OECD, 2019.*

1. Provision of hazards and threats information	12. Inspections and performance assessments
2. Voluntary information-sharing mechanisms or platforms	13. Fines for non-compliance with resilience requirements
3. Mandatory information-sharing mechanisms or platforms	14. Other types of penalties for non-compliance
4. Awareness-raising activities and training	15. Ranking based on inspection / performance results
5. Resilience guidelines for critical infrastructure operators	16. Reporting on operators' resilience
6. Fostering the development/use of professional standards	17. Sharing best practices
7. Incentive mechanism to assess risks and vulnerabilities	18. Public investments in infrastructure resilience
8. Incentive mechanisms for investing in resilience	19. Guidance for subnational levels of government
9. Sectoral prescriptive regulations dedicated to Critical Infrastructure Protection	20. Mandatory insurance for critical infrastructure
10. Performance-based regulations on business continuity	21. Peer reviews, monitoring and evaluation
11. Mandatory business continuity plans	22. Sectoral mutual aid agreements

4.2. Modelling and simulation

Throughout this section, we have made reference to the role of scientific disciplines such as network science in NCI applications; see also Galbusera and Giannopoulos (2019) for further discussion. The study of NCIs still requires important modelling efforts, ranging from topological aspects to dynamical processes and multi-layer networks. From the disaster risk management perspective, interesting insights can come, for instance, from network perturbation studies. Key aspects covered by the literature include the compromise between error tolerance and attack tolerance (Albert et al., 2000; Crucitti et al. 2004) and the representation of failure propagation processes (Newman et al. 2005). Eusgeld et al. (2009) provides further insights on the role of both network theory and object-oriented modelling in vulnerability analysis of CIs. As far as the research on cascading disasters is concerned, Alexander (2018) observes that 'some of the work covers the propagation of failures through networks, but this is largely restricted to individual categories of critical infrastructure'.

Aspects to cover in the development of modelling and simulation tools include reliability and dependability assessment, optimisation, large-scale simulation and the treatment of uncertainty. Examples of tools or approaches for NCI applications include Bayes networks (Schaberreiter et al., 2013), Boolean networks (Galbusera et al., 2018), probabilistic models for cascading failures (Newman et al., 2005), agent-based approaches (Panzieri et al., 2005; Kröger, 2008), hierarchical holographic modelling (Haimes et al., 2002), input–output modelling (Galbusera and Giannopoulos, 2018), risk analysis-based models (Ezell et al., 2000), Monte Carlo simulation (Pant et al. 2016), Petri nets (Ghasemieh et al., 2013) and Unified Modeling Language-based approaches (Bagheri and Ghorbani, 2010). In the literature, surveys are also available to provide a broader picture of the emerging modelling approaches; see for instance (Bagheri and Ghorbani, 2008; Satumtira and Dueñas-Osorio, 2010; Ouyang, 2014) ([6]).

From the community perspective, the development of models should also be accompanied by initiatives to facilitate their exchange, validation and use even beyond the boundaries of particular specialisms. Knowledge management initiatives such as the creation of inventories of models, methods and tools may serve this purpose.

([8]) Further examples of resources that could be used for cascade effect analysis can be found at Poljanšek et al. (2019, pp. 115–118).

Work is also needed to facilitate the interoperability of models and to relate them to disaster risk management practices. The necessity for extended paradigms for the analysis and modelling of CIs is addressed in more detail by Zio (2016).

Finally, the development of modelling and simulation approaches with relevance to NCIs is coupled with the on-going scientific discussion on conceptual aspects such as the definition of the technical, organisational, social and economic dimensions of resilience; see Theocharidou et al. (2018) and related references for further analysis. See also Alderson and Doyle (2010) for a discussion on complexity in network-centric infrastructures, as well as Florin and Linkov (2016); Trump et al. (2018) for resources on resilience aspects.

4.3 New technologies

Emerging technologies have the potential to radically transform aspects of CI management, such as monitoring. For instance, the increased availability of data from satellite Earth observation is becoming important for damage prevention and restoration monitoring. Recent literature shows how such data, with different temporal and spatial resolution characteristics, can be used as a tool to evaluate the state of health of various CIs (Milillo et al., 2016; Chang et al., 2017; Huang et al., 2018), as well as to sample the surrounding environment, detect potential hazards and help to prevent potential damages (Peduto et al., 2017; Dai et al., 2018; Solari et al., 2018). However, there are still challenging issues to be addressed in order to provide fully operative tools for this purpose.

In parallel to satellite Earth observation, the development of short-range non-destructive techniques has grown significantly over the last 10 years. The appearance of drones has introduced great innovation in CI monitoring (Colomina and Molina, 2014), allowing damage inspection even in a number of difficult-access areas. In addition, the technological development of terrestrial sensors, such as radars and laser-based sensors, has provided a set of instruments to check both structural health and potential damage without interfering with the CI in question (Teza et al., 2009; Pieraccini, 2013; Luzi et al., 2014; Monserrat et al., 2014; Ham and Lee, 2018; Zhang et al., 2018). The use of these techniques, too, is still limited by various aspects such as costs or lack of awareness, or regulatory restrictions (e.g. in the case of drones).

Clearly, many other aspects of information technology are relevant to NCI disaster risk management. An example is the development of data-gathering and analysis platforms (Galbusera and Giannopoulos, 2017). Application-specific studies have highlighted the relevance of such kinds of data-backed initiatives. A recent study on bridge failures in the United States, for instance, points out the relevance of data collection on historical bridge failures to improving bridge specifications (Lee et al., 2013).

In recent times, the development of some apps and other information-sharing tools represents an excellent example of the use of technologies to foster citizen awareness and engagement. For instance, two-way alerting mechanisms may prove beneficial in reducing reaction time to critical events affecting network infrastructures, and may mitigate impacts on end-users.

4.4. Exercises and stress tests

Finally, an identified gap remains the need to perform joint exercises to better comprehend dependencies between CIs, thus generating more accurate risk assessments, and to jointly test risk treatment options. Such exercises may need to be designed with a different mentality with respect to the case of civil protection exercises, which focus mainly on the operational capabilities of emergency responders. Crisis scenarios that involve both public authorities and infrastructure operators are not widely analysed, but they can be a valuable tool to test risk and resilience strategies and plans, as well as to enhance collaboration (Poljanšek et al., 2019). An interesting example of an exercise initiative relevant to NCIs is the Homeland Security Exercise and Evaluation Program (HSEEP) by the US Federal Emergency Management Agency (FEMA, 2020). The HSEEP provides guiding principles for exercise projects and programmes, including aspects related to their design, development, conduct, evaluation and improvement planning.

A related concept is that of stress tests (Galbusera et al., 2014; Galbusera and Giannopoulos, 2019). A stress test is a systematic method of crisis scenario analysis and of evaluating measures taken to reduce the societal risk exposure stemming from networked CIs. It involves the owners, the users and other stakeholders of CIs. Following the use of stress tests in the banking sector after the 2007–2008 financial crisis and in the nuclear power sector after the 2011 Fukushima disaster, the European Programme for Critical Infrastructure Protection (EPCIP) (European Commission, 2013) recognised that there is a need for stress tests of critical non-nuclear civil infrastructure systems, to verify their risk exposure levels as well as to help increase the disaster resilience of European CIs.

To this end, a harmonised risk-based natural hazard stress test methodology for CIs was recently developed in FP7 project STREST ('Harmonized approach to stress tests for critical infrastructures against natural hazards') (Esposito et al., 2020). The STREST stress test is designed to cover a wide range of critical non-nuclear CIs. It can be conducted at different levels, characterised by different scopes and complexities of risk analysis, to suit the widely different capabilities and resources of different European CIs. The STREST stress test comprises the following phases. First, the goals, scope and risk analysis methods are defined, and the stress test team members are selected and organised. The stress test is then performed at both component (subsystem) and system levels, accounting for network dependencies and cascading effects, using a probabilistic risk analysis approach. A mechanism for an independent review of the stress test findings is built in. Furthermore, risk assessments are harmonised using a penalty system to compensate for the differences between different risk analysis methods, and levels of CI and hazard knowledge. The harmonised risk assessment results are compared with societally accepted risk levels using a STREST grading system. Finally, the STREST CI grade and risk assessment findings are transparently reported to the owners, stakeholders and the public to build public trust.

The STREST grading systems are conceptualised to enable a comparison of different CIs in terms of their own disaster risk exposure and the risk exposure they present to society. This is an essential step towards harmonised systemic risk evaluation of CIs across Europe. The grading systems contain a mechanism for continuous reduction of CI risk and improvement of CI disaster resilience enacted through mandatory repeated stress tests at risk-driven intervals. For example, if the CI system poses a risk that is greater than societally accepted risk exposure levels, the CI owners and stakeholders are obligated to take risk reduction actions by a specific deadline and to verify the achieved risk reduction in a subsequent stress test. The implementation of the STREST stress test was also illustrated using six different CI systems, characterised by different functions and dependencies, network structures, geographical extents and natural hazard exposures (Argyroudis et al., 2019).

In conclusion, it is important to observe that a comprehensive treatment of disaster risk management for NCIs extends well beyond the electricity and transport realms, which have been scrutinised in this section. The mosaic of contributions on this subject is made of many pieces, including insightful studies on finance (Gai and Kapadia, 2010; Glasserman and Young, 2015), gas (Cimellaro et al., 2015) and telecommunications (Sterbenz et al., 2013).

O'Rourke (2007) suggests that 'thinking about critical infrastructure through the subset of lifelines helps clarify features that are common to essential support systems and provides insights into the engineering challenges to improving the performance of large networks'. A scientific attitude to NCI analysis and assessment able to compare sectors and learn from disciplines can, therefore, be crucial to building resilient communities.

Policymakers

Policymakers should focus on stakeholder engagement and information sharing, including public–private partnerships with operators and citizen involvement initiatives. Existing constraints affecting the private sector should be taken into account, striking the right balance between mandatory and voluntary frameworks to ensure effectiveness in investments in risk reduction and resilience.

Practitioners

Practitioners face varying technical, financial, political, reputational, legal priorities and constraints. For better disaster preparedness and response by network infrastructure operators, the use of new technologies such as monitoring tools or information-sharing platforms can be valuable. Initiatives such as training and exercises or stress tests represent an opportunity to identify gaps and coordinate for better resilience.

Scientists

Scientists have a key role in the development of innovative modelling and simulation tools for network infrastructures. These can assist policymakers, operators and responders to better understand failure propagation through networks, identify mitigation actions and optimise response plans. Scientific effort should be devoted to tool interoperability, large-scale simulation, the treatment of uncertainty, reliability and dependability assessment, as well as resilience aspects.

Citizens

Citizens rely heavily on the use of network infrastructures. They can benefit greatly from new technologies, for instance as a way to get alerts about service disruptions and also to report promptly on the failures they observe.

3.4.3 Core industrial and energy facilities

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Krausmann, E., Fourtounas, A., Girgin, S., Hernandez Ceballos, M.A., Jung, D., Salzano, E., Šimić, Z., 2020, 'Core industrial and energy facilities', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Introduction

Industrial installations and energy facilities are susceptible to a variety of hazards, which can be natural, technological or intentional in nature. Some of these facilities pose a secondary hazard if they store, handle or transport hazardous materials. In case of spills, fires or explosions after natural-hazard impact, the associated risk is referred to as natural-hazard-triggered technological accident (Natech) risk (Krausmann et al., 2017a). Failure or disruption of these facilities can cause impacts on society, the environment or the local, national or global economy. Impacts can also occur as a result of business or service disruptions, such as power outages or a loss of production (Küfeoğlu, 2015). They can be exacerbated by cascading effects and (inter)dependencies between systems. In some cases, cascading effects across sectors can reach global proportions, resulting in a shortage of raw materials and finished products (Lohr, 2011).

There are many examples of incidents involving core industrial and energy facilities. In 2005, leaking fuel caused a major explosion and fire at an oil storage and transfer depot in Buncefield, United Kingdom, which engulfed 23 storage tanks (MIIB, 2008). The incident also revealed the complexity of supply chains conditioned by the just-in-time supply approach (Airmic, 2011). In the same year, Hurricanes Katrina and Rita destroyed or damaged 276 offshore platforms, 24 rigs and 457 underwater pipelines, and resulted in global price hikes for oil and gas (Pan, 2005; Cruz and Krausmann, 2008). A technical problem caused an explosion and fire at an Austrian natural-gas distribution and reception hub in 2017, causing Italy to declare a state of emergency due to a lack of gas supplies (Oltermann, 2017).

This section provides an overview of the risks to and impacts from selected industrial and energy facilities that are critical for the European Union (EU), such as chemical facilities, the pharmaceutical industry, refineries, oil and gas pipelines, and offshore facilities. It exemplifies the diversity of incident triggers, risk receptors and impacts by using three iconic case studies. It then discusses the gaps and challenges associated with reducing the risks and their impacts. The section ends with a summary of recommendations for the different stakeholder groups. Some of the discussions are equally valid for types of critical industry and infrastructure other than the ones mentioned above

2 Case studies

Numerous past events are testimony to the potential for major consequences of incidents at core industrial and energy facilities.

In the following, three detailed case studies demonstrate the different types of incident triggers, impacted infrastructure and consequences. The incidents not only affected the countries they originated in, but also had international impacts and influenced risk-management regulations and practices across countries and continents.

2.1 Spolana chemical accident, Czechia, 2002

In August 2002, heavy and long-lasting rainfall in central Europe led to major flooding of the River Elbe with unprecedented flood heights. On 15 August 2002, the flood hit the Spolana general chemicals facility in Czechia. The facility was protected against a 100-year flood; however, the flood waters exceeded the 100-year water level at the site by 1.3 m (eNATECH, 2018).

The anti-flooding measures implemented at the plant were inadequate for the magnitude of the flood, and the storehouses holding chlorine, a highly toxic and corrosive substance, were inundated. Several of the pressurised chlorine tanks were lifted by buoyancy and in the process the safety valves of a full chlorine tank were torn off, resulting in a massive leakage of over 80 tonnes of chlorine (Figure 1). On 23 August, a smaller chlorine release occurred (Hudec and Lucš, 2004; eNATECH, 2018).

Although nobody was killed during the accident, it had a significant impact on the environment and agricultural activities in the surroundings of the chemical facility. The chlorine entered the Elbe and the air, where the chlorine gas chemically burned the flora around the facility. Community life was disrupted, as the public had to shelter in place to escape the chlorine cloud. The operator was criticised for not properly warning the population after the chlorine release (Reliefweb, 2002). In addition, significant quantities of other hazardous substances (e.g. dioxins) were released into the Elbe and settled in sediments on its shores. In a village downstream from the damaged chemical facility, dioxin levels were found to be three times higher than safety norms (Gautam and van der Hoek, 2003). The company indicated that the direct costs to property due to flood damage amounted to approximately EUR 29 million (eNATECH, 2018).

Figure 1. *Chlorine release at the flooded Spolana plant.* ***Source****: © Václav Vašků.*

After the accident, on-site protection measures were updated to prevent the recurrence of such an event in case of a flood of the same or higher severity. Among the actions taken, chlorine storage was reduced to 50 % of the capacity before the accident, thereby significantly reducing the risk. The storehouse emergency exhaust system was improved to allow suction of the chlorine from the upper part of the storehouse, which is important if the retention basins are flooded.

From a policy perspective, discussions were launched to better understand how flood impacts of this magnitude could be prevented in the future. As a regulatory follow-up after this and other accidents triggered by natural hazards, the EU Seveso Directive on the control of major accident hazards involving dangerous substances was, inter alia, amended to render the need for protection against this type of risk more explicit (EU, 2012). The directive, which applies to over 10 000 industrial establishments in the EU (Gyenes and Heraty Wood, 2018), now explicitly requires the consideration of natural hazards as a threat to the safe operation of hazardous installations, including the demonstration that the risk is identified and mitigated.

2.2 Deepwater Horizon accident and oil spill, United States, 2010

The Deepwater Horizon oil spill was one of the largest marine oil spills in history. It was caused by an explosion on BP's Deepwater Horizon oil rig located in the Gulf of Mexico in April 2010. A natural gas surge blasted through a concrete core installed to seal the well for later use. The gas travelled up to the platform and ignited a series of explosions and a firestorm causing 11 fatalities and 17 injuries (Figure 2). The rig capsized and sank in 2 days, resulting in an oil spill lasting about 5 months and releasing around 4.9 million barrels of oil (Pallardy, 2018). A massive response with more than 100 000 people, 6 500 vessels and 4 000 km of boom ensued to protect the environment (BP, 2015). Extensive damage was caused to marine and wildlife habitats, and also to the drilling, fishing and tourism industries.

Figure 2. *Left, supply vessels combating the Deepwater Horizon fire; right, skimming oil in the Gulf of Mexico after the oil spill from Deepwater Horizon.* ***Sources****: left, photo courtesy US Coast Guard; right, photo courtesy National Oceanic and Atmospheric Administration (NOAA).*

An offshore drilling moratorium left an estimated 8 000–12 000 people temporarily unemployed (Snow, 2010). About one third of US federal waters in the Gulf was closed to fishing at the peak of a fishing ban (NOAA, 2010). Following the accident, BP's stock value fell by more than 50 %, resulting in a total loss in value of USD 105 billion (Tharp, 2010), and its petrol stations in the United States reported a drop in sales of 10–40 % due to backlash (Weber, 2010). In 2016, a historic USD 18.7 billion District Court settlement was approved, resolving all litigation with the government and the affected states over the economic and environmental claims. Overall, BP spent more than USD 65 billion in relation to the spill (Vaughan, 2018). Multiple companies and individuals were charged with federal crimes, but no charges resulted in prison time (Gill, 2016).

There were many investigations into the accident, addressing technical, organisational and human aspects (DNV GL, 2015). The government report stated that the accident was due to poor risk management, last-minute changes to plans, failure to observe and respond to critical indicators, inadequate well-control response and insufficient emergency response training (BSEE, 2011). A national commission concluded that the accident was avoidable and resulted from clear mistakes by the companies and also by government officials who failed to create and apply proper regulatory oversight (Graham et al., 2011).

The accident was a global wake-up call and caused major changes in the design and operation of offshore equipment, accident prevention measures, planning and management of spill response activities, safety culture and regulations. In the United States, the regulatory body was restructured, new requirements were issued for offshore operations, new standards for drilling and well control were published, the accident-reporting system was improved and research on offshore activities was promoted (DNV GL, 2015).

The European Commission launched an assessment of the offshore activities in EU waters to identify actions needed to maintain safety (European Commission, 2011). Subsequently, a new EU directive was published on the safety of offshore oil and gas operations to prevent accidents and respond promptly and efficiently if they occur (EU, 2013). The directive contains provisions on risk assessment and emergency response planning before exploration or production, to ensure that companies have the necessary technical expertise and are well financed before granting licences; independent verification of technical safety solutions; environmental protection measures; emergency preparedness by the national authorities; full liability of the companies for environmental damage caused in EU waters; and public information on safety and public stakeholder involvement on planning of installations (Moore et al., 2013).

2.3 Florakis naval base explosion and power blackout, Cyprus, 2011

In July 2011, an explosion of ammunition and military explosives at the Evangelos Florakis Naval Base in Cyprus caused the fifth-largest non-nuclear explosion in history, with a yield of about 2–3.2 kilotons TNT equivalent. The explosion led to cascading events causing damage not only to the naval base but also to its surroundings, including the Vasilikos power station (VPS), the largest power facility in Cyprus, and urban areas.

The blast destroyed the firefighting system of the VPS but the 60 000 t of diesel and 84 000 t of fuel oil stored there did not ignite, avoiding a domino effect. At the time of the explosion, 98 containers of highly explosive ammunition seized by the US Navy in 2009 had been stored in the open for over 2 years. Bad decision-making at the naval base, including lack of political willingness, ineffective logistics management and the lack of a viable firefighting plan (Florin et al., 2016), and the high temperatures and humidity of Cyprus caused the accident.

Since military and energy facilities were concentrated in a cluster, the power station was severely damaged in the explosion (Figure 3). It killed 13 people and injured a further 62 but also severely damaged all the buildings in Zygi village, displacing about 150 civilians (Evripidou, 2011; Hajipapas and Hope, 2011). The electricity supply to about half of Cyprus was interrupted, and for 15 days rolling blackouts affected cities, airports, hospitals, tourist areas and industrial facilities, causing outages and economic damage by disrupting business and society.

The Electricity Authority of Cyprus was forced to import generators from Greece and Israel while the damage, estimated at EUR 2 billion (almost 10 % of the country's economy), was repaired, with a recovery cost of EUR 900 million for the VPS alone (Hajipapas and Hope, 2011). Eight years after the accident, Cyprus reimbursed over EUR 4.5 million to citizens, and lawsuits by private companies claiming a total of EUR 8.5 million are still ongoing.

Figure 3. *Vasilikos power station after the Florakis Naval Base explosion, Cyprus.* ***Source****: photo courtesy IDE Technologies Ltd.*

The accident investigation report found that Cyprus had not applied the Seveso II Directive (EU, 1997), an omission that exacerbated the accident (Polyviou, 2011). Following the accident, the government took action to improve risk management. In 2013, the ZENON basic national plan on the management of risks from human-made or natural origin in critical infrastructure was issued (Cyprus, Ministry of Defence, 2013).

Exercises were organised to test the plan's effectiveness, train the personnel and inform the public. In the same year, the VPS issued a new handbook on the proactive identification of human-made and natural hazards, according to Seveso II criteria (Electricity Authority of Cyprus, 2018).

The handbook is reassessed periodically considering feedback from all stakeholders. In 2016, oil and gas companies located near the power plant were obliged to engage in continuous communication with each other to coordinate planning for security issues, as well as response to disasters (Cyprus, Ministry of the Interior, 2016). In 2017, the ZENON Coordination Center was inaugurated. It is the main executor and coordinator of the ZENON plan in case of man-made or natural disasters, declares alert states and is in contact with the relevant EU agencies. Since it may take time for help to arrive by air or sea, the aim of this centre is to respond promptly during the initiation of an event to avoid an escalation to catastrophic proportions, as well as to increase the risk awareness of society.

3 Reducing impacts – gaps and challenges

The factors that create risk to industry and energy facilities can be natural, technical or organisational in nature. Some underlying causes are linked to risk-governance challenges and socioeconomic context. Other factors, such as climate change, the ageing of infrastructure or the greening of production facilities, may introduce additional risks. The subsections below provide examples of risk drivers that directly or indirectly influence the impacts resulting from an incident.

3.1 Risk governance

Risk governance should be approached from a territorial perspective to capture the potential interactions of industry, infrastructure and communities.

Governance' refers to the actions, processes, traditions and institutions by which authority is exercised and decisions are taken and implemented. Risk governance applies the principles of good governance to the identification, assessment, management and communication of risks (IRGC, 2020). Gill and Ritchie (2018) emphasise that the occurrence of technological incidents highlights conceptual and theoretical gaps in disaster science, which has been focusing on sudden-onset natural hazards since the 1970s.

In addition, the risk management of a critical facility is often viewed in isolation from its surroundings rather than considering the potential interactions with other industry, lifelines and nearby communities. In the EU, land use planning around high-risk chemical facilities aims to protect the surroundings of the plant (EU, 2012); however, this is not always the case in other parts of the world or for other critical sectors. This means that the potential for cascading events and the impact on infrastructure resilience are not captured. Since natural hazards often affect large areas at the same time, this is even more relevant to Natech risks. Suarez-Paba et al. (2020) contend that a systemic view is required for the effective management of Natech risks, requiring a territorial approach to risk governance and incorporating physical (e.g. industrial facilities, lifelines, building stock), organisational and socioeconomic factors into the analysis. Decommissioned or mothballed facilities constitute a particular risk-governance problem.

Efforts to improve risk governance exist in all domains where modern government tries to reduce costs and ensure benefits. Some aspects of risk governance from different industry or infrastructure domains could be applicable universally (i.e. improved legislation, enforcement, inspections and experience feedback practice). However, systematic research into the applicability and effectiveness of different governance types for a variety of problems and under different conditions is lacking (NASEM, 2018). International organisations, such as the European Commission or the Organisation for Economic Co-operation and Development (OECD) facilitate risk-governance experience exchange in different domains (e.g. Tomic et al., 2008; NEA, 2018; OECD, 2003, 2014, 2015).

3.2 Data availability, collection and analysis

The availability of accurate, reliable and complete data affects the quality of risk analysis and all risk-reduction decisions based on it.

DData are the basis for gaining knowledge on the dynamics of incidents, through incident analysis and learning lessons. Data required for risk assessment must be accurate, reliable and complete, and must consider, e.g. in the case of Natech risk assessment, all natural hazards that an industrial plant can be subject to in a certain area, the likelihood of these hazards, their possible impact, the equipment's vulnerability to each natural hazard identified and the consequences of impact (Girgin et al., 2017; Krausmann et al., 2019). However, industry and infrastructure data or information on incidents is often not collected in a systematic way or voluntarily disclosed, owing to confidentiality issues. The availability of relevant and reliable data conditions the quality of risk assessment and all risk-reduction decisions that are based on it. Several studies have pointed out (e.g. De Almeida et al., 2015; Sengupta et al., 2016) the scarce availability of industrial data and associated databases, which can hamper the definition of a strategy for risk reduction. A recent study by Heraty Wood and Fabbri (2019) concludes that databases for chemical incidents are incomplete and fragmented. They add that an official international database for analysing global chemical accident trends does not exist and that only relatively few countries and industry organisations around the world maintain dedicated chemical accident databases.

Data mining and standards, i.e. harmonisation of data according to standardised procedures, are relevant to improve the feasibility and rapidity of analysis (OECD, 2012). The proper compilation and aggregation of data in well-structured databases allows experts to systematically assess risks to industry and energy infrastructure, and supports lesson-learning studies for better preparedness and loss prevention (Chakraborty et al., 2018).

3.3 Risk assessment

Methodologies, tools and guidance for Natech risk assessment are scarce.

Risk analysis identifies threats at industrial and energy facilities both during normal operation and in incident situations. It evaluates the risk based on the likelihood of occurrence of an event and its consequences. The analysis can be qualitative, semi-quantitative or quantitative. Quantitative risk analysis uses sophisticated models to simulate and analyse a high number of scenarios and requires significant time and expertise (Cox, 1998; Uijt de Haag and Ale, 1999; CCPS, 2000).

All approaches are subject to data and model uncertainties, whose magnitude needs to be quantified before risk-analysis results should be used for decision-making. Once the risk has been analysed, it needs to be compared with prescribed numerical acceptability criteria to determine if risk-reduction measures have to be implemented. In the EU, these criteria are not uniform among Member States, which hampers comparability between countries. The criteria can range from fully quantitative (occurrence probabilities) to deterministic (maximum permissible levels of overpressure, toxic concentration, etc.). Countries can also have different thresholds.

Certain identified risk scenarios are commonly removed from the assessment process when their likelihood is considered below a limit probability defined according to acceptability criteria. While this approach helps to save time and resources by screening out seemingly less important scenarios, this can only work if assumptions are sound and subject to low uncertainty. This approach also creates immediate problems for high-impact, low-probability risks, as they could be lost from the risk-management process (Nafday, 2009).

Natech risk analysis has been hampered by its multi-hazard risk nature and a lack of damage models and Natech scenarios, resulting in a lack of Natech risk-analysis methodologies and tools. Guidance on Natech risk assessment at industry and community levels is also scarce. Therefore, this risk source is not adequately taken into account in the industrial risk-assessment process, and preparedness levels are low, even in countries generally well prepared for natural hazards (Krausmann et al., 2019). Steps have been taken to address Natech risk analysis in a qualitative and (semi-)quantitative way at facility level or in national risk assessment (Cruz and Okada, 2008; Cozzani and Salzano, 2017; Krausmann, 2017; Krausmann et al., 2017b; Girgin et al., 2019). However, no assessment tool exists that captures all external hazard factors (Girgin et al., 2017).

3.4 Cascading effects

The risk of cascading effects is high for core industrial and energy facilities.

Today's industry and energy infrastructures are highly interconnected and mutually dependent in many respects: physically, spatially, logically and through the information infrastructure (Rinaldi et al., 2001; Petit et al., 2015). A dependency exists if one infrastructure relies (depends) on the service provided by another infrastructure in order to carry out its function (Bloomfeld et al., 2009; see also Section 3.4.2 of the present report). These dependencies (unidirectional) and interdependencies (bidirectional) can give rise to a percolation of failures, as a failure in one system can produce a failure in another. The spreading of failures can take place in a cascading (non-linear) manner, which can exacerbate the impact of the initial disruption. On the other hand, interdependencies do not per se give rise to risks, but can in some cases also be a source of redundancy and fault tolerance (Bloomfeld et al., 2009), which underlines the need to understand them clearly.

Energy production facilities are rich in interfaces between different infrastructures (e.g. energy, transport, communication). Industrial production processes usually require the transportation of raw materials and fuel, and the distribution of a product to consumers or to secondary industry, and thus depend on various infrastructures. Nearly all facilities depend on supervisory control and data acquisition systems required to control or monitor the system (cyberdependency). Furthermore, logical dependencies on the financial sector and governance exist. Disruptions to one of these essential services might not only result in economic losses, but also endanger the security of supply, with possible impacts on society if products are of vital importance to public security, societal well-being or economic prosperity. If at the end of the chain stands a service or (physical) supply of critical importance, dependencies along the chain could also be identified as critical.

In addition, industrial plants are often concentrated in clusters (as are transport networks), and an accident in one facility can cascade to multiple units in the same facility or to neighbouring plants, thereby increasing the severity and likelihood of negative impacts, which are called domino effects. This risk is significantly increased in cases of natural-hazard impacts on industry (Cozzani et al., 2013; Necci et al., 2015). Unfortunately, this domino risk is not systematically captured in industry because of the complexity of the analysis and the large number of data needed (Reniers and Cozzani, 2013). Novel modelling techniques have been proposed to address this problem (e.g. Khakzad, 2015; Kamil et al., 2019).

The risk of propagation of failures among different interacting infrastructures, e.g. between electrical transmission and natural gas systems (EU, 2008), has reached the attention of policymakers in recent years, partly because of the increased significance of gas-fired power plants as backup generators in the transition towards renewable energy sources. Many regions of the EU rely heavily on foreign natural-gas imports. The need to identify 'critical gas-fired power plants' has also been noted by policymakers at the European level (EU, 2017, Art. 11). In order to contain the risk, the relevant (inter)dependencies between infrastructures must be well understood.

It is usually impossible to fully analyse or understand the behaviour of a given infrastructure in isolation from its environment or connected infrastructures. The methodology to analyse interdependencies between infrastructures should match the needs of each specific problem and be based on a solid theoretical foundation, as are for example the well-developed theories of complex adaptive systems and of dependable systems (Avižienis et al., 2000; Laprie, 2008). A systematic approach is needed to describe the mechanisms, exposing a clear chain of causality, and to quantify the impact of dependencies and interdependencies between different systems and sectors.

3.5 Emergency management

Interfaces and procedures for multi-agency cooperation and communication are key for successful emergency management.

Emergency planning is at the interface between incident prevention and consequence mitigation, and ensures adequate preparedness in case of an event. The EU's Seveso Directive requires the preparation of internal and external emergency plans and the establishment of procedures to ensure that these plans are tested and revised as necessary (EU, 2012). The internal emergency plan is under the responsibility of the operator and aims to protect potential targets within a facility. Public authorities are in charge of the external emergency plan, which mitigates the risk to off-site targets. Similarly, other pieces of legislation for offshore operations or natural-gas supply include provisions to prepare for emergency situations (EU, 2013, 2017). It is vital that the various actors involved in emergency management cooperate effectively. The risk of transboundary impacts should also be taken into account for facilities close to borders (UNECE, 2015).

Although legislation and regulations are necessary to ensure the safe operation of industrial and energy facilities, they may not be sufficient to prevent or adequately prepare for incidents. Gyenes and Heraty Wood (2018) found a number of patterns related to failures in emergency management:

- lack of clear emergency response procedures with well-defined roles and responsibilities, and deficiencies in the emergency plan,
- lack of accident scenarios in the emergency plan due to their low frequency of occurrence,
- inadequate training of emergency managers and lack of emergency exercises,
- inadequate evacuation plans,
- inadequate public warning systems,
- inadequate communication and coordination between on- and off-site response services,
- unavailability of emergency power supply for safety-critical parts of a facility.

Additional problems arise because emergency planning usually does not acknowledge dependencies between critical infrastructures, possibly leading to deficiencies in crisis response and indirect impacts on the population. Moreover, multiple critical installations can fail at the same time because of common-mode failure or cascading effects (which are common occurrences during disasters of natural origin).

However, preparedness measures taken by operators, as well as by emergency responders, usually take into account only single failures (Boin and McConnell, 2007; Luijf and Klaver, 2009). For example, owing to its multi-hazard nature, Natech risk needs special treatment because of the complications generated by the natural-hazard trigger. The possibility of multiple and simultaneous accidents over large areas, the increased likelihood of cascading events and the accompanying challenges in managing the emergency might overwhelm on- and off-site response capacities alike.

4 Conclusions and key messages

Collaboration between the different stakeholder groups is essential for effectively reducing risks.

Industrialisation, urbanisation and climate change are increasing the risks from natural and man-made hazards. Damage or disruption of industry and energy facilities may severely affect society either by the consequences of technological accidents or through effects on the supply chain. Management of these risks is essential for reducing losses but also for sustainable industrial growth. This requires a concerted effort by policymakers, scientists and practitioners with the involvement of citizens.

In the following, recommendations for addressing existing gaps for each stakeholder group are proposed ([1]). The need for open and effective communication to share relevant information applies to all stakeholders.
The adequate handling of potential data sensitivities must also be ensured.

Policymakers

- Base policy development on experience and science with transparent justification and independent verification.
- Approach risk governance from a territorial perspective that views the safety and security of critical facilities in conjunction with their surroundings.
- Encourage corporate and government leadership at all levels, and promote new governance models fostering the sharing of responsibility for a risk.
- Exploit risk governance insights from different sectors, and especially from high-hazard activities, as they are universally applicable. International organisations such as the European Commission, OECD, the United Nations Economic Commission for Europe (UNECE) or IAEA could help support arrangements to identify and disseminate risk-governance experience across different regulatory domains.
- Mandate that all risks to industry and energy facilities be analysed, including cascading risks, starting from a national level, and provide a framework for emergency management to clarify responsibilities. Potential transboundary risks should also be taken into account in this context.
- Ensure (with the help of practitioners) that the results of research projects, e.g. new or improved risk-analysis methodologies, are disseminated and applied.
- Encourage knowledge transfer and experience sharing between (inter)dependent sectors to guarantee a more efficient use of resources.
- Promote public–private partnerships to provide solutions linking science, practice and policy-making. For the sake of societal resilience, these partnerships should not be driven by market forces.
- Incentivise private bodies to invest in risk-management structures that help to prevent, prepare for and respond to infrastructure failures and their societal repercussions.

([1]) Please note that policymakers include governmental authorities and that practitioners include operators, emergency responders and insurance.

Practitioners

- Collect data and make them accessible (including to scientists) to enable risk analysis and to prepare for emergencies. New technologies, e.g. artificial intelligence, can support the data collection.
- Explain the results of risk analyses, with their underlying assumptions, completeness and level of uncertainty, to facilitate communication with policymakers and citizens.
- Verify the validity of design criteria, construction standards, and prevention or mitigation measures considering industry-specific conditions (e.g. ageing) and hazard-specific conditions (e.g. climate change affecting natural hazards' frequencies and intensities).
- Promote the use of good practices in risk management, including cross-fertilisation between sectors.
- Develop business continuity plans to facilitate recovery after infrastructure failure. For example, facilities could stockpile spare parts to ensure that service recovery is fast after an incident.
- For Natech accidents, assume in on-site emergency plans that off-site response resources and lifelines might be unavailable.
- Assess physical emergency-response capacity, including protective equipment, and the capacity needed in case of cascading events, when competition for scarce resources will manifest.
- Review and test emergency plans periodically to ensure they are up to date. Also outline actions to take if assumptions are exceeded (e.g. if a natural hazard exceeds design criteria). For industry in natural-hazard areas, assume that the natural event will render the response more complex (e.g. no possibility of shelter in place or evacuation).
- Train emergency responders and security personnel on how to handle releases of hazardous materials when providing assistance to citizens affected by a natural hazard.
- Make medical services aware of the risks at industry and energy facilities to ensure that they have sufficient and suitable resources for treating the victims of hazardous materials releases.
- Emergency planning and response should exploit new technologies, such as new communication systems, 3D photography, robots and drones.
- Evaluate investments to ensure they are risk sensitive and do not aggravate existing risks.
- Use financial incentives (e.g. lower insurance premiums) to increase resilience by rewarding risk-averse behaviour.

Scientists

Make existing data, models and tools for the analysis of impact risks available to practitioners, including guidance on their use and limitations, and recommend best practices for risk analysis.

- Carry out benchmarking exercises for methodologies for risk analysis of critical infrastructures, to understand their reliability and applicability.
- Identify and quantitatively assess (inter)dependencies and propose actions and measures that could be taken to eliminate or mitigate them.
- Develop methodologies for better estimation of environmental damage and economic losses. These methodologies should also consider cascading impacts.
- Engage in studies that measure the relative costs of prevention and preparedness versus response and recovery.
- Carry out systematic research into the applicability and effectiveness of regulatory approaches across different sectors and conditions.

Citizens

- Proactively request information about risks from industry and energy facilities in the neighbourhood, unless already provided by authorities, making use of citizens' rights under the Aarhus Convention (UNECE, 1998). New media and information technologies should be employed to draw citizens' attention to risks.
- Participate in emergency drills to train the correct behaviour during hazardous material releases.
- Request the inclusion of disaster risk management in school curricula, stressing the importance of both natural and technological risks, their possible interaction and the factors that drive risk.

3.4.4 Communication systems

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Chaudhari, K., Lund, D., Paruthummootil, J.P., De Toro, P., Cerreta, M., Marin, J.L., Halat, M., 'Communication systems', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Introduction

Humans and other life forms have communicated for millions of years, interacting to coexist, co-create and develop our societies to where we are today. Only the last 140 years have seen the mainstream use of electronic communication, marked by the award of the telephone patent to Alexander Graham Bell in 1876.

However, within the last 20 years we have witnessed an information revolution. Communication capabilities have moved rapidly, from 'text messages' and voice only, to highly rich media allowing simultaneous communication of live video, audio and large amounts of information, which are vital for speeding up and improving economic activities. The coming 5–10 years will see use of immersive, augmented and mixed reality, whereby communicated information will become even more pervasive within our physical world augmented by new artificial intelligence capabilities.

Legislation gives varying degrees of support to classifying communication systems as critical infrastructures. The information that is carried by these systems should define the level of criticality. For example, a tweet may not be considered as critical information as a medical record. However, our distinct social and business reliance on the internet and mobile communication systems must consider the most critical information flows as the common baseline to determine that a communication system must be classified as a critical infrastructure.

In this section we discuss:

- the role of communication systems and their varying degrees of responsibility regarding the transfer of information of varying critical natures;
- information and communication systems as critical infrastructures;
- rapid advances in technology – fast-changing communication infrastructure and services;
- the dependency of EU society on information and communication systems;
- cybercrime as an emerging challenge – new modalities of disaster;
- the cascading impact of compromised communication systems on other critical infrastructures;
- social impact and isolation when communication systems are not available;
- case studies;
- proposed solutions and key messages.

As we become more and more dependent on our communication systems, we will become more vulnerable and helpless when those services that we depend on are no longer available. When disaster hits, and communication services fail, then we, as citizens, will become blinder than ever.

We must prepare to enable our public safety responders with communication capabilities in the face of disaster. They must be able to collaborate whenever and wherever disaster hits within and outside Europe. Mission-critical communication should not be bounded by geopolitical borders as it is today. New communication capabilities to enable operational mobility for public safety responders are crucial to achieve this. This reflection should encourage commercial mobile communication operators to improve reliability and response action in the face of disaster, hence providing more resilient services for all, and not just for public safety responders.

2 Information and communication systems as a critical infrastructure

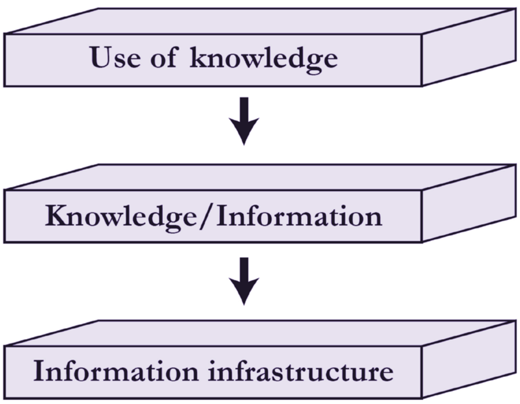
2.1 Critical information infrastructures

Critical information on infrastructure involves three levels: critical service information, business information and consumer information.

The definition of critical infrastructure (CI) is often confused with the definition of a critical information infrastructure (CII). This confusion lies in different perceptions of the definition of a critical asset. When are physical assets that constitute a communication infrastructure considered to be critical? The answer, in fact, is dependent on the information that this physical infrastructure carries, the knowledge that the information represents and the use of that knowledge for motivated reasons.

To aid the understanding of criticality of an information infrastructure throughout the present report, a conceptual framework relating to an information communication system and consisting of three layers, as shown in Figure 1, is considered.

***Figure** 1. Conceptual framework for information and communication. **Source**: Authors*



The use of knowledge differs in criticality depending on the need that drives the use of that knowledge. We give examples here with the aim of differentiating the following three levels of criticality required for knowledge exchange.

Critical. Critical knowledge and/or information is required for the provision of critical services supporting vital societal functions. Such information may even be considered mission critical for some functions, in that the knowledge or information is vital to the functioning of an organisation or the accomplishment of a mission. Examples include public protection and disaster response services, control of utilities (energy generation and distribution, water, etc.), logistics (delivery of food etc.) and transport (cars, buses, trains, aircraft, shipping, etc.).

Business. Business knowledge and/or information is related to the provision of economic development activities requiring high degrees of confidentiality and integrity in information exchange, e.g. development of new products and services (intellectual property), sales and marketing, delivery of products and financial markets.

Citizens/consumers. Such information and/or knowledge is useful for exchanging with friends and family. We expect confidentiality and our privacy must be under our control.

2.2 Rapid advances in technology – fast-changing communication infrastructures and services

Rapid change in technology involves many actors in providing services, which could be a challenge for the security an d quality of the service.

Communication operators will experience increased use of software-defined systems. This is set to fragment the communication system value chain. A transition is expected with the advent of fifth-generation (5G) mobile technology, whose standards allow for new, different and diverse business models. The provision of mobile virtual network operations is likely to change, allowing more agile and dynamic provision of mobile services.

New security challenges will be faced with the increased virtualisation of communication services, whereby they will no longer be physically separated. It is likely that more software components and services will be provided by more actors. This raises new challenges regarding the quality and security assurance of these software components and therefore trust in them.

New challenges will also be faced with the increased dynamics of sharing virtual resources, especially considering the fact that critical, business and citizen communications will probably be hosted on the same physical infrastructure.

2.3 High level of dependency of European society on information and communication systems

With increased use of mobile services, we have more to lose when they become compromised and unavailable.

According to the GSMA (2019), the mobile market is estimated at:

- 5 billion mobile subscribers, constituting 66 % of the world's population, rising to 71 % by 2025;
- 43 % of them using mobile internet, rising to 61 % by 2025.

In Europe there are:

- 465 million mobile subscribers, constituting 85 % of the European population, rising to 88 % by 2025;
- 72 % of them using mobile internet, rising to 82 % by 2025.

There are 3.19 billion users of social media (42 %) globally (Chaffey, 2018), increasing by 13 % year on year. These statistics do not differentiate usage by the three different classifications of criticality described earlier. The majority of users are expected to be citizens communicating with each other, and businesses communicating with each other and with citizens.

As we rapidly move forwards from voice communications to a richer media and immersive environment, we reach an important point to reconsider work carried out in the 1960s by Professor Albert Mehrabian. Mehrabian (1971) studied the role of non-verbal communication, developing the 7–38–55 % rule of personal communication. This rule shows the importance of non-verbal cues in communication, which extend the effectiveness of communication over and above spoken words. In this rule, 7 % represents spoken words, 38 % voice and tone, and 55 % body language.

This original study related only to feeling and attitudes but gives an important point to consider, now that we can communicate with high-quality voice, which improves tone, and more than just voice, as video calling can also communicate body language (gestures and facial expression). Augmented and virtual reality will extend this. As the use of mobile services increases, we have more to lose when they become compromised and unavailable.

2.4 Cyber-dependent crime as an emerging challenge – new modalities of disaster

It is challenging to identify cybercrime as technology changes quickly and those changes increase complexity.

Cyber-dependent crime (that is, crime that can only be committed using information and communication technology) is an evolving challenge. As vulnerabilities are patched, and new techniques countered, new vulnerabilities and techniques are adopted by criminals.

According to Accenture and Ponemon Institute (2017) the global average cost of cyber-dependent crime was of USD 11.7 million, having increased by 22.7 % in one year. Small companies are also a target, and so suffering losses, but only 14% of small businesses are prepared for cyber-attacks (Accenture and Ponemon Institute, 2019).

Cyber-dependent crime itself can be the root cause of a disaster. Cyber-dependent crime is not just focused on monetary theft or data breaches. It is a primary vector yielding both malicious and non-malicious severe consequences, for example on key utilities that provide our services (electricity, water, etc.). Cyberterrorism must be continually countered to protect these critical infrastructure services.

A report by Europol (2018) focuses on both cyber-dependent crime and many other online threats, such as child sexual exploitation, payment fraud, online criminal markets and Terrorists are becoming increasingly proficient in hiding their traces and activities by using encryption tools and services. Furthermore, the anonymity provided by crypto currencies, and their preferential use in the trades taking place on dark markets, seems to be leading terrorists to invest in this currency. Goods and services offered on Dark net.This ranges from malware, to illegal goods like stolen weapons, to crowd funding sites claiming to support terrorist groups..

The report explains how mobile malware has not yet been reported as a significant issue but is set to become more prominent in the coming years. A major vulnerability and associated mobile malware were discovered in July 2019, affecting WhatsApp (NCSC, 2019), which is used by 1.5 billion users in 180 countries. The deployment of 5G faces some challenges technically and institutionally (Blackman and Forge, 2019). Steadily increasing demand for efficient spectrum utilization as part of the fifth-generation (5G) cellular concept. The rising demands associated with communicating over 5G will make lawful interception and, therefore, investigation and law enforcement more difficult.

Higher degrees of virtualisation in mobile networks will minimise capital expenditure and optimise operating expenditure costs of service delivery. Software components will become smaller and will be delivered by more providers. Security assurance of these virtualised solutions will become even more challenging.

2.5 Vulnerability of physical structures of communication and network systems

The quality and connectivity of communication systems depend upon different service providers, released frequency spectrum and network infrastructure.

Physical aspects of communication systems can be classified in two ways:

1. the crucial physical medium that is required for communication:
   (a) radio spectrum;
   (b) copper and optical fibre;

2. the physical components required to carry out and manage the communication operations, e.g.:
   (a) traditional wired telephone networks – public switched telephone network (PSTN), Integrated Services Digital Network (ISDN), etc.;
   (b) point-to-point high-capacity backhaul:
      i. wired (copper and optical),
      ii. wireless (e.g. microwave, free space optical links, etc.);
   (c) mobile telecoms infrastructures:
      i. mobile base stations, switching facilities, etc.,
      ii. mobile terminals;
   (d) satellite ground stations, and satellites themselves;
   (e) network operation centres.

The radio spectrum is a valuable, yet vulnerable, resource. Any actor can transmit on any frequency. It is easy to listen to transmissions and/or jam radio communications. Jamming, while easy to achieve, is often used in combination with other factors. For example, jamming a 4G mobile connection can be used to force a mobile device to automatically move to 3G or 2G. Attacks such as this are often accompanied by the use of fake base stations to either capture identities or act as a man-in-the-middle.

Spectrum access is heavily regulated, yielding high revenues for governments. Unlicensed spectrum is available but accessed opportunistically. Reliability of unlicensed communication can be questionable, depending on context and circumstance of use. Licensed spectrum often comes with obligations to use a protocol that adopts methods allowing the fair sharing of spectrum resources between users.

Physical components of telecommunication systems require physical security measures to avoid physical compromise. They are often situated in public places requiring strong enclosure which protect 5G equipments or set up to be difficult to reach. At the same time, the whole communication system fails if there is no power.

3 Impacts

3.1 Insights from ENISA reports on incidents

Impacts of natural and human-made disasters on digital services, digital infrastructure and service providers need to be understood to improve services.

As reported by the EU project RAIN (2019), network outages in the telecoms sector are not audited openly or with the same level of public detail as is customary in the power sector, which probably reflects the fact that the telecoms sector is less regulated([1]). It is therefore hard to obtain good, detailed study cases for disaster risk management specialists to analyse. However, incident reporting became mandatory in the EU thanks to Article 13a of Directive 2009/140 EC (the common regulatory framework for electronic communications networks and services).

The European Union Agency for Network and Information Security (ENISA) requires each EU Member State to report incidents affecting the following communication services and networks: fixed telephony (e.g. PSTN, voice over internet protocol over digital subscriber line, cable, fibre), mobile telephony (e.g. Global System for Mobile Communications, Universal Mobile Telecommunications System, Long-Term Evolution), fixed internet access (e.g. digital subscriber line, fibre, cable) and mobile internet access (e.g. General Packet Radio Service/EDGE (IMT Single-Carrier, based on GSM), Universal Mobile Telecommunications System, Long-Term Evolution).

ENISA has collected the data and published annual reports summarising them, starting in 2011. These deal mostly with outages, i.e. disruption in the telecoms service provided by carriers. In the last few years ENISA has supplemented these with additional reports that cover incidents at higher levels of the information infrastructure stack, namely trust providers (which secure electronic transactions, e.g. digital signatures, digital certificates, electronic seals and timestamps) and digital service providers (cloud, online marketplaces and search engines). However, in the following we focus only on incidents related to the core communication services.

One of the first non-trivial insights arising from the data is that the vast majority of incidents are due to system failures (hardware failures and software bugs), followed by human errors and weather events. Incidents caused by malicious intent (i.e. cybersecurity incidents and physical vandalism) represented less than a 10% of the total (Figure 2). We see that, contrary to what all the talk about cybersecurity threats suggests, the actual data tell us that we should be more worried about common equipment failures, human errors and extreme weather events.

Of course, this picture is likely to be different if we consider other, non-telecom, information services, such as trust providers and general cloud service providers, as those are inherently more dependent on internet-exposed information technology systems. Likewise, the severity of the incidents labelled as minor and large are on the rise (Figure 3).

([1]) See *https://ec.europa.eu/digital-single-market/en/policies/telecom-laws*

Figure 2. *Incidents reported by root cause.*
Source*: Authors using the Cybersecurity Incident Report and Analysis System – Visual Analysis Tool (ENISA, n.d.).*

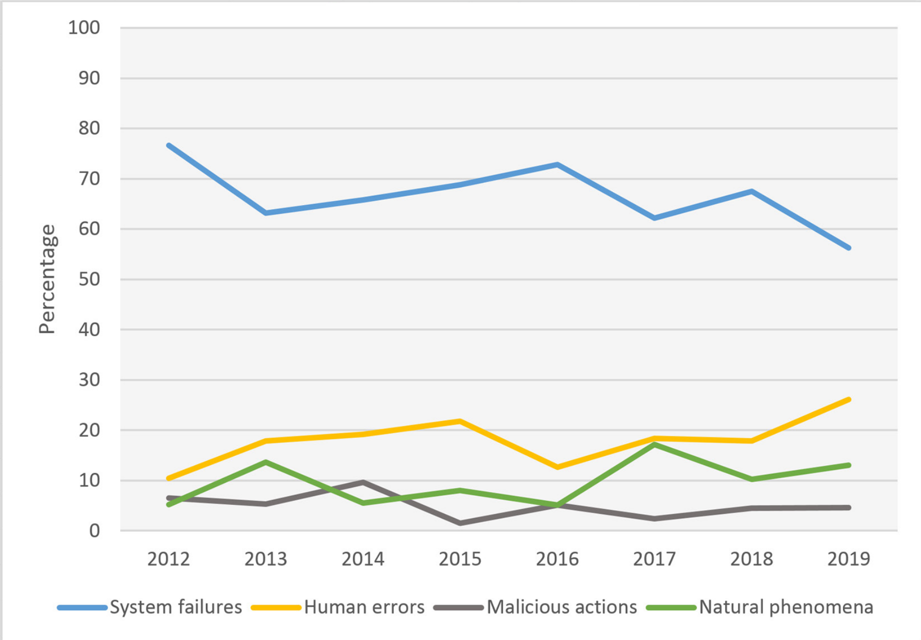
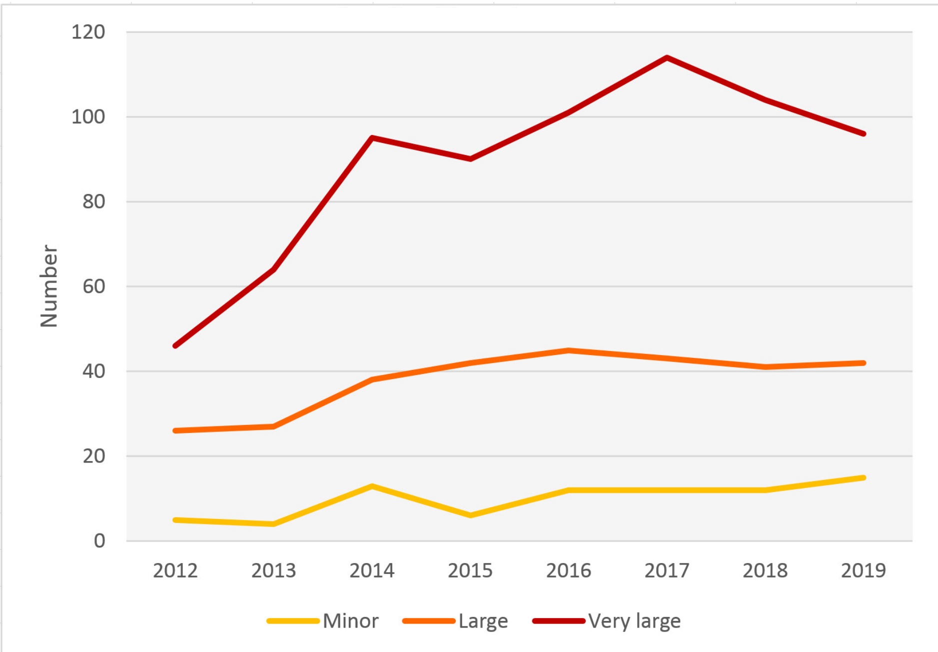


Figure 2. *Incidents reported based on their severity of impact.*
Source*: Authors using the Cybersecurity Incident Report and Analysis System – Visual Analysis Tool (ENISA, n.d.).*



Here are other relevant insights to extract from these reports, over the 7 years they have been running.

- Incidents due to extreme weather are trending upwards: heavy storms, major floods or wildfires caused by extreme drought are being spotted more often.
- Natural phenomena (in particular, wildfires) also cause the highest number of user-hours lost per incident, on average, amounting to 56 800 user-hours in 2017.
- Most incidents have an impact on mobile telephony and mobile internet. In 2017, 51 % of all reported incidents were in mobile telephony.
- Incidents in mobile telephony and mobile internet affect, on average, the most users: on average, around 500 000 users per reported incident, or around 8 % of the national user base.
- Human errors affect, on average, a high number of user connections. In 2017, human error was the category of root cause affecting the most users per incident (around 1.2 million user connections on average).
- Regarding network assets, mobile phone base stations (9 %) and controllers and mobile switches (8 %) were the network components most affected by incidents.

3.2 Societal impact and isolation when communication systems are not available

Multiple services depend on communication systems and if they fail, then it creates anxiety in society. People become ready to pay more to back up the service.

Assessing the socioeconomic impacts of outages, and in particular of the effects of major disruptions, is key to correctly assess the risk and vulnerability of a geographical region and population. Target D of the Sendai Framework for Disaster Risk Reduction addresses damages and destruction of critical infrastructures and the services disrutptions, including Information and Communication Technology (ICT) systems (UNISDR, 2017).

The direct impact of a disruption of service is usually assessed in economic terms, in the form of the value of lost service, which is one of the most commonly accepted measurements. However, social effects are not easily incorporated into impact measurements. Collaboration between economists, engineers and social scientists helps in quantifying these effects. When communication systems fail, we will naturally find a way to retrieve information. We will talk to neighbours, physically moving to seek out knowledge of the situation. We will look for alternative methods of communication. In the Storm Desmond example described below, some people sought other communication systems to get information. In this case, the individual involved had technical knowledge. Many others will not, which may result in a feeling of isolation.

Regarding the measurement of other social effects beyond the direct economic impacts of an outage, many different approaches are used. Most studies have been on power outages, but the methods could be easily extended to analyse the effects of telecommunication system disruptions. Four of them are listed below, the first three methods being the most commonly used (Walker et al., 2014; Linares and Rey, 2013; Centolella, 2013; Grünewald and Torriti, 2012). (Rain Project, Milenko Halat)

- Customer surveys. Customers are asked their willingness to pay (WTP) to avoid outages or their willingness to accept compensation for having a higher number of interruptions. This direct method is also called the stated preference approach.

- Case studies. Past events are analysed; thus, estimations of costs are more detailed and based on actual outages. However, only limited and specific information is available (the incidents occurred in particular circumstances).

- Production function approach. The goal is to get the total value of service loss by computing the ratio of an economic measure, such as gross domestic product, and a measure of electricity consumption, e.g. kWh. Then, it is usually given in terms of EUR/kWh. Finally, cost of lost leisure time can be also included. It can be monetised by using Becker's model (Becker, 1965) as de Nooij and colleagues propose (Nooij et al., 2007).

- Market behaviour. This approach is based on the expenditures on backup devices/facilities, and the price of interruptible contracts. These expenses can reflect what is the WTP of the customers (it is a form of revealed preference). However, in regions with high reliability there are no market signals (the user trusts the service); and some community service providers (e.g. hospitals) must be equipped with backup systems by law

4 Cases: scenarios where communication networks have failed – examples of impact

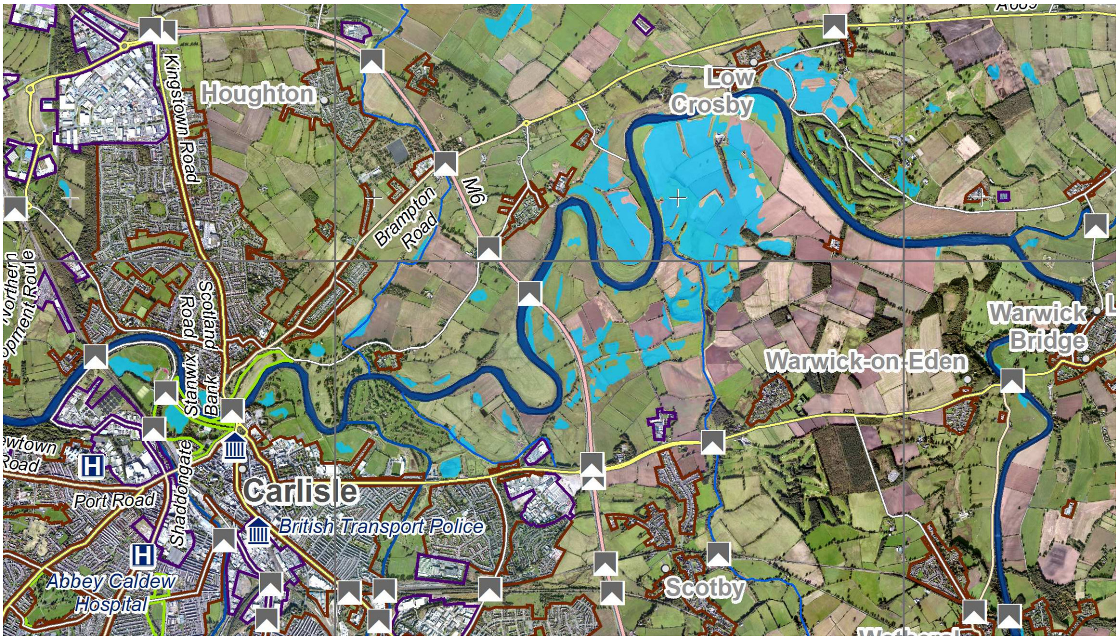
Systems need to be prepared for post-disaster situations in case there is a power failure, to avoid interruption of communication systems and protect the communication infrastructure.

4.1 Storm Desmond: communication services lost as result of power outage due to flooding

Storm Desmond was an extratropical cyclone that caused significant damage in North West England in December 2015. One month's rain fell over 24 hours. The counties of Cumbria and Lancashire were hit especially hard, with severe flooding causing significant damage to critical infrastructure and three fatalities. More than 60 000 properties in northern England were without power and more than 1 000 people were evacuated because of the floods (Davies and Glanfield, 2015).

Flood defences at Carlisle and Kendal's main electricity substations protected power supplies but the flooding of smaller sub-stations and properties resulted in a substantial number of properties losing power. At the peak of flooding, it was estimated that more than 17 00 costumers lost electricity, the majority of these in Carlisle district (Cumbria County Council, 2015) (Figure 4). It is known that telecommunication systems were impacted although the number and location of costumers is unknown as well as the duration of the disruption (Cumbria County Council, 2015; Environment Agency, 2018).

Figure 4. *Situation of Carlisle city and its surroundings on the 7th December 2015*
Source*: extracted from Copernicus, 2015. © European Union, 2015.*



The description below is of the direct experience of one of the authors, who suffered the power outage. Although it remains a partial narrative, it serves to illustrate the impact of the event.

The loss of power occurred around 22.00–23.00 on a Saturday evening. When residents woke up on Sunday morning, power had not been restored. For a local resident in the outskirts of Lancaster city centre, who had previously only experienced short power outages of 1–2 hours in recent years, this already longer outage was worrying. It was difficult to find out the status of power loss. With no electricity, there was no television reception, no ADSL (asymmetric digital subscriber line) internet access and no mobile network coverage. Although mobile phones retained battery power, there was no mobile signal. Landline telephones and local radio both remained usable. However, use and reception required knowledge and equipment that the general public would typically not have to hand. Initial attempts to connect by landline telephone were not successful owing to the use of digital enhanced cordless telecommunications (DECT) cordless phones. The base unit of a DECT system requires power, so it was inaccessible. On searching through old stores, the author found an old PSTN wired telephone. This unit was operational, as the PSTN telephone line had retained power and connectivity. A call was made to family living in a different region of the United Kingdom confirming, from internet news, that the power outage was due to flooding of the substation. However, details were limited.

As the author of this section has technical knowledge, author knew it was known that the BBC local radio service was responsible for notifying the public in cases of emergency. In this case BBC Radio Lancashire was the relevant outlet. The majority of radio receivers in the home relied on mains power and were therefore unusable. A battery-powered receiver was found. The radio was usable; however, a scan on the frequency modulation (FM) band did not find BBC Radio Lancashire. A commercial local station was found. On listening for more than an hour, no news was received but only a cycle of automated music with no presentation intervention. The author scanned again and found a weak signal for BBC Radio Cumbria. Regular announcements were made every 15 minutes regarding closed roads, where to find aid and a lot of useful supporting information. However, this information was useful in Cumbria and not entirely relevant to the locality of Lancaster, where information regarding the power outage was sought. The safety of refrigerated and frozen food became a concern after more than 12 hours of power outage.

Listening for 1–2 more hours, the author heard an announcement that power to the local FM transmitter for Lancaster had also been lost, so listeners in Lancashire should tune to the medium wave (MW) band. The specific tuning frequency was announced but unintelligible owing to the reception quality. The landline was used again to make a call to remote family to request a web search for BBC Radio Lancashire's MW tuning frequency. Details were obtained, the radio tuned and local information received on a regular basis. It became apparent that risk to the author's property was thankfully minimal, yet the power outage would persist for many days.

Initially, generators were deployed and prioritised to the local hospitals. Reports were heard that mobile coverage was restored in the locality of the hospital. Over the next 24–48 hours generators were set up and for 4–5 days they supplied the majority of the 55 000 properties until the substation could be repaired.

This case study suggests that, during disaster, effective and immediate communication is essential. It can be achieved through regular training of local stakeholders on communication systems.

4.2 Manchester Arena bombing – communication services lost as a result of poor processes and configuration

At just after 22.30 on Monday 22 May 2017, a suicide bomber detonated an improvised device in the foyer of Manchester Arena. Around 14 000 people, mainly teenagers and their families, had travelled from across the United Kingdom to attend a concert by Ariana Grande, which was just coming to an end. The foyer was busy with exited concertgoers, waiting family members and merchandise sellers.

The bomb killed 22 people including many children. Over 100 were physically injured and many more suffered psychological and emotional trauma. Paramedics treated many walking wounded in the city centre. Hospitals in Greater Manchester treated people with serious injuries, transported by the ambulance service, while others made their way to hospitals across the wider region. Kerslake (2018) cites a failure of Vodafone to set up a national mutual aid telephony system. This system provides a telephone contact service for relatives to call. This failure caused significant stress and upset to the families involved that night, who were seeking to find out more about the situation of their loved ones. Some resorted to a frantic search around the hospitals of Greater Manchester in their search for information. This is an example of a typical human-made communication failure based upon commercial decisions. There was no technical fault, yet citizens' stress was exacerbated and could have been avoided. Figure 4 shows the blast area, between the main arena and neighbouring Victoria Station. It blew people off their feet and caused widespread panic. Witnesses described hearing an explosion and seeing a flash of fire.

5 Proposed solutions

The following solutions are proposed in order to build resilience, on both a societal and a technological level.

Empower local groups/communities to respond independently

We must prepare the public for disaster in case of lost digital communication connectivity, both to obtain information regarding the situation, so that they can help themselves, and to be able to still communicate by means that have fewer capabilities but are more reliable.

Local resilience forums should work to educate the public to know how to communicate in times of crisis or communication failure. This work must take clear note of the digital divide, to offer modes of alternative communication that individuals will be able to easily use and access.

Operational mobility for responders – Europe-wide communication capabilities for public protection and disaster response

Public safety operations will be enhanced by the availability of pan-European mobile broadband. 'Operational mobility' means that a public safety responder will be able to carry out their operations wherever they physically are, and with anyone in their communication group wherever they are. All communications should not be restricted by geopolitical boundaries. BroadWay (2019) is carrying out pre-commercial procurement of technical solutions to enable operational mobility.

Explore/innovate communication technologies that can function independently from the physical infrastructure

We must not lose sight of existing, highly resilient, low-bandwidth communication techniques. Long-range services, such as low frequency, high frequency and very high frequency, can also be used to provide voice and low-speed data services, where more capable broadband is not possible. FM, amplitude modulation and short wave services have been relied upon since the early 1900s. A high number of amateur radio enthusiasts around the world continually develop new ideas to communicate over long distances. This skill set is valuable and its practitioners should be encouraged to take part in situations where response and additional communication methods are needed in times of disaster.

Capacity building to 'build back better': speedy restoration of the communication system

Reliance only on fixed infrastructure for mobile phones leaves us vulnerable. Preparation should seek to rapidly replace service in circumstances where service is lost to equipment failure or damage. Tactical networks should be prepared to enable fast replacement of mobile coverage. Airborne coverage may be provided by aircraft, balloons, satellites, etc. Cells on wheels can be deployed to provide additional or replacement coverage.

Legislation

Policy and legislation should make operators of communication infrastructures responsible for maintaining a high level of resilience, taking into account all possible options to keep people connected. especially in compromised technical situations, and especially when social situations require additional support when disaster hits. Citizens should remain connected. This is becoming a societal expectation.

Mobile communication services for public safety responders should have the highest priority over and above all non-safety-critical communications. Service availability of mobile communication for responders should be the same everywhere, at all times and whatever the conditions when a responder needs to operate.
Legislation about public alerts should require guarantees of service to reach the public with information regarding developing situations where public safety is at increased risk.

Building a resilient communication capability

Legislation should aim to guarantee availability of communication services. The need to power new communication systems reliably is crucial, especially in terms of crisis, but awareness of the need is diminishing. When power fails, communication networks fail in a cascade. Communication failure leads to limited response by emergency services, restricted communication to and from the public, potential for lack of coordination, and the possibility of lost lives and/or public disorder. Current mobile communication connectivity is not resilient and cannot be relied upon, yet the public and business increasingly depend upon it.

For example, the highly trusted wired ISDN/PSTN communication infrastructure (landlines) will be turned off by 2025 . Security systems for both building security and fire protection have relied on this highly reliable wired service for more than 30 years. ISDN and PSTN lines carry voice, data and, crucially, their own autonomous source of power, independent from the power grid. Replacing ISDN with optical fibre or wireless communication removes the possibility of delivering dedicated power over a long range. Power will have to be delivered locally, creating a significant reliance on power supply for communication equipment to be locally resilient.

Building a secure communication capability

New cybersecurity certification processes, as a result of the EU Cybersecurity Act, are under development at the time of writing. They will be focused on new challenges posed by the development of new communication network infrastructures such as 5G. Those certification processes should, however, retrospectively apply to all existing communication infrastructure. Communication networks of all natures should be covered. This includes national terrestrial and international satellite infrastructures, ranging from fully licensed, managed and regulated systems to unlicensed self-deployed systems and even amateur radio.

6 Conclusions and key messages

Policymakers

- Enhance and enforce reliability policy and standards. Take a cue from the power sector regulatory standards and require something similar for telecom operators. Standardise and refine reliability indicators for all large telecom networks. Ensure that telecom and mobile network operators are fully accountable when their services fail. Policy should encourage backup power sources for mobile infrastructure and rapidly deployable coverage to improve resilience in circumstances of unavoidable communication network failure. Availability of mobile communication has become a societal expectation, especially when disaster strikes.

- Pay more attention to disaster risk and extreme weather events using quantitative analysis. For example, risks related to extreme weather receive less concern than cybersecurity, but the actual statistics tell us that weather events are a greater risk. Their impacts are greater, since other infrastructures (most notably power) are often affected simultaneously. Telecom networks are complex infrastructures, so quantitative analysis of failure is important for decision-making during an event, and to understand where to invest in future preparedness.

- Monitor our growing dependency on information infrastructures and online information technology services. Outages in information infrastructure and online services (e.g. global positioning system navigation maps, messaging apps, banking apps) are not considered as critical as an outage of the underlying telecom service. Ensure that actors within local resilience forums (or any coordinated disaster risk forum) are aware of the vulnerability of mobile communication and information services and are prepared to use alternative communication networks and information services when mainstream mobile networks and services become limited or unavailable.

- The cybersecurity of communication networks must be of primary concern. Common certification processes should assure communication for crime and disaster response to high levels of assurance, shared across all EU Member States and collaborating countries.

Practitioners and scientists

- Strive to provide quantitative risk studies. Promote and require engineering-based, quantitative risk assessment methodologies, especially when making investment decisions. Purely qualitative studies based on vague risk matrices are no longer adequate.

- Team up with engineers, statisticians and data scientists. Modern techniques, such as Bayesian networks and Monte Carlo simulation, allow engineering-based models to be combined with data-based machine learning approaches to obtain better quantitative results. Extreme weather events are becoming more important. Weather is behind a relatively small number of incidents, but those have the greatest impact because of the disruptive effects on other critical infrastructures, and because of the long times to recovery. Keep an eye on climate change trends.

- All information systems should be widely usable, and acceptable to both the public and responders'. Minimisation of the effects of the digital divide should be driven by the need for improved resilience. Ethical, legal and societal issues in different contexts of use should be a key consideration. Societal Impact of new communication methods and tools should be understood, and negative impacts mitigated.

Citizens

- Citizens must have no significant burden placed on them whereby communication technology may become a risk to societal life. Responsible behaviour is essential during disaster communication. Only authoritative and confirmed information should be communicated, to stop civil unrest during emergency period. False messages and fake news should not be circulated using social media, which would put unnecessary pressure on disaster management workers.

- Become aware of your dependency on telecoms and information services. Citizens must be offered education to make them aware of the limitations of their mobile communication and internet access technologies and information services.

- Become prepared for outages. Citizens must be provided with knowledge of how to communicate or obtain information when their familiar mobile communication or other internet connectivity becomes unavailable during compromised situations. Citizens must be prepared for outages in phone lines, the internet or online services. Keeping batteries or small generators for powering radios and phones can sometimes save lives.

- Citizens must join with policymakers, practitioners and scientists to take action for better preparedness', to protect society in the face of disaster, crime and terrorism. Regular scrutiny and mechanism should be developed to identify false information, fake news, etc., in order to avoid confusion and reduce the burden during emergency periods.

Conclusions

Critical infrastructures are complex assets and systems. This subchapter has focused on some of the CI assets and systems at risk and the potential impacts should such assets and systems be disrupted for any reason.

Section 3.4.1 provided a set of examples, with guidelines for continuity management and policies formulated in order to reduce vulnerability and increase flexibility during worst-case scenarios. It emphasised integrating cascading events into emergency management and business continuity practice, increasing awareness of interconnected dynamics and reassessing the locations of critical infrastructure based on hazards and vulnerabilities, as steps towards improving the organisational resilience of emergency facilities.

Section 3.4.2 discussed networked infrastructures, the centrality of which provides some degree of resilience by design but also results in fragilities being not only intrinsic to each technological layer but manifest at the boundaries between systems. Policymakers should focus on stakeholder engagement and information sharing, including public–private partnerships with operators and citizen involvement initiatives. Practitioners are encouraged to use new technologies, such as monitoring tools or information-sharing platforms, when faced with varying technical, financial, political, reputational and legal priorities and constraints. Training and exercises or stress tests represent an opportunity to identify gaps and coordinate for better resilience. Citizens can benefit greatly from new technologies, for instance as a way to get alerts to service disruptions and also to report quickly on the failures they observe. Scientists can assist policymakers, operators and responders in better understanding failure propagation through networks, identifying mitigation actions and optimising response plans. Scientific effort should be devoted to tool interoperability, large-scale simulation, the treatment of uncertainty, reliability and dependability assessment, as well as resilience aspects.

Section 3.4.3 addressed risks to society and the environment from damage to core industrial and energy facilities due to human-made and natural hazards and how these impacts can be prevented or reduced in the future. Policymakers (including government authorities) are encouraged to develop policies in a transparent manner, based on experience and science. Risk governance insights from different sectors, especially from high-hazard activities, could be useful guidelines in this area. Practitioners should adopt good practices in risk management, including cross-fertilisation between sectors, and develop plans to facilitate recovery after infrastructure failure.

Section 3.4.4 discussed the role of the communication systems and their varying degrees of responsibility for the transfer of information of differing levels of criticality. Decision-makers are urged to enhance and enforce reliability policies and standards, using quantitative analysis to integrate disaster risk in the political decision-making process, and being aware of modern societies' reliance on information and communication technologies. Practitioners and scientists should strive to provide quantitative analyses of risk and to use multidisciplinary approaches when supporting investment and public policy decisions. The interoperability of information technology equipment is also emphasised as a critical area for practitioners. Lastly, citizens are encouraged to prepare for disaster-generated outages of information technology and other CI.

Protecting CIs requires a comprehensive, collaborative, risk-based and integrated approach at the regional, national and cross-border levels. The protection of CIs necessitates a system that builds on and elaborates the requirements of the European Critical Infrastructure (ECI) Directive, currently under review by the Directorate-General for Migration and Home Affairs, while taking into consideration the challenges stemming from the inherent technical complexity of infrastructure systems, the diversity in ownership, geography, asset and system types, and national and EU regulations.

The organisation and structure chosen to protect CIs should allow all levels of government, all jurisdictions, all disciplines and all actors (public and private) to work together to reduce the risk from all hazards and threats to CI. Relevant EU legislation should be applied and incorporated into national law, using an integrated rather than piecemeal approach, reducing ambiguity and minimising added requirements of CI operators.

A comprehensive risk assessment is to be adopted, combining the national risk assessment requirements emerging from the Union of Civil Protection Mechanism (Decision No. 1313/2013/EU) of the European Parliament and of the Council of 17 December 2013, with the assessment of risk to CI's in the context of the ECI Directive of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection (Council Directive 2008/114/EC) and the designation of essential services in line with the NIS Directive of 6 July 2016 concerning measures for a high common level of security of network and information systems across the Union (Council Directive 2016/1148/EU), at the heart of the process. Embracing a combined contingency and systems approach helps to identify hazards, vulnerabilities and threats, update the list of critical infrastructures and essential services, determine interdependencies and ultimately define capability targets.

All interested and affected parties should be involved in the process within specifically set up national sectoral bodies or forums. This can be best achieved through their security liaison officers as defined by the ECI Directive (Council Directive 2008/114/EC). Multi-agency coordination, both in the steady state and during crises, is best driven by the CI bodies/sectoral forums. National CI bodies and/or forums should bring together the public and private entities involved.

Information and communication technologies are leveraged to help build and sustain a common operational picture. Training and knowledge sharing play a central role in the process. Workshops and crisis response exercises are conducted on a regular basis, while the involvement of relevant EU institutions helps to ensure consistency at the EU level and augment local capabilities.

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3.4.2 Network infrastructures

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Super Case Study

4

Forest fires in Portugal in 2017

Online Version

Super Case Study 4:

Forest fires in Portugal in 2017

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CONTENTS

1 Introduction

Fire is an integral agent of forest ecosystem dynamics in many climate-diverse regions of the world, but especially in Mediterranean-type climate regions and dry-season climates in general, where weather conditions make it easy for wildfires to ignite and spread.

These Mediterranean ecosystems have been shaped by a coupled socioecological system of fire and humans (Moritz et al., 2014), creating a vast array of highly human-modified landscapes (Pausas et al., 2009) to make the use of forest and wilderness areas more profitable. In some regions of Europe, farmland and lower-biomass shrubland were replaced by fire-prone conifer or eucalyptus species of higher economic profitability, increasing the risk of fire, especially in areas where fuel management is not in place. However, many of the areas that were intensively managed in recent decades for forest resource extraction and fuel production are currently depopulated or abandoned, posing a high risk of wildfires as fuels have accumulated, and leading to new and more complex scenarios for fire management (Montiel Molina and Galiana-Martín, 2016; Castellnou et al., 2019).

In addition, climate change is affecting forest ecosystem dynamics, altering species succession and often making ecosystems more vulnerable to wildfires, and has caused changes in fire regimes, lengthening the fire season and altering fire size, intensity and frequency. Areas that were traditionally fire prone have experienced an increase in critical fire events that challenge traditional wildfire management practices, such as in recent fire seasons in Portugal (2003, 2005, 2013, 2016, 2017, 2018), Spain (2006, 2009, 2012), Italy (2007) or Greece (2007, 2018).

It is therefore essential to reassess wildfire dynamics and risks at the European and global scales, taking into account the effects of climate change, including droughts and the growing frequency and intensity of extreme heatwaves. These effects are not only changing fire regimes but may drive critical fires that exceed anything currently known. Landscape changes, derived from growing population and urban sprawl, and the use of unappropriated policies have also contributed to a more fire-prone landscape by increasing afforestation and reforestation with fire-prone species, enlarging the wildland–urban interface (WUI), in which fires threaten human lives and assets.

Portugal, like other Mediterranean countries affected by wildfires (e.g. Spain, France, Italy or Greece), has focused on enhancing wildfire-fighting capabilities, often neglecting wildfire prevention. Although the overall burned area in the EU has shown a slight decrease since the 1990s, the number of intense and critical fires has not decreased, with extreme fire episodes still happening every year. In recent years EU Member States have suffered critical wildfires that have caused the loss of human lives, in addition to substantial economic and environmental losses.

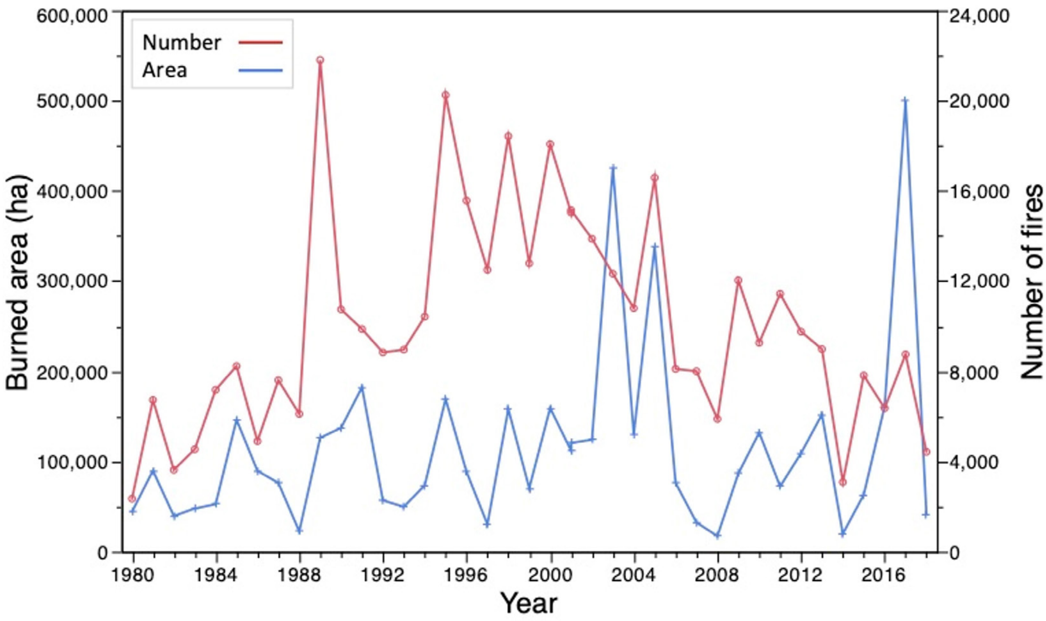
2 Background of fires In Portugal

Within the EU, Portugal is one of the Mediterranean Member States that periodically suffer serious damage from forest fires.

Trends in wildfires in the country in the last two decades show a decrease in the number of fires, although they show high variability in the area burned each year. Furthermore, Portugal suffered a critical concentration of multiple fire events in the last few years, which hampered the efficient extinction of the wildfires. This phenomenon has been observed in the most critical fire episodes in Europe in recent decades. Nearly two thirds of the area burned in Portugal in 2016 was the result of fires that occurred in the space of 10 days.

The year 2017 presented extreme meteorological conditions, with a severe heatwave and extreme atmospheric instability in June and the influence of Hurricane Ophelia and record breaking-drought in October. These extreme conditions led to a multiplicity of wildfires, many active fire fronts and explosive fire behaviour, contributing to the catastrophic fires in the central and northern regions of the country, with heavy impacts on human lives and assets. These critical fire episodes, often referred to as megafires or extreme wildfire events (EWEs) have been documented in several scientific publications (e.g. San-Miguel-Ayanz et al., 2013; Tedim et al., 2018). Figure 1 shows the numbers of fires and extent burned areas in Portugal each year from 1980 up to 2018 (ICNF, n.d.). Almost 3 million ha has been burned in Portugal since 1980. This corresponds to nearly one third of the total area of the country.

Figure 1. *Burned area and number of fires in Portugal between 1980 and 2018..* ***Source:*** *ICNF, n.d.*
Note: *Fire occurrences smaller than 0.1 ha and agricultural burned area were excluded to guarantee consistency across the time series.*



3 Analysis of fire events

Two major events occurred in June and October affecting central region of Portugal.

3.1 June events: the fire of Pedrógão Grande

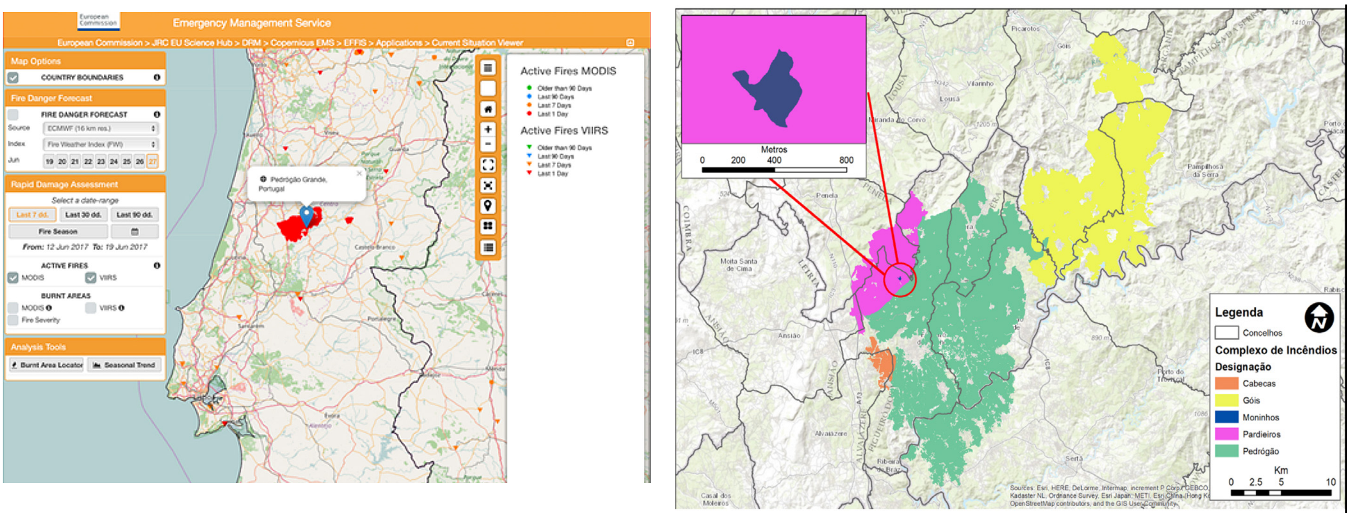
In the afternoon of 17 June, a series of forest fires broke out in Portugal, including two outbreaks near Pedrógão Grande (PG) and Góis, south-east of Coimbra, which extended to Castanheira de Pêra, Figueiró dos Vinhos, Pampilhosa da Serra and Penela. Viegas et al. (2017) and Guerreiro et al. (2017) produced detailed reports on these fires. The locations of the origins of these fires, their times of alert and of conclusion and the burned areas are given in Table 1 and their final perimeters are shown in Figure 2. Of this complex of fires, the most important was the one that started at two different points along a 25 kV electrical line, because the tragic loss of 66 lives that it caused. The locations of the fires and the map of the final perimeters are visible in Figure 2.

Table 1. *Data on the Pedrógão Grande complex of fires.* ***Source****: EFFIS, n.d., and Viegas et al., 2017.*

Place	Alert	Conclusion	Burned area (ha)
Escalos Fundeiros e Regadas	14.43, 17 June	23.49, 22 June	24 164.6
Fonte Limpa – Góis	14.48, 17 June	19.30, 22 June	16 119.2
Moninhos – Figueiró dos Vinhos	15.41, 17 June	18.38, 17 June	7.1
Cabeças – Alvaiázere	20.41, 17 June	10.35, 20 June	637.9
Pardieiros – Penela	21.15, 17 June	00.48, 21 June	4 399.8
Total			***45 328.6***

Figure 2*. (A) Maps of the locations in the European Forest Fire Information System (EFFIS) and (B) map of the final perimeters of the Pedrógão Grande complex of fires.* ***Source****: EFFIS, n.d., and Viegas et al., 2017.*

A) B)



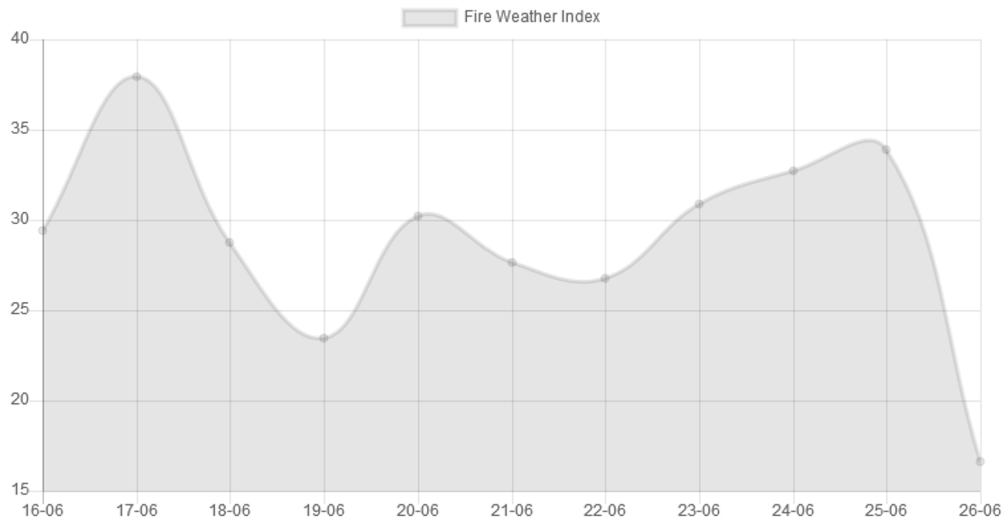
a. Conditions in Pedrógão Grande

The area of PG fire has a complex orography, covered by forest composed mainly of pine and eucalyptus plantations. The population density is about 30 persons/km2, who live in small towns, villages or houses scattered in the landscape. A good network of roads serves the region but fuel management was mostly absent.

A severe drought characterised 2017, with drought code values around 300 in the central region of Portugal in mid-June, well above the average value of 180 for that time of year. In mid-June, a series of days with maximum temperatures above 40 °C contributed to the Fire Weather Index (FWI) reaching record values of around 40, whereas the average is around 10. Therefore, fire danger in the region was extreme and the moisture content of fine dead fuels measured at the nearby station of Lousã was around 7 % (Viegas et al., 2017), which is consistent with extreme fire danger.

European Forest Fire Information System (EFFIS) predictions for 17 June showed very high fire danger conditions in these areas, which would expedite the spread of fires, which would burn with very high intensity, given the large accumulation of fire fuels in those areas (Figure 3). On the same day, a convective thunderstorm system developed in the region to the south-east of the area of PG, producing a large number of lightning strikes, some of which caused fires. During the afternoon, this system travelled towards the north-west and started influencing the area of the fire around 15.00. At one stage it was assumed that the fires of PG had been caused by lightning, but this hypothesis was discarded later (Viegas et al., 2017). Although this thunderstorm did not cause the fire, it affected its development in an unusual and unexpected form.

Figure 3. *FWI time series from 16 to 26 June 2017 in the area near Pedrógão Grande.* ***Source****: EFFIS, n.d.*

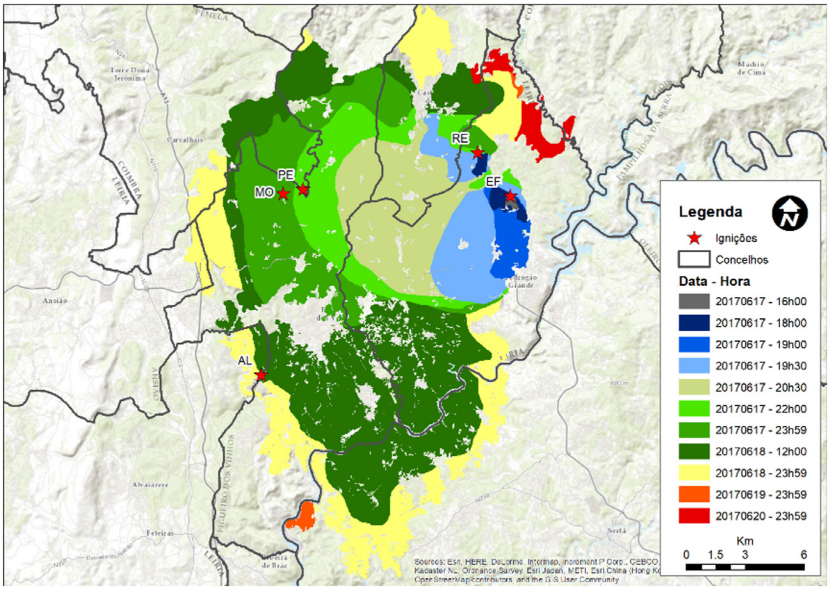


b. Evolution of the fires

The fires of PG had two separate origins, as shown in Figure 4: one around 14.43 at Escalos Fundeiros, and the second at 15.30 near Regadas, 3 km from Escalos. Both ignition points were located below a 25 kV electrical line. Evidence of contact between the line and vegetation was found, and it was declared the major cause by Viegas et al. (2017) but not proven by Guerreiro et al. (2017). Given the almost simultaneous occurrence of four fire ignitions in the same area, firefighting resources were dispersed and, owing to the very difficult terrain and meteorological conditions, control was not achieved during the first few hours.

Around 18.05, a strong interaction between the thunderstorm and the two fires of Escalos Fundeiros and Regadas, including a near 90° rotation in wind direction, caused their very rapid spread through a large area to the south-east of where they started, making the control of both fires virtually impossible. Between 19.30 and 20.30, the fire spread very rapidly in a roughly circular area with a diameter of 10 km. During this critical period, the fire spread at an estimated average rate of 5 km per hour, with fireline intensity up to 60 MW/m, and burned 7000 ha (Guerreiro et al., 2017). The fire trapped hundreds of persons who lived in this region or were travelling through it, and 66 lost their lives, many of them when trying to run away from the fire.

Figure 4. *Evolution of the Pedrógão Grande fire* ***Source****: Viegas et al., 2017*
Note*: red stars represent the ignition points.*



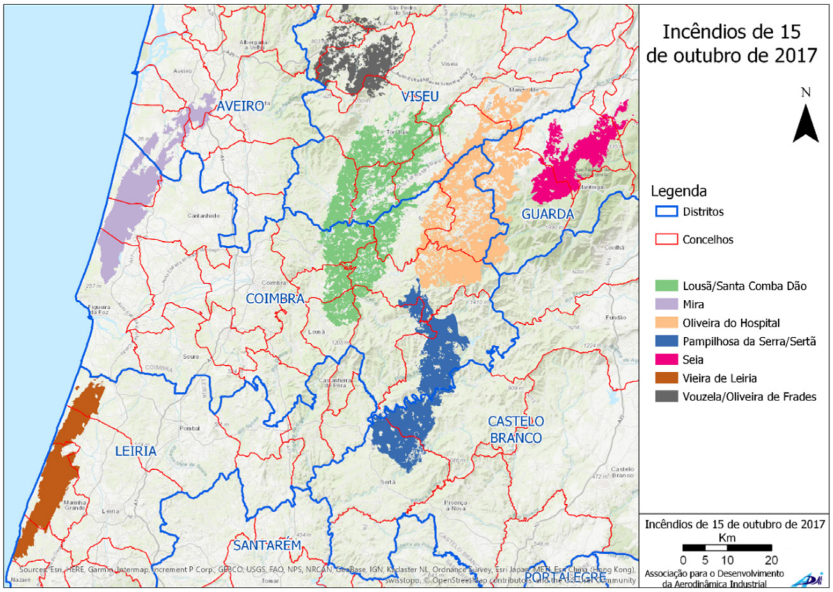
3.2 October fire events: the second disaster

After 17 June several serious fires occurred in Portugal, mainly in its central region, but the worst situations occurred on 15 October and the following days. During this period, a second disaster hit Portugal, with a much larger loss of forested area (but also shrubland and agricultural areas) and property, and the loss of 51 lives. It also affected some protected areas managed by the Portuguese government. These fires were studied by Guerreiro et al. (2018) and by Viegas et al. (2019). On 15 October more than 500 fires started and several of them developed into major fires burning a very large area (244 000 ha) in a relatively short period of less than 10 hours and causing devastation in a much wider area than the fires of PG. According to Viegas et al. (2019), there were seven major complexes of fires, which are listed in Table 2. Most of them had more than one ignition and were the result of several fires spreading in the same area. The time of alert indicated in Table 2 corresponds to the earliest ignition of a given complex. The burned areas of these seven fire complexes are shown in Figure 5.

Table 2. *Data on the main forest fire complexes on 15 October 2017.* ***Source****: Viegas et al., 2019.*

Designation	Time of alert (h)	Burned area (ha)	Fatalities
Seia	06.03	17 003	1
Lousã	08.41	54 407	15
Oliveira do Hospital	10.26	51 429	23
Sertã	12.02	30 977	2
Leiria	13.51	20 014	0
Quiaios	14.36	23 844	0
Vouzela	17.21	15 959	10
Total		***213 633***	***51***

Figure 5. *Map with the areas burned by the seven major fire complexes that occurred on 15 October 2017 in central Portugal.* ***Source****: Viegas et al., 2019*

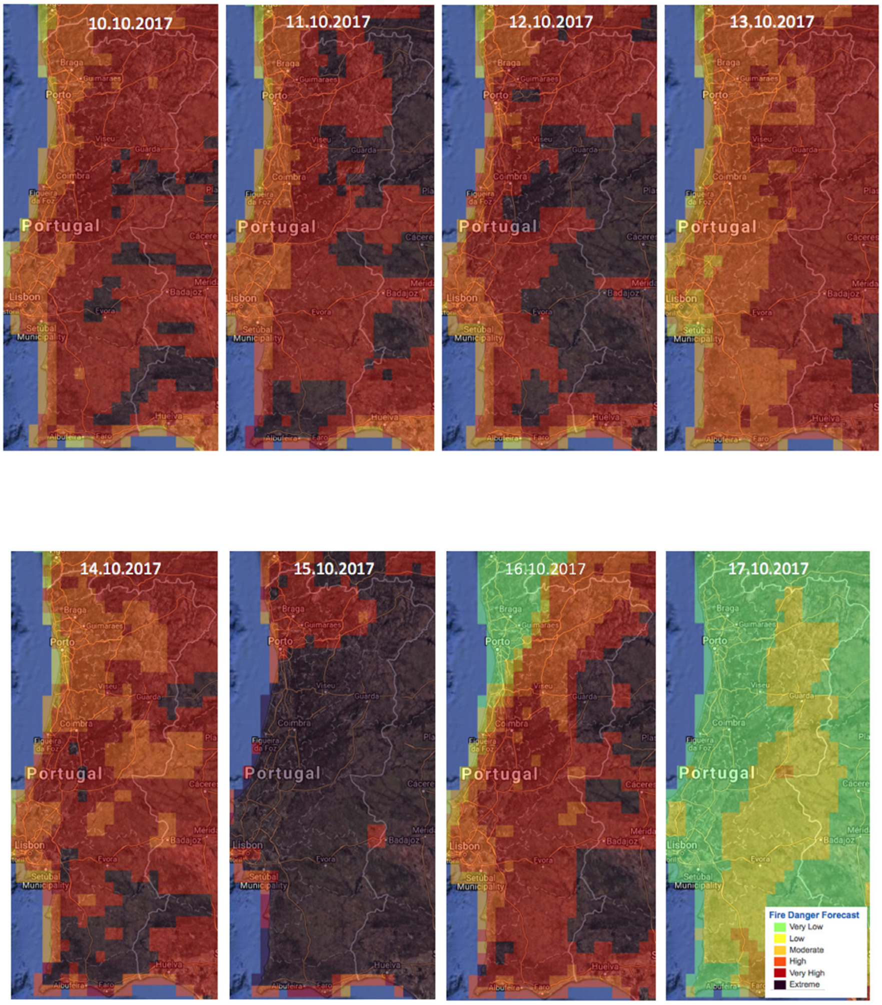


a. Conditions in central and northern Portugal

The very dry conditions that were felt throughout the summer of 2017 continued in mid-October with the drought code for Coimbra reaching record values of 800, well above the average value of 400 for the time of year. The FWI conditions prior to and during the wildfires are presented in Figure 6. This shows very high and extreme cumulative fire danger conditions prior to the days in which the fires spread and during the weekend of 14 October. The storm winds from the hurricane Ophelia induced a very strong southerly wind that blew hot and dry air from North Africa over the major part of the territory, increasing fire danger during 14 and, especially, 15

October. For example, the overall average value of the FWI for Portugal was 62 on 15 October and in Coimbra it reached an all-time record value of 82, making it impossible to control fires that escaped the initial attack. On 17 October there was precipitation in most of the country, decreasing the fire danger and helping to control most fires on 18 October, with only minor fires still burning north of Figueira da Foz. Critical fire events burning in extreme fire danger conditions, such as those described in this report, can only be extinguished when the weather conditions improve and fire danger decreases.

Figure 6. *Fire danger conditions (Fire Weather Index) in Portugal prior and during fire events,* ***Source****: EFFIS n.d.*



The information on fire danger conditions provided by EFFIS indicates the capacity of a fire to ignite and spread, linked to the resources required for fire control. Fire danger above an FWI value of 50, which was predominant in the whole Portuguese territory during 15 October, implies that fires cannot be controlled by either ground or aerial firefighting. They launch burning material that produces spot fires, up to 3 km ahead of the fire front in the 15 October events (Guerreiro et al., 2018), posing a major threat to firefighting crews, and increasing the number of simultaneously active fire fronts. For the Portuguese Institute for Sea and Atmosphere, the extreme fire behaviour classification starts at FWI = 38.

b. Evolution of fires

The five major EWEs of 15 October reached maximum rates of spread in excess of 3 km/h and up to 9 km/h. Between 16.00 on 15 October and 04.00 on 16 October the area burned by these fires in an hour ranged from 7 000 to 14 000 ha (Guerreiro et al., 2018). Firestorm conditions were felt at night after the cyclone winds had dissipated; they were caused by fire–atmosphere interactions and, possibly, interactions between fires. As in the PG fires, the most severe fire behaviour coincided with the timing of most human fatalities and occurred when air temperature was decreasing and relative humidity was increasing. In these fires a much smaller proportion of persons lost their lives while running away from their houses. As the fires spread mostly at night, many persons were surprised by the fire and did not have time to react.

4 Impacts

The Portuguese government reported about 21 000 wildfires in 2017, which burned an area of 539 920 ha of forests, shrubland and agricultural land causing 117 deaths (116 civilians and one firefighter).

One hundred and fifty municipalities were affected in the centre and north of the country, causing huge losses of private and public property, including buildings and industrial infrastructures, energy network infrastructure, roads, telecommunications, forestry and agriculture resources. The Portuguese government estimated the total cost of the damage by fires in 2017, between June and October, to amount to approximately EUR 1.5 billion, divided into physical damage (97 %) and intervention costs (3 %) (San-Miguel-Ayanz, 2018). Table 3 shows the estimated costs provided by the Portuguese government by type of damage.

Table 3. *Total estimated costs costs provided by the Portuguese government..* ***Source****: San-Miguel-Ayanz, 2018*

EFFECTS	
DAMAGE TYPE	**COST (MILLIONS EURO)**
Network infrastructure (Water/waste water, transport, bridges, energy, telecom, etc)	94.4
Public assets (airports, ports, hospitals, schools, etc.)	2.3
Business (Commercial and industrial activities)	311
Agriculture	209.7
Forestry	634
Residential (private homes and assets)	102
Cleaning up	63.9
Cost of emergency operations/rescue services	39
Total	***1456.3***

The June fires (including PG) burned around 49 000 ha (2 555 ha of Natura 2000 protected areas), caused the deaths of 66 people, injured many others and resulted in enormous damage to human infrastructure and the environment, affecting large forest areas, and more than 500 houses and rural infrastructures. One salient aspect of this event was that many of the victims who died were not usual residents of the region, as was also the case in Mati (Greece) in July 2018; this lack of familiarity with the countryside in general and such large-scale forest fires in particular may have had implications for their behaviour and response to the events. This aspect also suggests that assessment of potential or actual population exposure requires geospatial data that go beyond resident population and further detail population distribution in the daily (day/night) and seasonal cycles. Such data are now available for the EU-28 as part of the JRC's enhancing activity and population mapping project (Batista e Silva et al., 2016).

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The second critical episode took place on 15 October, with multiple simultaneous fires that resulted in the deaths of 51 people. In the period of 14–17 October a total of 32 wildfires were mapped by EFFIS, and resulted in a total burned area of 296 613 ha (44 200 of Natura 2000). The wildfires affected mainly the central region of the country. The damage costs estimated by the Portuguese government were approximately EUR 500 million and EUR 1 billion for the June and October fires respectively. Table 4 provides information on the environmental damage by Corine land cover class (Copernicus, 2020) and the amount of pollutants emitted by both events in the study period. They are responsible for 60 % of all the CO2 emissions released by all the fires during the 2017 fire season and around 15 % of Portugal's total CO2 emissions for the year reported by the Portuguese Environmental Agency.

Table 4.*Environmental damage due to the fires in 2017 (June and October).* ***Source***: *EFFIS, n.d.*

CORINE Land Cover	JUNE		OCTOBER	
	Area (ha)	%	Area (ha)	%
Broad-leaved forest	7 075.15	14.31	16 916.83	5.70
Coniferous forest	8 284.85	16.76	69 165.01	23.32
Mixed forest	10 461.72	21.16	39 709.71	13.39
Sclerophyllous vegetation	0	0	209.91	0.07
Transitional vegetation	16 815.74	34.02	78 400.75	26.43
Other natural land	2 390.25	4.84	30 849.75	10.40
Agriculture	3 602.05	7.29	55 463.54	18.70
Artificial surfaces	194.09	0.39	3 530.94	1.19
Other land cover	608.23	1.23	2 366.97	0.80
Total	***49 432.08***	***100***	***296 613.4***	***100***
NATURA 2000	***2 555.18***	***5.17***	***44 200.3***	***14.9***

Table 5. *Amount of pollutants emitted by the fires in 2017 (June and October).* ***Source***: *EFFIS, n.d.*

Type	Quantity (tonnes)	
	JUNE	OCTOBER
Carbon dioxide	775 512	4 156 584
Carbon monoxide	38 258	193 427
Methane	1 978	9 853
Particulate matter 2.5 m	3 676	18 511
Particulate matter 10 m	4 338	21 852
Non-Methane hyfrocarbons	1 564	7 908
Volatile organic compounds	1 886	9 546
Nitrogen dioxides	2 736	13 485
Organic compounds	2 116	10 769
Elemental carbon	234	1 216
Particulate matter	5 952	30 221

5 Response

In the critical period of the fire season (July–September), the Portuguese Special Firefighting System integrated 9 740 operational staff, 2 065 vehicles and 48 aircraft, mainly during the Charlie Phase (1 July to 30 September).

All the available resources in Portugal responded to the critical fires in 2017. In the critical period of the fire All the available resources in Portugal responded to the critical fires in 2017. These resources were supported by the Intervention and Relief Group (GIPS) of the National Republican Guard, the Institute for Nature Conservation and Forests and the Association of Pulp Industries, with a total of over 2 300 personnel. Aerial forces intervened in 7 457 firefighting missions totalling over 9 000 hours, which was a much higher figure than those of previous fire campaigns.

On 18 June, Portugal requested support to fight the fires through the Emergency Response Coordinating Centre of the Directorate-General for European Civil Protection and Humanitarian Aid Operations (ECHO), and resources were provided by France (two Canadair planes and one Beech reconnaissance aircraft), Spain (two Air Tractors) and Italy (two Canadair planes). ECHO sent a liaison officer to arrive in the country in the afternoon of that day. Spain made four additional Canadair craft available through its bilateral agreement with Portugal, and Morocco provided one Canadair craft. According to Portuguese authorities, the PG fire was under control on 21 June. These fires were extinguished by 23 June.

Several official emergency actions were taken at the political level, such as activating the civil protection emergency plans of several municipalities and declaring a state of public disaster for the adoption of preventative measures by the Portuguese Council of Ministers. Additional emergency measures were taken during the critical phase, mainly at the health and social protection level, relocating the population affected, reorganising and repositioning critical infrastructures, etc

6 Lessons learned

Changes on the operational level (civil protection structure and operational/ firefighting response) and in the spatial planning of the territory (fuel management measure, protection of residential and industrial areas, forestry public investment) were proposed.

The tragic dimension of the fire events of 2017 in Portugal, both in terms of loss of human lives and in terms of economic and social harm, has also brought into question misguided current fire management policies focused only on reactive fire suppression. The effects uncovered the structural and operational vulnerabilities of the current system of fire prevention and suppression. The firefighting trap policies contributed to continuous fuel accumulation and landscape fuel continuity, leading to increased fire hazard and risk (Moreira et al., 2020). This led to several official actions and a renewed effort to address this issue.

Technical reports were requested by the government to analyse both fire episodes (June and October). The Assembly of the Republic created an independent technical commission to study the events and to recommend solutions, and consequently government reforms were announced (see for example Guerreiro et al., 2018). Recommendations on the operational level (civil protection structure and operational/firefighting response) and on the spatial planning of the territory (fuel management measures, protection of residential and industrial areas, public investment in forestry) were included in these technical reports (Guerreiro et al., 2017, 2018).

The commission also suggested the creation of the Agency for the Integrated Management of Rural Fires (AGIF), a public institute that coordinates all entities whose missions contribute to dealing with rural fires, such as the Institute of Nature Conservation and Forests, the National Authority for Emergency and Civil Protection, the National Republican Guard, the armed forces, fire brigades and all private agents (Resolution 12/2018). A Technical Independent Observatory was created by the National Assembly to support its members in the assessment of the system and in the preparation of legislation on the issue. Following Resolution 12/2018, the System for Integrated Management of Rural Fires was established under AGIF coordination, with the purpose of protecting the population, territory and assets from forest fires. Among other resolutions from the Council of Ministers of Portugal, a programme for the regeneration of the pine forests of Inner Portugal (Resolution 1/2018) was adopted, pointing out the need to make available information derived from Earth observation, including forecasts of meteorological fire danger and maps of structural fire danger.

Realising the need for preparedness and self-protection in the new reality of rural fires, a programme designated as “Aldeia segura, pessoas seguras” (Republica Portuguesa, n.d.) was adopted to increase the risk awareness, preparedness and coping capacity of settlements and populations in rural areas, including a focus on fire prevention, warning, evacuation of settlements and preparation of shelters. Many of these resolutions were adopted and are being put into practice. For example, extensive programmes of fuel management around houses and settlements have been performed throughout the country, and improved vigilance and self-preparedness on the part of the population are now observed. In addition, a national research programme was promoted, specifically to fund research initiatives applied to forest fire research, enhancing the availability of information and tools for fire managers to assess and understand fire regime, dynamics and post-fire recovery (Guerreiro et al., 2018; Viegas et al., 2017).

7 Discussion

The existing scientific literature on critical fire events, known as megafires or EWEs, shows the limited effectiveness of firefighting against high-intensity and fast-spreading wildfires.

Figure 8. *Trajectory of Hurricane Ophelia, fuelling wildfires in Portugal and blowing the smoke plume north.*
Source*: NOAA National Hurricane Center, 2017*

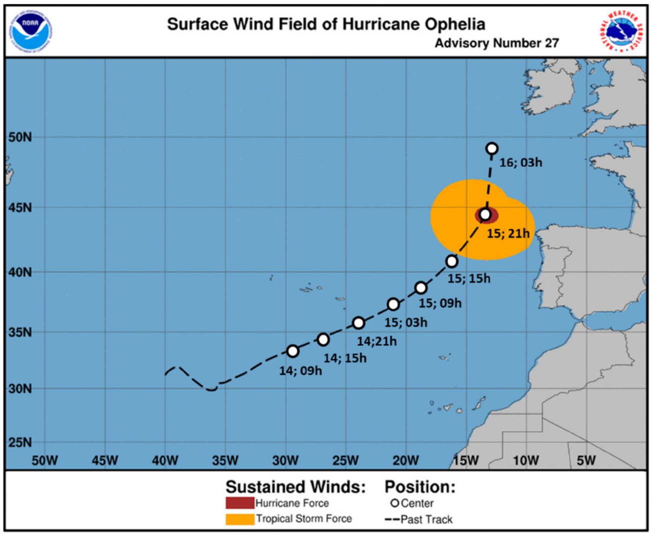
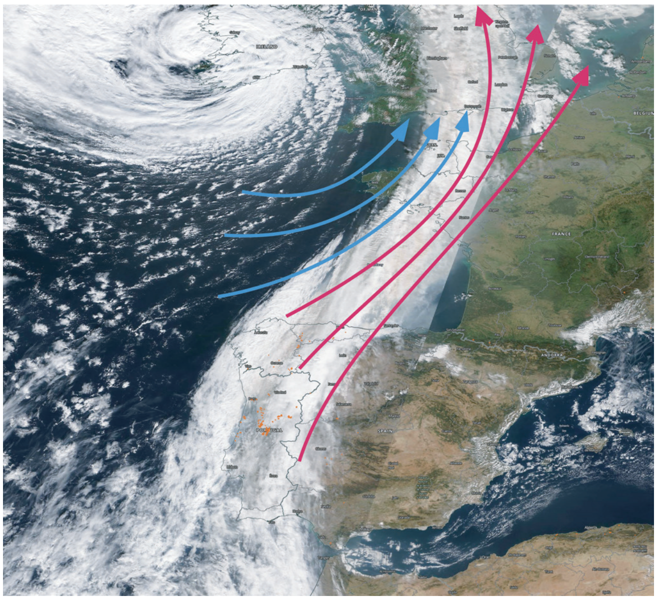


Figure 9. *Burned scars of the fires in Portugal and Spain superimposed on NASA Terra satellite images*
Source*: NASA Worldview, 2020*



The JRC analysis of fire danger conditions prior and during the wildfire events in the period 14–16 October 2017 in Portugal shows an unprecedented weather situation in which any ignited fire would spread with high intensity and speed. Very strong winds created by hurricane Ophelia, associated with extremely low relative humidity in the existing fuels, led to wind-driven wildfires. Those were the initial major causes of the very fast spread of the wildfires and the catastrophic damage they brought about. The existing scientific literature on critical fire events, megafires or EWEs, shows the limited effectiveness of firefighting against high-intensity and fast-spreading wildfires. These extreme events can only be controlled when weather conditions improve, which happened on 17 October, when the fire danger conditions decreased dramatically (see Figure 2).

At least one of the fires in October was caused by electrical lines but the major causes were fire use (36.0 %), arson (35.7 %) and rekindling (10.7 %); these percentages refer to the total number of fires in the period 14–15 October for which a cause could be determined. The shape of the fire perimeters indicates wind-driven fires with elongated scars following the direction of the predominant wind when fires ignited; these wind were generated by hurricane Ophelia.The effect of the hurricane , which created very strong winds from south to north, as far as Ireland and the United Kingdom, is shown in Figure 8 and 9. The images show the unusual trajectory of Ophelia, the fire scars in Portugal and northern Spain, and how the smoke plume was pushed north along the coast of France into the British Isles.

8 Conclusions

The results of the analysis of the very large fires that occurred in Portugal in 2017 show how predominant critical weather conditions during a short time period can trigger extreme wildfire events, causing enormous economic damage and human casualties.

These fire events are a serious challenge to societies, as they exceed the control capacity in critical weather conditions, causing destruction and fatalities because of their high intensity, erratic behaviour and strong spotting activity (Tedim et al., 2018).

This type of event is rare, but the fires in central Portugal in 2017 should not be viewed as isolated events. Similar clustering of large fire events has been observed in recent fire seasons in Portugal (2003, 2005, 2013, 2016), Spain (2006, 2009, 2012), Italy and Greece (both 2007). Forest fires such as the 2017 disasters are rather complex events arising from the interplay between social and natural conditions, processes and factors throughout the wildfire temporal cycle. Some of the major factors that potentially increase the frequency of these major disasters are the following.

- Changes in forest and fuel management, land use and land cover (both natural and human-made, e.g. afforestation, fire-prone forests of eucalyptus and pine). Land use management is critical in hindering critical fires, through land use planning to avoid continuous forest landscapes, and through fuel treatment to reduce the amount of fuel and decrease wildfire intensity and spread.

- Spatial planning and governance mechanisms (land tenure and land use conflicts, sharing responsibilities, coordination).

- Changes in the socioeconomic dynamics, such as the increasing depopulation of rural areas. For instance, population density in the Pedrógão region went from 34.1 individuals per square kilometre in 2001 to 26.8 in 2018 (PORDATA, 2019), leading to farmland abandonment and contributing to increased fuel continuity, making it easier for fires to ignite and spread.

- The increase in the wildland–urban interface, where fires are highly damaging to human lives and assets. This has been dramatic in the last decades.

- Climate change, with higher temperatures and longer drought periods influencing wildfire dynamics, leading to longer and more intense fire seasons.

These extreme events seem to be inducing a vicious circle, contributing to land use changes and depopulation of rural areas, which increase the propensity for more frequent, larger and more destructive fires even in areas that years ago were not fire prone. Considering current trends in Europe (and especially in Portugal, where most fires are caused by humans), the hazard component appears to be a rather inflexible part of the risk equation, with a negative future outlook. Promoting a shift from suppressing fires, which often burn on continuous fuel layers of fire-prone vegetation, to mitigation, prevention and preparation measures can surely contribute to better control of EWEs, reducing the socioeconomic and ecological effects of fire (Moreira et al., 2020). The management of fuels, including the deliberate use of fire or using it for grazing or for energy to reduce fuel loading are possible solutions to develop. In addition, the vulnerability component poses important challenges such as the ageing of population, which has various implications for prevention, preparedness and response measures (i.e. firefighting) in rural areas.

This leaves most of the reduction in risk and impacts to be achieved by managing fuels and by reducing vulnerability (when possible) and, especially, decreasing direct human exposure to fire, in order to prevent human casualties. This requires a special focus on early warning and self-protection measures, but also Investment in fire prevention, both in education campaigns and engagement of local communities, making them more resilient and ready to defend themselves from the effect of extreme fires, and in forest management (fire use regulation).

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Chapter 3

Assets at risk and potential impacts

3.5

Environment and ecosystem services

Online Version

3.5 Environment and ecosystem services

CONTENTS

3.5

Environment and ecosystem services

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1 Introduction to ecosystem services at risk

The impact of disaster on ecosystem services is dependent on the state of ecosystem degradation. There is a complex and often geographically specific relation between vulnerability to disasters and ecosystem services degradation.

According to the 2007, Potsdam G8 global initiative on The Economics of Ecosystems and< Biodiversity (TEEB), ecosystem services are defined as the contributions that ecosystems make to human well-being (Haines-Young and Potschin, 2018). They are important because they support, directly or indirectly, our survival and quality of life. Back in the 1990s, Costanza et al. (1997) valued the ecosystem services of the world at around USD 33 trillion. Interestingly, that value is about twice the gross domestic product of the world in the same period.

When we talk about impact on ecosystem services, the concept of measuring direct losses is not applicable. Direct losses are mostly monetary value (see subchapter 3.6), valid for human-made objects, whereas ecosystem services do not have market prices. Current efforts to calculate the impact of a disaster on the complex network of ecosystem services tend to underestimate the real cost. Some ecosystem services are interlinked; the degradation of one could trigger cascade effects, and the consequence of disasters, in some cases, will only appear over time. For the EU, accounts have been generated as pilot studies on specific ecosystem services such as water purification (La Notte et al., 2017); on crop pollination and outdoor recreation (Vallecillo et al., 2018); and on crop and timber provision, global climate regulation and flood control (Vallecillo et al., 2019) (Section 3.5.3)..

The earthquake and tsunami that struck southern Thailand in 2004 revealed the relation between vulnerability to disasters and ecosystem services. Well-preserved coastal ecosystems in Thailand functioned as a natural barrier to absorb the energy of the wave, whereas the effect was the opposite in areas where the coastal ecosystem was degraded (Wilkinson et al., 2005). It was only after 2007, with the establishment of the Global Network of Civil Society Organisations for Disaster Risk Reduction, that the relationship between the quality of ecosystems and the impact of natural hazards became evident. In 2015, the Sendai framework for disaster risk reduction emphasised the need to address underlying causes of disaster risk and to prevent the emergence of new risks. However, it fails to capture ecosystem services and the environment among the assets to protect.

It is increasingly recognised that conventional engineered ('grey') infrastructure measures such as dykes and sea walls have shortcomings, as they typically address protection needs without addressing the underlying drivers of risk. The scientific community has raised concerns about the necessity to move from reactive approaches to a proactive one, optimising all functions and ecosystem services (Sebesvari et al., 2019). Nature-based solutions or green infrastructures in combination with bioengineering in urban areas have proved a long-term success for specific regions in central Europe (Dushkova and Haase, 2020). Important differences from grey infrastructure are that green solutions may also attenuate the hazard itself and they can self-adjust.

In the European context, the RECONECT project ([1]) demonstrates the effectiveness of nature-based solutions for hydro-meteorological risk reduction in rural and natural areas. Nevertheless, these initiatives need to continue

([1]) http://www.reconect.eu/

upscaling to a regional level, which will require financiers and investment support. To that end, it is essential to have a business plan template from successful case studies, making it easier for financiers to step in and contribute to upscaling nature-based solutions (RECONECT, 2019). The NAIAD project ([2]) aims to operationalise natural assurance schemes, defined as a range of schemes to internalise the insurance value of river systems. Natural assurance schemes can reduce risk, especially of drought and flooding, and this risk reduction can be assessed and incorporated within insurance schemes.

In this subchapter, we discuss the need for investing in long-term assessment of impact on ecosystem services. We also think that governments should keep supporting national accounting of ecosystem services and that they should use the Common International Classification of Ecosystem Services (CICES) for that purpose. Mapping and assessment of the assets can also be employed for ecosystem accounting. Ecosystem services impact assessment, even though it is very important and necessary, cannot hide the facts that disaster risk management should move towards an ecosystem-based approach and that ecosystem degradation must be reversed. It is also important to highlight that impact on ecosystem services triggers a cascading effect that could be reflected in direct and indirect losses. These elements are discussed in detail, and we provide examples of and bibliographical references on how the ecosystem-based approach stands as a promising approach that can impact all elements of the disaster risk equation: mitigating hazards, reducing exposure, reducing vulnerabilities and increasing the resilience of exposed communities.

2 Classification of the Ecosystem Services; the CICES Subdivision

CICES uses a five-level hierarchical structure for ecosystem mapping and assessment. The first four levels can be employed for ecosystem accounting.

There are several (international) classifications for ecosystem services. The Millennium Ecosystem Assessment (MA), TEEB and CICES have proposed commonly used classifications. In essence, they are closely related to each other; all three include provisioning, regulating and cultural services. CICES is commonly used in the EU, since it was also proposed as a typology for ecosystem services under the Mapping and Assessment of Ecosystems and Their Services initiative as part of the implementation of the EU biodiversity strategy to 2020.

CICES has a five-level hierarchical structure. The detailed class types make the classification user-friendly and clarify what ecosystem services are included within each class. Using a five-level hierarchical structure is in line with United Nations Statistical Division (UNSD) best practice guidance (Haines-Young et al., 2012), as it allows the five-level structure to be used for ecosystem mapping and assessment, while the first four levels can be employed for ecosystem accounting without reducing the utility of the classification for different users.

At the highest level are the three familiar sections of provisioning, regulating and maintenance, and cultural ecosystem services.

- Provisioning ecosystem services cover all nutritional, non-nutritional material and energetic outputs from ecosystems as well as abiotic outputs. Examples are crops for food, livestock feed and textiles, fish, timber, water, medicinal plants, genetic resources and biofuels.

(([2]) http://naiad2020.eu/

- Regulating and maintenance ecosystem services represent all the ways in which ecosystems can mediate or moderate the ambient environment that affects well-being. Examples are pollination, water retention and flood control, maintaining a liveable climate, and cleaning polluted air and water.

- Cultural ecosystem services are the non-material, and normally non-rivalrous and non-consumption resources, outputs of ecosystems that affect physical and mental states of people. Well-known examples are nature-based recreation and the aesthetic values of biodiversity and ecosystems.

Table 1 shows a shortened version of CICES at the level of groups ([3]). Subchapter 3.6 discusses additional methods to assess the value of cultural heritage in which monetising is further developed than with ecosystem services.

Ecosystem services have a dual role in the impact and mitigation of disasters. On the one hand, provisioning ecosystem services, such as crop provision, and cultural ecosystem services can be severely affected by disasters. Some ecosystems are particularly vulnerable to extreme events such as floods or droughts, or human-induced disasters such as chemical pollution. Depending on the extent of exposure to a disaster and on the resilience of an ecosystem to cope with disturbances, the capacity of a system to deliver its services will reduce.

On the other hand, ecosystems can also mitigate disasters. In this context, regulating ecosystem services are important, specifically when ecosystems act as transformers by changing the magnitude of flows of matter and energy (i.e. act as buffers; La Notte et al., 2019a). Wetlands, floodplains and riparian areas can store water and prevent downstream flooding in periods of extreme precipitation. Forest soils hold water and release it during droughts. Dunes and coastal wetlands are living barriers against seaborne storms, and protect people and infrastructure from damage. Wetlands and estuaries act as natural wastewater treatment plants and can process large amounts of chemical or nutrient pollution. Forests on steep slopes protect against rockfall or avalanches. Putting ecosystems to work for the benefit of people, including in the management of disaster risk, is currently operationalised in the framework of nature-based solutions (Maes and Jacobs, 2017) or ecosystem-based adaptation (Sebesvari et al., 2019).

A useful method to assess how ecosystems and their services are affected by disasters or contribute to disaster mitigation is to cross-tabulate disaster types against ecosystem services and score either the impact on or the mitigation capacity of each service for each disaster type. This methodology is commonly known as the matrix method and regularly applied in ecosystem services research to assess how ecosystems contribute to human well-being (see for instance Burkhard and Maes, 2017, for examples).

In addition, ecosystem service accounts (for which purpose CICES was developed) can provide key statistics to quantify the economic impact of disasters on ecosystems. Ecosystem service accounts quantify the physical and monetary flows from ecosystems into the economy. In the case of flood control (Vallecillo et al., 2019), it was possible to assess (1) which are the upstream areas providing the service flows and (2) who are their downstream beneficiaries; while a decrease is assessed for the former, a remarkable increase is reported for the latter that results in a critical amount of unmet demand, i.e. areas without protection by the ecosystems.

The outcome in physical terms is translated into monetary terms by using the avoided damage cost. Disaster risk reduction (DRR) by ecosystems is typically accounted for by using avoided damage costs as a valuation technique. The assumption is that damage costs of disasters would be higher in the absence of the mitigating functions of ecosystems, and this value is attributed to ecosystems. Vallecillo et al. (2019), thanks to the valuation of avoided damage costs based on the return period that is affected by the existing level of artificial defence measures, were able to separate those areas where artificial defence is enforced by ecosystem defence from those areas that are protected only by ecosystems.

([3]) *The complete classification is available at* https://cices.eu/.

Table 1. *A shortened version of CICES version 5 with relevant disaster impacts and mitigations*
Source: *Authors, based on CICES.*

I*=impacted,* ***M****=mitigated,* ***ES****=Ecosystem services,* ***ES*** *affected by disasters;* ***M****,* ***ES*** *can contribute to mitigating disaster*

SECTION	GROUP	HAZARDS	HAZARDS (that negatively affect ES)	HAZARDS (mitigated by ES)
Provisioning (biotic)	Cultivated terrestrial plants for nutrition, materials or energy	I, M	Floods, wind storms, forest fire, drought	Soil erosion, runoff, drought
	Cultivated aquatic plants for nutrition, materials or energy	I, M	Floods, tsunami	Flow speed or wave impact
	Reared terrestrial animals for nutrition, materials or energy	I, M	Floods, forest fire, drought, diseases, heatwaves	Forest fire
	Reared aquatic animals for nutrition or materials	I, M	Floods, tsunami, drought, diseases	Pests
	Wild plants (terrestrial and aquatic) for nutrition, materials or energy	I, M	Floods, wind storms, forest fire, drought	Floods, drought, heatwaves
	Wild animals (terrestrial and aquatic) for nutrition or materials	I, M	Floods, wind storms, forest fire, drought	Forest fire
	Genetic material from plants, algae or fungi	I, M	Forest fire, drought	Diseases, antibiotics resistance
	Genetic material from animals	I, M	Forest fires, drought, diseases	Venomous bites, vaccines, serums
	Surface water used for nutrition, materials or energy	I, M	Drought, contamination	Drought, forest fire
	Groundwater used for nutrition, materials or energy	I, M	Drought, contamination	
	Other aqueous ecosystem outputs	I, M	Floods, drought	
Regulation and maintenance (biotic)	Mediation of wastes or toxic substances of anthropogenic origin by living processes	M	Floods	Contamination
	Mediation of nuisances of anthropogenic origin	M	Floods, drought	Wind speed
	Regulation of baseline flows and extreme events	M	Floods, drought	Extreme floods and drought
	Life cycle maintenance, habitat and gene pool protection	M	Diseases, disruption of balance between prey, predator and vector disease	Pests, pandemics
	Pest and disease control	M	Heatwaves	Epidemic
	Regulation of soil quality	M	Drought	Floods
	Water conditions	M	Drought	Drought
	Atmospheric composition and conditions	M	Drought, heatwaves, wind storms	Pollution mixing
Cultural (biotic)	Physical and experiential interactions with the natural environment	I	All	
	Intellectual and representative interactions with the natural environment	I	All	
	Spiritual, symbolic and other interactions with the natural environment	I	All	
	Other biotic characteristics that have a non-use value	I	All	

3 Quantifying the economic costs of ecosystem services losses.

The real cost of disaster to ecosystem services is much higher than the current assessment predicts. Additional attempts are being made to create a full overview of the economic value of ecosystem services and to understand the economic costs of hazards to ecosystem services.

Natural capital and particularly ecosystems play a dual role in disasters and climate change from an economic perspective, as ecosystem services are affected by disasters and they can help to mitigate them (see Section 2). On the one hand, hazards and climate change have direct impacts on exposed ecosystems, affecting their structure and functioning. These impacts create economic costs through the changes in the ecosystem services to people, the economy and society. On the other hand, ecosystems have the potential to provide a cost-efficient or cost-effective way to reduce the impacts, and thereby reduce the need to allocate resources to risk reduction measures or emergency response. In the standard ecosystem service classifications, this is categorised as a regulating service. They are the foundation for nature-based solutions (see Sections 1 and 6).

In this subchapter, we describe the challenges and current attempts to develop a comprehensive understanding of the economic impacts of disasters and climate change in addition to the loss of life. However, assessments of the economic impacts of disasters and climate change on ecosystem services are scarce. To date, the assessment of the economic impacts has been limited to standard, market-based services, mainly in agriculture and forestry, and not focused on ecosystem services, which do not have market prices. For instance, an assessment published in 2009 estimates that climate change could reduce agricultural production in Europe by 10 %, which would translate into additional losses of 0.32 % of annual gross domestic product (Ciscar and Soria, 2009).

The challenge with monetising the impacts of disasters and climate change on ecosystem services is that, in most cases, ecosystem services do not have markets, and therefore they do not have market-determined prices. This has led to the development of various methods to assess the economic value of ecosystem services. The methods are based on people's stated or revealed valuation of the benefit. The stated preferences are assessed by asking people how much they are willing to pay for the ecosystem service (Wainger et al., 2018), or what kind of ecosystem loss they would accept. The revealed preferences are assessed by studying people's actual behaviour and related costs, for instance by collecting data on the money that people allocate to travel to the ecosystem in question (the travel cost method).

The first step in understanding the economic costs of hazards to ecosystem services is up-to-date knowledge of the current value of ecosystem services. Abiotic (such as fossil fuels and minerals) and biotic (ecosystems) natural capital is a concept used to emphasise the crucial role of the natural environment as a life-sustaining system on Earth. Efforts to incorporate natural capital in decision-making include the UN System of Environmental-Economic Accounting (SEEA), which provides an international framework for developing integrated physical and monetary environmental-economic accounts (United Nations et al., 2014a). Within this context, the EU Regulation on European environmental-economic accounts (EU, 2011) provides a legal basis for harmonised collection of comparable data from countries.

The seventh environment action programme and the EU biodiversity strategy to 2020 include objectives to develop natural capital accounting in the EU, with a focus on ecosystems and their services. The knowledge innovation project on an integrated system of natural capital and ecosystem service accounting aims to develop a set of experimental accounts at the EU level, following the SEEA – Experimental Ecosystem Accounts (United Nations, 2014). Ecosystem service accounts are constructed following three main steps: (1) biophysical assessment; (2) translation into monetary terms; and (3) accounting in both biophysical and monetary terms.

Monetary valuation is thus an inherent component of natural capital accounts: the translation into monetary terms implies a direct connection between the amount of change in biophysical terms and the value it presents to the economy. Moreover, valuation techniques employed in natural capital accounting should comply with traditional economic accounting to allow consistent integration and analysis with economic accounts that follow the System of National Accounts (SNA).

Work is ongoing to establish the relationship between ecosystem service accounts and the monetary estimates of ecosystem assets through ecosystem capacity accounts (Hein et al., 2016; La Notte et al., 2019b). The concept of ecosystem capacity becomes important in considering resilience: the current status of capacity accounts and the trend over time can show in what ways ecosystems are more or less resilient in different countries, and how their values change as a consequence of legal directives, policy actions and management practices that lead to increase/decrease in degradation (see the water purification example in La Notte et al., 2019a).

An important advantage of dealing with accounting frameworks, and specifically with ecosystem service accounts, lies in the supply–use structure, which allows one to track (1) which ecosystems provide the service flow and (2) which users/beneficiaries receive the service flow. Use tables are classified by economic sectors (e.g. agriculture, manufacturing, transport, construction, wholesale) and households. Economic sectors and households represent the demand side, which, by interacting with the ecosystem potential supply, generates the ecosystem service flow used (i.e. the actual flow). Once each actual ecosystem service flow is assessed (and valued), it is systematically allocated to its users and beneficiaries. One of the most important advantages of SEEA (and thus of Integrated System for Natural Capital and Ecosystem Services Accounting in the EU - INCA) lies in its consistency and alignment with the SNA: all the measurements generated can be used to make direct comparisons with economic indicators, from interregional trading to macroeconomic impacts.

4 Drivers of ecosystem services losses

Human activities such as urbanisation, intensive cropping and grazing animals, deforestation or intensive forest management accelerate land degradation and reduce the capacity of ecosystems to deliver precious services..”

Human activities take advantage of many kinds of ecosystem services in providing natural resources and living environments, but they also affect ecosystem services intensively (Zheng et al., 2003). The degradation of ecosystem services caused by anthropogenic activities often triggers significant harm to human well-being in both the long and short terms (Millennium Ecosystem Assessment, 2005). Herein, we present some of the anthropogenic threats to ecosystem services, other than those related to climate change. The aim is not to provide an exhaustive list of human-related activities that might deplete the provision of ecosystem services. Instead, we will only address those that by decreasing some ecosystem services could potentially exacerbate the impact of an extreme event.

Substantial effort has been invested in quantifying the individual directional impacts of humans on nature and nature on humans (Milner-Gulland, 2012). The potential damage on ecosystem services due to anthropogenic activities has been extensively documented, and covers the three familiar sections of provisioning, regulating and maintaining, and cultural ecosystem services (UNEP, 2016). Some of the anthropogenic activities that negatively affect ecosystem services and biodiversity worldwide are land use changes such as urbanisation, cropping and grazing animals, deforestation or intensive forest management practices, industrial development and, to a lesser degree, mining. Besides land use and land use change, pollution, introduced invasive alien species and resource exploitation are major drivers of biodiversity loss. These pressures can trigger direct or indirect effects when an extreme event happens.

Through soil sealing, urbanisation reduces the surface area through which rainwater can percolate, thus reducing the inflow to aquifers, increasing the risk of drought and exacerbating the speed of surface water flow, worsening the impact of both extreme flash and riverine floods. Soil sealing is one of the worldwide threats to the functioning of soils; healthy soils can provide regulating and maintenance services such as recycling of wastes or flood mitigation (FAO, 2017). The United Nations estimates that 4.2 billion people live in cities, and projects that another 2.5 billion will join them by 2050. While cities offer opportunities for jobs and resources for human needs, one element closely tied to well-being is often overlooked or neglected: connection to nature. Jiang and O'Neil (2017) predict that the level of urbanisation in western Europe could increase from 77 % to 99 % in 2100. As a result, the number of hectares affected by soil sealing is also expected to rise. This could potentially decrease rainwater infiltration, thereby making urban areas more vulnerable to flooding and lower groundwater levels under the cities, leading to subsidence. Akter et al. (2018) found that in central Europe flood risk would increase significantly with both urbanisation and climate change.

Recently, governments and companies have increasingly turned to nature for disaster risk mitigation (Tyrväinen et al., 2014; Nesshöver et al., 2017; Lafortezza et al., 2018). For example, in managing flooding, nature-based solutions include widening of natural floodplains, protecting and expanding wetlands, restoring oyster and coral reefs and investing in urban green spaces to reduce runoff (Jongman, 2018). Improved planning, through a land-use approach, can also be used to mitigate flood risk by prohibiting building in flood-prone areas. Areas with a high risk of flooding can be developed for nature or recreational purposes (Akter et al., 2018).

In the near future, urban environments need to develop into high-functioning, low-maintenance systems for municipalities and the public. This needs to be achieved not only to improve flood management but also because they contribute to water filtering, waste treatment, reducing stormwater runoff, cooling down the cities and mitigating effects of climate warming (Eggermont et al., 2015; Pauleital et al., 2019; Eldridge, 2019). Urban green solutions, considered as a multifunctional network of urban green spaces situated within the boundary of the urban area, are a promising opportunity to adapt cities to climate warming, mitigate the impact of disasters and preserve ecosystem services. Nonetheless, the right mix of them (street trees, green areas, green roofs and walls, urban gardens and parks) needs to be selected and adapted to the local context (Maes et al., 2016; Rocha et al., 2015). In the next decade, efforts towards the development of sustainable cities will lay the framework for future growth that will substantially affect global sustainability throughout the 21st century.

Soil erosion can be accelerated through intensive agriculture, deforestation and grazing, which could generate off-site costs that are generally paid by society. These include siltation in reservoirs, impacts of sediment on fisheries, poorer water quality for irrigation or other uses (e.g. water eutrophication) downstream, loss of wildlife habitat and biodiversity (Tsiafouli et al., 2015), increased risk of flooding, damage to recreational activities, land abandonment and destruction of infrastructure such as roads, railways or other public assets (Telles et al., 2011). Land degradation due to soil compaction from crop farming or grazing intensification is one of the potential drivers of the increasing flood magnitudes in Europe in recent years (Alaoui et al., 2018). Extreme flooding is not the only impact when soil is lost. The process cannot be reversed. The area will subsequently remain prone to droughts and landslides and in some cases agricultural productivity will be reduced significantly. Even though the ecosystem services and other functions of soils play an essential role in the urban and agricultural ecosystem, they are still poorly taken into consideration in land planning.

Likewise, soil erosion constitutes a subindicator for SDG 2.4 (target 2.4.1; UN General Assembly, 2015): 'By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.' In a worldwide analysis, Liu et al. (2018) found that well-designed and properly managed mixed-species plantations can be more productive and have more advantages in biodiversity, economy and forest health than monocultures. Moreover, Zald et al. (2018) suggested that intensive plantation forestry characterised by young forests and spatially homogenised fuels was a more significant driver of wildfire severity than pre-fire biomass'.

5 Ecosystem services and a hotter climate

World climate warming will lead to unexpected changes in ecosystem functions (carbon storage in soils, nutrient cycling, water purification, pollination, etc.) that will increase disaster risks, especially, but not only, with regard to river floods, coastal floods, heatwaves and wildfires. Understanding of local ecosystems in climate change scenarios is needed to anticipate the risk and to protect the ecosystem services.

A failure to mitigate and adapt to climate change is seen as the risk with the greatest potential to cause economic damage in the world in the years to come; this is the first time ever that the World Economic Forum has ranked an environmental issue as the highest risk (WEF, 2016). A report by the European Environmental Agency, based on over 40 indicators, predicts profound impacts of climate change on ecosystems; unfortunately, there are still major uncertainties about the response of ecosystem services to a hotter climate (EEA, 2017). In 2019, the WEF already listed five environmental risks in the top 10 disasters most likely to occur. Biodiversity and ecosystem collapse is mentioned in the eighth position, before asset bubbles in the economy.

Broadly speaking, increased temperature is accompanied by heat and precipitation extremes, floods, droughts, storms, hail, glacier retreat and rise in sea level. All of them can become true disasters with a high risk of loss of ecosystem services as we know them now. Gradual warming first affects species phenology and then causes alterations of species composition and functional traits (including increases in alien invasive species, loss of highly specialised species and northward migration of economically important species). In turn, for instance, predator–prey and pathogen–host interactions will change and this domino effect might lead to system reorganisation, altering processes such as biogeochemical cycling and changing the stability thresholds of our ecosystems (Bahn et al., 2014). In Figure 1 a warming trend all through several decades can be observed for Europe according to the data registered in the European Drought Observatory.

Climate change is envisaged to have different, but not exclusively negative, effects on ecosystem services across Europe (EEA, 2017), and these are very complex and difficult to fully anticipate. First, long-term warming might have different impacts on some ecosystem services from extreme weather events: the maintenance service of carbon sequestration in soils, for instance, is expected to increase as a result of the warmer climate and increased vegetation productivity in temperate and boreal regions; disasters such as heatwaves, droughts and storms (and associated disturbances) might, however, completely nullify this expected increase (Reichstein et al., 2013).

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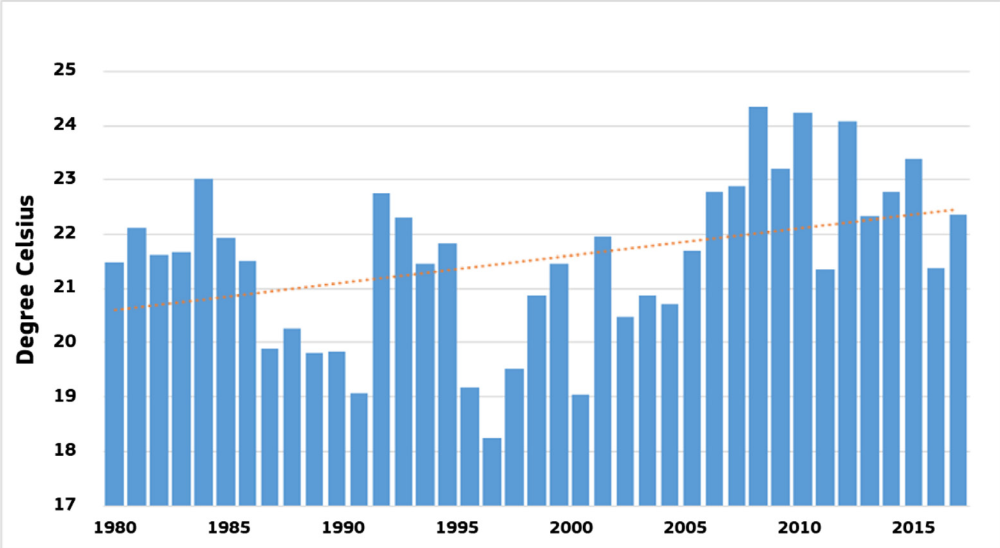
Another example illustrates this complexity. Provisioning services such as timber production are projected to increase in northern Europe (accompanied by substitution of coniferous with broadleaf trees), and to substantially decrease in global South (Kovats et al., 2014). At the same time, this increase in the provision is jeopardised by the risk of decreasing the regulating services in global North (increase in forest pathogens and damage from winter storms; see for example Malmström and Raffa, 2000). Moreover, summer droughts and warming are expected to increase wildfire risks in the Mediterranean area (Moreno, 2014), and have already led to significant forest damage in central Europe in recent years (because of drought, storm or pest disasters in conjunction with mono-species production forest ecosystems)

***Figure 1:** Averaged high temperature, of the first ten days of June from 1980 to 2018, in Europe from the Atlantic Ocean up to the Caspian Sea, displaying annual variability up to 6 degrees but also a warming trend. **Source**: Authors using data from EDO, n.d*



However, increased biomass accumulation and changed weather can also induce wildfire risks in areas so far not prone to burning, such as in the Greek mountains (Koutsias et al., 2012) or Siberia (Malevsky-Malevich et al., 2008). Furthermore, for instance, bumblebees, insects that provide the important regulating service of pollination, will not be able to migrate northwards, and their habitat will be seriously restricted (Kerr et al., 2015). On the other hand, pollination in European grasslands might be maintained by complex interactions of climate change and alien species, in a rather new, unexpected manner (Schweiger et al., 2010).

In general, provisions from natural and ecologically fragile (especially Mediterranean and Alpine) ecosystems are expected to be at the highest risk. Furthermore, climate warming will exacerbate the risks posed by the existing pressures (habitat fragmentation, urbanisation, intensive agriculture, deforestation and grazing, pollution and biodiversity loss, as mentioned in section 4. Hence, while we wait for science to come up with early warning signs of critical transitions in our ecosystems and deliver operational guidelines on ecosystem service vulnerability and priority actions (Schulp et al., 2014; Dunford et al., 2015), we can choose to follow the best available practice (e.g. Bonn et al., 2014). In the case of ecosystem services, good stewardship that increases ecosystem resilience (in particular, maintenance of biodiversity and habitat connectivity; Harrison et al., 2014) is a safeguard option to give nature a chance.

The list displays the problems that civil protection and other local authorities have to address the various extreme events through evacuation. If events occur in conjunction then the evacuation advice might even be contradictory. Especially if diseases occur after an extreme event, the situation might get out of control. If as a result of war or other conflicts the civil protection service is malfunctioning, all disasters might become potentially deadly for human beings. Warlords, strategically thinking politicians and generals also use such scenarios during conflicts. Evacuation is normally temporary but, especially during conflicts, part of the population might not be willing or able to return.Extreme events have also a negative impact on the ecosystem service and can even permanently damage (a part of) an ecosystem. For example, a coastal storm can wash away a beach used for access by fishermen. In Table 3, we focus on the natural adaptation methods to lessen the potential impact of an extreme event. In the third column, some of these adaptation methods are listed. Typically, one can choose engineering methods to adapt to the occurrence of an extreme event or choose a method that collaborates with nature. Floods, droughts and wildfires are the most typical events that present us with such choices.

Table 2. *Impacts of extreme events.* ***Source****: authors*
Note: *Very quick evacuation represents an evacuation of around 15 minutes, quick evacuation in the order of hours, medium quick in the order of a day, slow in the order of 2 days.*

Event	Positive impact ecosystem	Negative impact ecosystem	Adaptation means	Evacuation
Volcano outburst	Fertile ashes deposition	Fires, loss of forest, air quality. Harvest loss. In degraded soils, ash deposition may increase soil erosion and wind erosion Arnalds et al., 2016.	non-burnable construction materials, flight restrictions	Quick, out of the area
Earthquake	Landscape formation, topography formation, the release of minerals	Instability of slopes, avalanches	Absorbent (ground floor) wooden constructions	Difficult to predict, to open spaces, using tents
Tsunami	Could have helped seeds to colonize remote islands and to shaping community structures and biodiversity in local and regional habitats (Urabe et al., 2016)	Destruction of beaches, impacting coral reefs, sea life, fish stocks	Partial abandoning low coastal areas, alarm systems, nature-based solutions (coral reef, coastal vegetation and mangrove protection)	Very quick, to higher grounds
Flood	Sedimentation of fertile earth, increased elevation of low terrain, washes out pesticides and toxic waste.	Soil erosion due to heavy rain, decreased soil fertility upstream, partial harvest- or livestock loss, displacement and downstream accumulation of toxic materials	Grey infrastructures for control and flood regulation (levees, dykes, etc), nature-based solutions (vegetation, river and watershed meandering, floodplain soil water infiltration, etc)	Slow and predictable, to higher grounds
Drought	Provoking roots to root deeper, stabilizing vegetation	Depletion of both ground and surface water resources, escalating to other disasters such as wildfires, low air quality, dust, wind erosion. Drought can potential lengthening of the fire season (Cardil et al., 2019). Eventually, also soil erosion, decreased fertility. Important harvest loss. Cracking of soils might provoke damage to roots, foundations and pipelines, wildlife loss	Building reservoirs, river diversion, irrigation systems, groundwater pumping. Nature-based actions (drought-tolerant crops, sustainable soil management practices, sustainable agricultural, grazing practises, reforestation)	Not needed if the water supply and eventually food supply are guaranteed. If land becomes increasingly arid (desertification) it might trigger migration and abandonment
Wildfire	Contributes to the vegetation cycle and it could enhance local biodiversity	Reduce C fixation and increases CO_2 emissions, losing climate change mitigation capacity. Genetic impoverishment. Soil becomes more vulnerable to water and wind erosion. Burned wildlife and/or livestock.	Construction standards, cleaning, grazing, biomass management, selecting and planting native vegetation with the most fire-resistant genes, forest fire prescription. Citizen awareness campaign and legislation (cigarette butts, pyromaniac behaviour)	Quick, direction difficult to advice
Storm/Wind	Renewal of vegetation, old branches, cleaning and mixing	Some loss of forest, mostly over-stressed and damaged trees. Partial harvest loss	Specific construction standards. Increasing forest resilience and healthy trees, enhancing native species and forest heterogeneity.	Medium quick evacuation to strong shelters
Hail	Renewal of vegetation	Harvest loss, small areas, soil compaction	insurance	No, shelter
Thunder	Weathering of rocks, mineral release	Fires, loss of forest	adaptation of constructions often omitted in poor households	No, shelter
Diseases	Largely unknown, some proteins of viruses appear to be useful to combat cancer	Disruption of balance in ecosystems between predators and prays. Pest may therefore follow	Vaccination, hygienic standards, sewage systems, clean water supply, separation humans – animals, wild-animals - livestock	Quarantine

Table 3. *Selected engineering and ecological adaptation methods.* ***Source****: authors.*

Extreme event	Engineering adaptation	Ecological adaptation
Flood	Dike, deepening of riverbeds	Vegetation along embankments, meandering, unleveling upstream fields, increasing storage and draining capacity
Drought	Reservoir, irrigation	Afforestation, agroforestry, silvopasture, unleveling, increasing retention capacity, sustainable agricultural practices
Wildfire	Traditional forest fuel reduction	Introducing (wild) grazing animals, changing forest structure, native fire-resistant vegetation

Engineering adaptation and ecological adaptation are not mutually exclusive, but an overall strategy is needed, in general within a watershed, in order to reduce the risk of impact. Measures can be very different in their impacts on society and on the landscape. For example, by creating a reservoir to reduce the risk of drought impact, farmers can continue to produce the crops they are used to. If the area converts to agroforestry, then the economy of the area will change.

The advantage of this agroforestry option is, however, that it reduces the risk of suffering from so great a drought that no harvest at all can be collected. The reservoir option will fail if the reservoir is emptied, leading potentially to complete loss of the harvest. With floods, a similar sequence of events can be expected. If the dyke breaks during an exceptionally high flood, all is lost, whereas the ecological solution might lead to flooding when waters are high but the system as a whole will not generate a destructive flood, since the flow velocity of the water is reduced and the watershed as a whole can cater for more water storage. The eminent advantage of the ecological adaptation is that the positive ecosystem impact of an extreme event is preserved (see Table 2), whereas this is not the case with engineering solutions. The challenge for the engineer and the ecologist is to quantify, for both options, the expense of construction or occupation of land as well as the risk to life if the adaptation fails in the case of an extreme event. If both options are equally competitive, the tendency should be to choose the ecological solution, since then the positive ecosystem impact is also preserved (sedimentation of fertile ground in a floodplain for floods, improved deep rooting for drought, continued CO^2 sequestration for wildfires).

6 Working towards solutions: restoration and ecosystem-based solutions

Restoration actions and ecosystem-based solutions can help protect biodiversity, enhance resilience and improve the quality and quantity of ecosystem services. The ecosystem-based approach stands as a promising approach that can influence all elements of the disaster risk equation.

6.1 Restoration and disaster risk reduction

The United Nations Office for Disaster Risk Reduction examined the links between DRR and economic development in the context of the 2030 Agenda for Sustainable Development and the Sendai framework for disaster risk reduction 2015–2030. In the resulting document, Aitsi-Selmi et al., (2015) emphasises that reducing risk and building resilience should be addressed from a multidimensional perspective in which ecosystems play a central role. The UN General Assembly declared on 1 March 2019 that we are about to enter the UN Decade on Ecosystem

Restoration 2021–2030 (Cross et al., 2019; UNEP 2019). The United Nations Environment Programme called ecosystem restoration among the most profitable public investments for economic growth and overcoming poverty (Nellemann and Corcoran, 2010). Throughout the past few years, ecosystem restoration has increasingly been promoted and funded as an important contribution to urgently needed responses to environmental degradation, biodiversity loss, and anthropogenic and climate change throughout the world. Restoration actions, when implemented effectively and sustainably, contribute to protecting biodiversity; improving human health and well-being; increasing food and water security; delivering goods, services and economic prosperity; and supporting climate change mitigation, resilience and adaptation (Gann et al., 2019).

Ecological disturbances such as wildfires and insect outbreaks can interact with climate variability to precipitate abrupt changes in ecosystems and landscapes. These changes may concern biotic components of the ecosystem first, and then the abiotic framework, and can be virtually irreversible without human intervention on a short time scale (Whisenant, 1999).

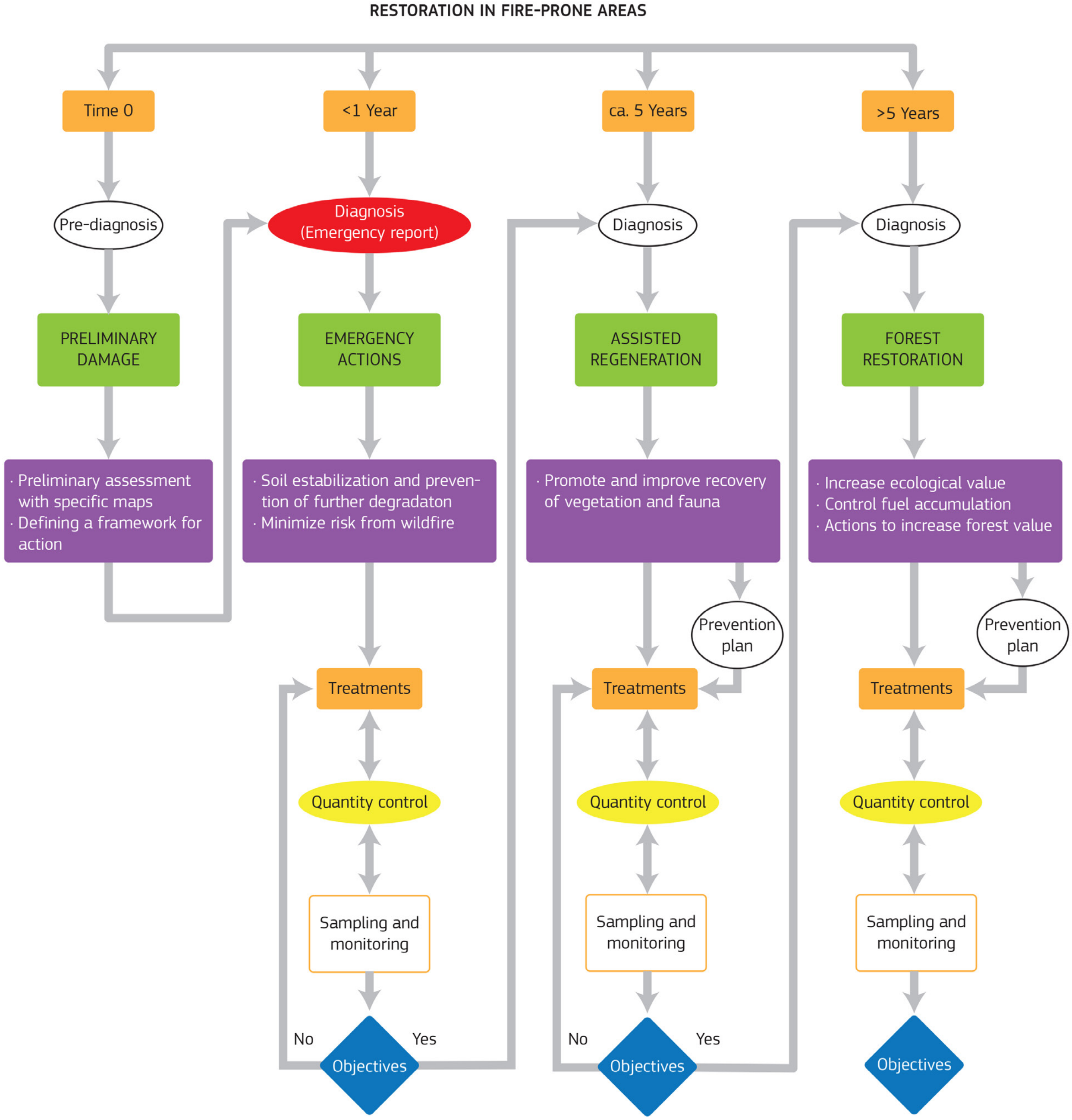
Ecosystems have an intrinsic capacity for recovery after a disturbance, which depends on the intensity and magnitude of the disturbance and the resources available (Holl and Aide, 2011). Underground bud banks, also known as lignotubers, are crucial for regeneration after disturbance (Ott et al., 2019). The presence of a seed bank in the soil, the heterogeneity of the landscape and the seed dispersal capacity of the adjacent systems increase ecosystem and landscape resilience following disturbance (Pausas et al., 2008).

Many human-impacted ecosystems have lost both their capacity to recover after disturbance and the ability to provide ecosystem services. There is a need to assist the recovery of these systems by reinforcing the ecological processes that support resilience: resistance, recovery and reorganisation (Falk, 2017). Targeting ecosystem resilience and social-ecological resilience in international environmental management programmes has gained increased attention but it still needs to be included in disaster risk management, climate change adaptation, impact assessment and land planning. For instance, the Intergovernmental Panel on Climate Change, in its special report on climate change and land 2019 (IPCC, 2019), draws special attention to amplifying social and ecosystem resilience by supporting ecological restoration. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Montanarella et al., 2018) underlines that there is a body of evidence suggesting a positive association between diversity, especially functional biodiversity, ecosystem services and ecosystem resilience to disturbance. Therefore, restoration measures are considered a good tool to build resilience, reduce disaster risk and increase adaptation to climate change.

Restoration efforts have been applied worldwide to assist in recovery and increase ecosystem and landscape resistance and resilience. Thus, increasing ecosystem resistance for soil protection and hydrological control have been and still are major motivations of large-scale tree planting in drylands (Del Campo et al., 2014; Garcia-Peman and Hierro, 2017). In forests in Arizona (USA), post-fire restoration efforts involve assisted gene flow – selecting and planting native pines with the most fire-resistant genes in the most vulnerable areas (Falk, 2018). They include assisted migration and thinning dominant fire-prone species while introducing fire-resilient species. The implication of this is to generate an ecosystem that is adapted to changes in forest fire regime.

Similarly, restoring stand structure and modifying landscape configuration are being implemented at large scales to change wildfire regime and protect human settlements (Alloza et al., 2014; O'Donnell et al., 2018). Establishing resprouting species in pine forests as a way to increase their resilience has also been integrated with forest management programmes in the Mediterranean basin (Gavinet et al., 2015, 2016). These and other measures can be found in more detail in the Super Case Study 4 on the forest fires in Portugal. Notably, the region of Valencia in eastern Spain has developed a framework for the restoration of fire-prone areas that takes into account both the risks generated and amplified by wildfires and actions to increase ecosystem resistance and resilience to wildfires (Figure 2). Such a local-driven restoration solution and ecological approach could be scaled up to a larger area, or serve as an example for other European regions with similar forest fire and wildfire risks.

Figure 2*. A conceptual framework for the different phases of a restoration project in a fire-prone area*
Source: *Translated from Spanish, from Alloza et al., 2014.*
Note: *In this figure, preparedness actions are allocated to time 0. The forest fire event triggers response actions (emergency actions to be conducted in less than 1 year): soil stabilisation to avoid further degradation, and wildfire risk reduction. Over a period of 1 to 5 years, mitigation actions (assisting regeneration) will start. After 5 years, the restoration actions focus on a prevention plan that increases the ecological value of the area, meanwhile controlling biofuel accumulation and promoting the recovery of native forest vegetation.*



In Europe, there are also context-driven and local solutions that focus more on reducing forest fire risk.

This is the case of the fire blocks project promoted by the European Agroforestry Federation, in which cattle are used to reduce forest fire risk in some areas of Catalonia. An important recognised driver of increased fire risk is the abandoning of rural areas in hilly and mountainous areas in Europe, leading to growth of the forest understorey, no longer cleared for firewood harvesting, and spontaneous growth of fire-propagating shrubs and bushes on abandoned fields. Reforestation policies in most areas of Europe have focused solely on planting trees and not on restoring native forests or addressing the rural exodus itself (see the conclusions of Super Case Study 4).

Rewilding is a subset of practices under the broader umbrella of restoration: all rewilding is restoration (of species, but especially ecological processes), but not all restoration is rewilding (Anderson et al., 2019). Trophic rewilding, in which large and potentially dangerous mammals clear the understorey, is an option poorly exploited in Europe, mainly because of the presence of remaining human population, the interests of hunters and shepherds, and the unorganised character of the rural exodus thus far.

The upfront cost of restoration is expensive and may become economically and technically infeasible as abiotic resilience thresholds are crossed, even when the trade-offs of restoration scenarios result in long-term benefits. Ultimately it is the benefit–cost ratio that matters, as stated in the TEEB 2010 report on restored wetlands (Kettunen et al., 2010): the project would deliver net benefits to the community of some USD 2 million in 2010 value terms, after deducting the costs of restoration and opportunity costs. The benefits were mainly accounted for by biodiversity (USD 2.6 million), recreation (USD 663 000) and increased flood storage capacity (USD 417 000), and far outweighed the current benefits provided by agriculture (Olsen and Shannon, 2010).

Peh et al. (2014) suggest that restoration is associated with a net gain to society in the order of USD 200 per ha per year, for a one-off investment in restoration of around USD 2 400 per ha. Recently, Logar et al. (2019) conducted a cost–benefit comparison showing that river restoration is economically justified. It is not all about cost; there are many examples of restoration and rehabilitation programmes launched to reduce the risk of environmental disasters. For example, along the Mediterranean coast near Guardamar in south-eastern Spain, shifting sand dunes threatened the village by the end of the 19th century. A large-scale project was implemented to stabilise the dunes.

The project relied on techniques that had been previously developed in France and elsewhere, which were introduced and adjusted for the needs of this particular semi-arid landscape. After a few decades, trees had stabilised the dunes and the people of Guardamar adopted this new landscape as part of their cultural identity. According to Pagán et al. (2017), the restored dune system acts as a dyke preventing inland flooding but there is concern about the increasing rate of beach erosion.

Mainly, beach erosion is due to the lack of sediment supply, the cut-off in the longshore transport by breakwaters and other anthropic actions. Dune restoration and habitat protection have substantially reduced vulnerability to wind storms and coastal flooding, and ultimately helped the local population to comprehend the limits to urban growth (Murti and Buyck, 2014).

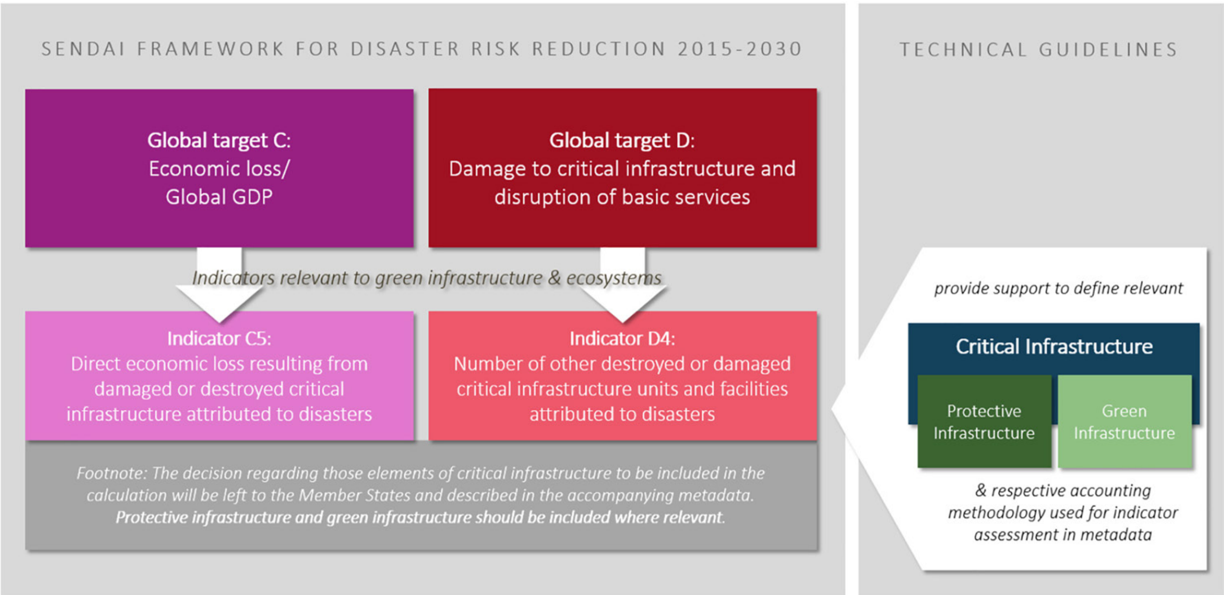
6.2 Ecosystem based adaptation to increase resilience and reduce vulnerability of societies

Ecosystem-based adaptation includes sustainable management, urban green infrastructures, nature-based solutions, conservation and restoration, and makes use of biodiversity and ecosystem services as part of an overall strategy to help people adapt to the adverse effects of climate change. Ecosystem-based solutions have gained attention to complement or replace grey infrastructure (Sebesvari et al., 2019). Ecosystem-based adaptation contributes to repairing ecological damage and rebuilding a healthier relationship between people and the rest of nature. It aims to maintain and increase the resilience, and reduce the vulnerability, of ecosystems and people in the face of the adverse effects of climate change (Gosnell et al., 2017).

Meanwhile, the ecosystem-based approach is also relevant to various dimensions of DRR; it is one of the few approaches that can have an impact on all elements of the disaster risk equation: mitigating hazards, reducing exposure, reducing vulnerabilities and increasing the resilience of exposed communities (Renaud et al., 2013). In addition, Sebesvari et al. (2019) highlighted that an ecosystem-based approach can reduce physical exposure to hazards and increase socioeconomic resilience. Nature-based solutions in restored and maintained wetlands, such as floodplains, marshes, peatlands and lakes, help to increase rain infiltration and thus reduce peak river discharge (Javaheri and Babbar-Sebens , 2014) but also buffer low-flow events and thus water scarcity (Acreman and Holden, 2013), sustaining local livelihoods and providing essential natural resources.

Over the past few years, there seems to have been increasing interest in the opportunities presented by the ecosystem-based approach as a response to the increasing frequency of extreme disaster events (Renaud et al., 2013). Nevertheless, there is a need for better comprehension of how ecosystem-based approaches can be effectively implemented and governed across different spaces and scales to benefit human resilience against hazard impacts (Triyanti et al., 2017). Sebesvari et al. (2019) proposed that customising targets and indicators to countries' needs within the SFM (Sendai Framework of Disaster Risk Reduction) (Figure 3) might be a more practical way to report on both losses and progress.

***Figure** 3. Indicators on green infrastructure and ecosystems in the Sendai Framework. **Source**: Sebesvari et al., 2019.*



7 Case study 1: damaged ecosystem services at increased risk in a floodplain

How far can we stretch our ecosystems? Here we present a long-term study, hardly feasible under real-life conditions in Europe, of a worst-case scenario in a mining industry with high risks, where everything that could have prevented a disaster failed. We show that in the long run our ecosystem can be unexpectedly highly resilient and adaptive, but, if human negligence is combined with the effects of climate change, further disasters are inevitable.

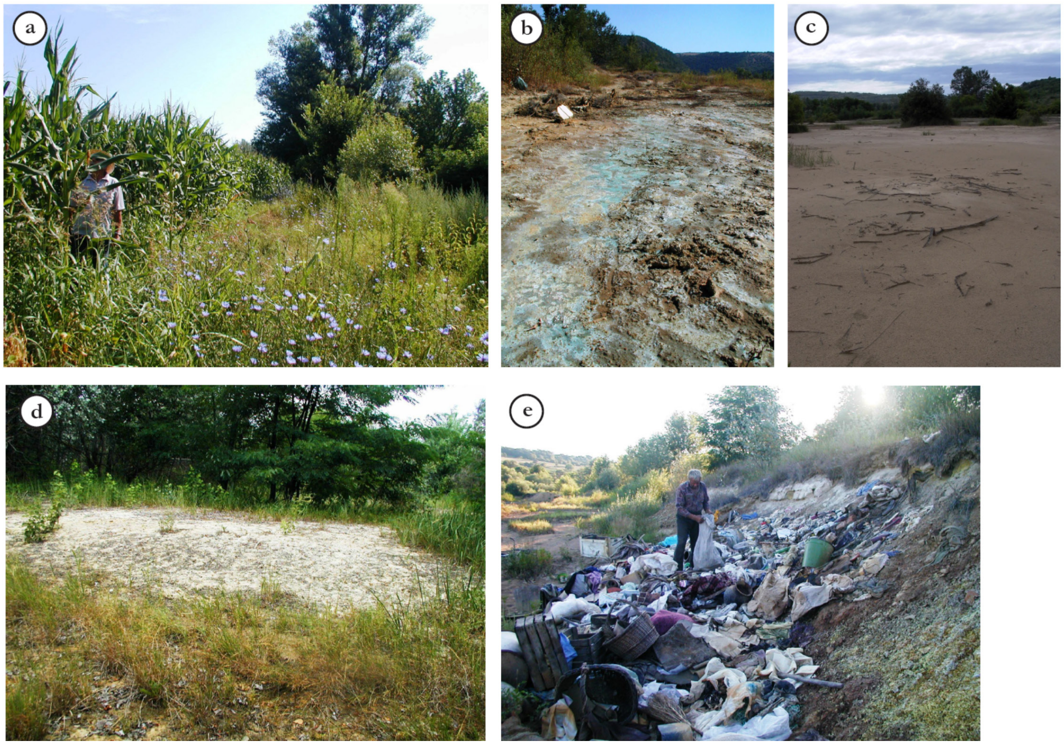
Risks intrinsic to copper (Cu) extraction are high even when the best available practices are followed. Cu mining generates more waste (solid and liquid) than that of any other metal (Dudka and Adriano, 1997); tailing dams (containing toxic slurry after ore processing) have a failure risk more than two orders of magnitude higher than that of conventional water dams (ICOLD, 2001); finally, if the ore contains sulphides, which are prone to oxidation to sulphuric acid when exposed to the air, the combination of metal toxicity, acidification and nutrient deficiency in affected soils becomes a very serious obstacle to restoration (Bradshaw, 1997). The RTB Bor mining complex in eastern Serbia, which exploits one of the largest sulphidic copper deposits in Europe, has had the reputation of an infamous regional environmental hotspot for the last 100 years.

Negligence gradually turned all these risks into an enormous disaster when RTB Bor, back in the early 1940s, ignoring all the legal and ethical issues, began to release the untreated, highly sulphidic Cu tailings into the local river system, estimated at 22 million m3 annually (Wolkersdorfer and Bowel, 2005). Unprecedentedly in Europe, this discharge of pollution went on for about 50 years (Nikolic and Nikolic, 2012). The provision services in the Timok floodplain (a former major granary of this part of Serbia, spread along about 40 km of the meandering river (Figure 4), till the confluence with the Danube) are permanently lost for agriculture and timber production (Nikolic et al., 2011; Nikolic and Nikolic, 2012). The pollution has also affected neighbouring Bulgaria and Romania.

The public has remained silent. Although the operations of RTB Bor provoked the first successful environmental uprising in Europe as early as 1935 (see Nikolic, 2014), this problem remained virtually invisible during the period of the state-controlled economy, when industrialisation was set as an absolute priority; the issue of soil productivity loss for local farmers was ignored. Neither have the intermittent political tensions with Bulgaria and Romania over this pollution issue (UNECE, 2003; Peck, 2004; Stuhlberg et al., 2010) prompted any land reclamation efforts.

Most of the deposited toxic sediments have so far, due to particular geomorphic processes, remained in this floodplain; our very conservative estimates are based on at least 300000 tons of Cu per ha (to a profile depth of 50 cm), highly prone to the risk of oxidative weathering and further Cu release into the environment. If left without vegetation, for instance, 10–35 tons per ha of Cu can be leached down the soil profile in a couple of decades, with pH lowered by 4 (Nikolic et al., 2016, 2018). The persistence of dense vegetative cover is an absolute necessity for the build-up of soil organic carbon (SOC) and the phytostabilisation of Cu (Mendez and Maier, 2008), i.e. for the immobilisation of Cu by plant roots and their metabolites, which thus keep it at bay. The process of spontaneous revegetation is extremely dependent on free floods, in terms of both water supply and nutrient fluxes (Nikolic et al., 2018). Unluckily, in the period immediately after the mine closure (early 1990s), critical for the revegetation onset, climate change accelerated: the affected floodplain received up to 45 % less precipitation, and the temperature increased five times faster, than when the tailings were leaking and pollution was being deposited (Popović et al., 2006). Concomitantly, floods are considerably decreasing.

Figure 4. *Fertile floodplain fields (a) have been destroyed by long-term deposition of mining effluents: Cu toxicity (b) and extreme nutrient deficiency (c) turned them into wastelands (e). Spontaneous restoration fails (d) when, due to increasing droughts, floods cannot reach the area any more. Photos were taken 20–50 km downstream from the leaking tailing ponds.* ***Source****: © Nikolic.*



Currently, 30 years after cessation of pollution influx, more than 10 000 ha is still barren, while a far larger area is covered with three discernible types of spontaneous forest vegetation with practically no economic value. They have a well-defined spatial pattern, very different species composition and structure parameters, and markedly distinct potential for the delivery of the major regulating and maintenance service of Cu stabilisation and SOC build-up. Lowland poplar forests (natural vegetation of this riparian area) are re-establishing themselves at the lowest pollution levels (farthest from the river channel). These are the oldest, densest formations, with the highest retention of Cu in soils (nowadays over 200 parts per million plant-available fraction), the highest SOC levels and the highest plant species diversity, but they cannot spread to the most polluted areas. There, the imposed abiotic stresses pass the resilience thresholds of the natural ecosystem, and only a novel, sparse and depauperate birch and aspen forest, very atypical of the region and limited to the proximity of river channels, eventually appears (Nikolic et al., 2016). Some of the underpinning natural processes of such 'novel ecosystems' (Hobbs et al., 2009) are functional adaptations to low pH and soil phosphorus, and other mineral stresses (Nikolic et al., 2014). The development of a third forest type (the slow-growing, xerothermic black locust and Hungarian oak communities) is solely a consequence of the increased drought incidence and decreased reach of floodwaters. These forests have about 50 % less area of trunks per ha, and about 30 % less potential to sequester organic carbon in soils, than the birch and aspen forests growing on the most polluted and degraded soils (Nikolic et al., 2018, 2019).

To summarise the cascading sequence of events: risky metal-mining operations lead to a disastrous loss of production service of polluted floodplain agricultural land; the public is not informed and remains silent; no restoration is undertaken; nature tries to recover and keeps the metals immobilised by spontaneous regreening; climate change has adverse effects; now even regulating and maintenance services are declining; and the area is again at high risk of further spreading of metal.

Lessons learned

Public awareness of environmental issues and a thorough understanding of the complex and occasionally rather unexpected adaptive responses of nature are crucial for risk mitigation. For example, if all the provision services of a former agroecosystem are lost as a result of a pollution disaster, the ecologically fragile, spontaneously establishing forest vegetation with little economic value still performs the key regulating service of metal immobilisation and soil carbon sequestration. However, accelerating climate change and increasing droughts in this floodplain are severely modifying the course of the spontaneous restoration process, and hence jeopardising the delivery of this essential ecosystem service, exacerbating the risks of pollutant mobilisation and extended damage to adjacent ecosystems.

8 Case study 2: the 2014–2016 South Africa droughts

Southern Africa was affected by a prolonged drought from 2014 to 2016, which was the worst in 23 years and had serious impacts on people's livelihoods, assets, the economy and the environment. The low rainfall was exacerbated by the strongest El Niño weather pattern for 50 years, which affected the whole Southern African Development Community region during the southern winter of 2014/2015. The disastrous effects of this drought event led South Africa to declare a national state of disaster. However, KwaZulu-Natal, North West, Free State and Western Cape were the worst affected provinces, with the sectors of agriculture, tourism, rangeland and water supply hit hard. South Africa is ranked as the 30th driest country in the world and is considered a water-scarce country.

Taking into account climate change and population development predictions, South Africa's water demand may outstrip water supply by 2025 (National Treasury of the Republic of South Africa, 2012) (Hippo, 2016). The average annual rainfall amounts to 492 mm, having a decreasing gradient from west to east, while the temperature and evaporation increase from west to east (Rijsberman, 2006; Unesco, 2006; Rand Water, 2017). The South African Weather Services has over the years observed a decreasing trend in rainfall and an increasing trend in temperature, resulting in changes in evaporation, relative and specific humidity, and soil moisture. Most of these changes are associated with the effects of climate change, made more visible by frequent droughts and extreme rainfall events since the 1950s (Cisneros et al., 2014). Besides being a water-scarce country, South Africa loses between 37 % and 42 % of municipal freshwater owing to human factors such as leakage, wastage, illegal abstraction, pollution and poor water management (South African Government, 2015). Water pollution, for example, creates functional water scarcity even in countries with abundance of freshwater supply (Frauendorfer and Liemberger, 2010; Mckenzie et al., 2012; Musingafi and Tom, 2014).

The 2014–2016 drought in South Africa severely affected the water sector. Reservoir levels dropped from 70 % of full capacity in 2015 to 40 % in January 2016 (Piesse, 2016). Agricultural production was severely affected and dropped by more than 20 %. Maize production decreased from 14.3 million tons in 2014 to 7.2 million tons in 2016, and sugar cane production reportedly fell by about 33 % (Piesse, 2016). The planting surface for potatoes and onion reduced by about 10 000 ha and, in many areas, planting periods had to be delayed by more than 2 months (Piesse, 2017). The tourism and energy sectors were not spared; electricity interruptions occurred (load shedding), businesses (especially small businesses such as car washes) closed down and the general environment suffered (rangeland conditions were very dry. The agricultural sector employs about 800 000 workers; in the commercial agriculture sector an estimated 30 000 jobs were lost in Western Cape Province alone. Municipal revenue from water fell considerably as, for example, the agricultural sector, which is the highest consumer of water, had to cut water use by about 60 %. For the Western Cape Province, losses on the province's gross value added due to the 2014–2016 drought were estimated to add up to ZAR 5.9 billion, which is approximately EUR 95 billion. This represented 20 % of the Western Cape provincial production decline.

The response applied consisted of four actions: water restrictions, water supply, supply of animal feed and renovation works.

- Water restrictions. Some individuals responded by storing water using rainwater collection tanks, and most municipalities instituted water restriction measures such as valve management and lowered water pressure to control the use of water, and restricted water use to certain periods and for certain users only. Severe punitive measures were put in place for those who violated water restrictions. The city of Cape Town tried to desalinate seawater using reverse osmosis techniques but this proved very expensive, so an alternative option of inter-basin water transfer was contemplated.
- Water supply. Following the declaration of the state of drought disaster by the South Africa National Disaster Management Authority, government departments adopted extraordinary measures. The Department of Water Affairs and Sanitation supplied many cities, towns and rural areas with water tankers. Non-governmental organisations such as the Gift of the Giver also came in with water tankers and bottled water, to help mitigate the drought impacts on vulnerable communities.
- Supply of animal feed. Farmers were assisted with animal feed, first by the Department of Agriculture, Forestry and Fisheries (DAFF) and later by donors. Most farmers did not have enough fodder to last them through the drought, and the prolonged drought made assistance to the farmers from DAFF unsustainable. Supplies came in late and some farmers had already lost stock. In most cases, the response activities were not properly coordinated. A long and uncoordinated supply chain was also a problem. For example, at one point, potatoes imported from Ireland were brought in from Cape Town to feed cattle in the Free State, whereas local supplies could have been bought, which would have been cheaper and faster.
- Renovation of old boreholes and drilling of new boreholes. DAFF tried to renovate many boreholes and drilled new boreholes in farming areas, especially in the Free State and Limpopo provinces. The danger of this response strategy was that no feasibility studies were made to ascertain the quantity and quality of the groundwater in most areas where these boreholes were drilled.

Lessons learned.

The comprehensive impacts of the 2014–2016 drought disaster in South Africa have not ended, since some response strategies are still being implemented more than 2 years down the line. However, some key lessons should be learned from the 2014–2016 drought disaster. (1) Issuing, understanding and acting upon early warning systems are crucial. (2) Drought preparedness and response plans are needed at municipal level. (3) Drought disasters require extensive national coordination. (4) Constant monitoring and rehabilitation of water sources and watercourses, including wetlands, are needed and were missing. (5) Provinces need to undertake a scientific drought risk assessment. (6) Sustainable use of water, energy and other natural resources is not negotiable. Most of these lessons also apply to the European context, especially to areas with high water use for agricultural use or areas where soils are drained to enable access for heavy equipment. During droughts such practices become very counterproductive and regional authorities mostly lack insight into the extent of these practices, so during a disaster they are surprised at the extent of the impact.

9 Lessons learned about the role ecosystem services play in disaster risk reduction

The risk of applying short-term economic thinking to ecosystem services exists, and this misperception could lead to undervaluing any single ecosystem service. Only a valuation that captures the large-scale, long-term benefits to society is likely to provide the correct incentive to reduce degradation. We know from the literature that there is a network of interconnection among ecosystem services at different scales. Ecosystem services present mutual interdependencies, diversity and underlying complexity of ecological processes (Barnaud et al., 2018), which complicate a comprehensive framework for ecosystem management. Bearing in mind this complexity, we therefore list in the following subsections a series of incentives for four groups of users of the ecosystem services, which can help them to be more patient with and respectful of the offerings of nature. Besides the various groups of users (policymakers, economic actors, households and civil protection) we address legal instruments, avoiding vague terms such as 'stakeholders'.

9.1 Long term incentives for policymakers

European laws require international collaboration and enforcement. In order to create incentives in the political system, guardians of the long-term interest are to be empowered, both judges enforcing the law and constitution as well as citizens who are not constrained by short-term interest groups. Member States need to keep working on sharing data on successful initiatives in nature-based solutions.

Policymakers, provided they are backed up by a functioning democratic state, have an incentive to satisfy their voters within terms of 4 to 5 years. Most of the time, politicians are organised in interest groups and political parties, aiming at longer time spans, even up to the length of a professional career. Therefore, policymakers have a long-term interest in keeping their party in power and in their personal career. If the voters are not concerned about the environment, which can be the case for many reasons, ranging from ignorance to selfishness or political motivation to counteract state influence, then the politicians elected by these voters will have no incentive to protect the environment.

Some authors (Van Reybrouck, 2016) propose introducing into the decision-making process citizens selected randomly and therefore not representing a specific interest group. Administrators with long-term experience to make up for the limited knowledge of randomly appointed temporary officials can support such citizens selected by partitioning. Thus they can play a role in safeguarding the long-term interests of society. The challenge of the 21st century is to develop economic, social, and governance systems capable of ending poverty and achieving sustainable levels of population and consumption while securing the life support systems underpinning current and future human well-being. Essential to meeting this challenge is the incorporation of natural capital and the ecosystem services it provides into decision-making (Guerry et al., 2015), and these efforts need to be shared and upscaled among Member States.

9.2 Long-term incentives for economic actors

Reputation is probably the main driver for economic actors to make sure that ecosystem services function well. Other profit drivers, such as the product's price and the variable and fixed costs, remain limited to the economic domain. Companies that do not deliver directly to the consumers have therefore few motives to take care of the environment. Labelling might help, as might a universal legal obligation to enhance the resilience of (socio)ecological systems within a reasonable time.

Economic actors such as industries, fishers or farmers act in competition with each other. The lowest possible price for their products is their main way of dominating the market. As well as the lowest price, the reputation of the company and the quality of the product also play roles, and environmental protection incentives can be found in these areas. For extractive industries, such as mining, drilling or timber-producing companies, the incentives of reputation and product quality are of less importance, since these companies tend to create products not sold to the consumer market. Working behind the scenes, their main incentives are shareholder value and market dominance due to low pricing and delivery guarantees.

The current economic model cannot provide appropriate incentives to protect ecosystem services from the extractive behaviour of these types of economic activities. Therefore, as long as the political model, as mentioned before, does not create explicit incentives to contain the expansive behaviour of economic actors, utmost care must be taken with regard to their proposals. Before mining companies are allowed to extract material from the subsoil, a landscape repair fund must be set up into which a fixed percentage of the profit should be transferred. Such funds must be free of links to the company in order to avoid the fund being tapped if the company goes bankrupt. Disaster repair funds can also be set up for oil extraction and chemical factories, which can potentially lead to disasters that damage ecosystem services, quite apart from loss of life. The latter is often dealt with by legislation whereas damage to the ecosystem services is not.

Responsibilities in the economic value chain, in which many providers together create one final product, should be made more explicit. This can be done by labelling the full origin of a product using understandable, not legalistic, language. Such labelling, and especially its certification, comes at a cost, however. The 'commons' such as – air, fresh water, soil, subsoil, landscapes and sea with its seafood – lack a clear price and custodian in our economic model. If they are damaged or altered, no consequences are faced by the party that caused the reduction in the functioning of the Ecosystem Services (ES). In order to make a level playing field, economic actors need internationally enforced rules allowing their expenses in taking care of the commons to be comparable.

Probably the best example of functioning policies protecting a part of the commons is the various freshwater regulations, in which industry is allowed to extract water provided it is delivered back to the river with the same composition and at the same temperature. For the commons with an unbounded geographical scope, such as the sea and the air, such policies are lacking or have been only partly successful up to now. Often pricing is proposed, such as CO_2 pricing. The pricing can, however, only be successful if the acquired funds are used to restore the composition of the air to its initial state. Otherwise, altering the composition of the atmosphere becomes a privilege for the more prosperous economic parties, leading to further exacerbation of an already unequal economic playing field.

The use of nature-based solutions for adapting to climate change is justified by their multiple benefits, and one of the reported benefits is their cost-effectiveness compared with alternative solutions (Kabisch et al., 2016). However, there have been very few systematic assessments of the economic benefits and costs of nature-based solutions, only since 2014 studies started to inventory the projects done to date (Doswald et al., 2014). In assessing the benefits and costs of ecosystem services, social and environmental costs and benefits have been more systematically assessed than economic ones. According to Doswald et al. (2014), the majority of published economic efficiency evaluations assess the economic costs and benefits at a rather general level. In the majority of reported cases, the net present value of a nature-based solution is positive when considering social, environmental and economic benefits. Projects such as NAIAD (see Section 1 above) seem to be good initiatives to assess the insurance value of nature-based solutions to prevent disasters, especially flooding and drought risk.

The economic benefits of nature-based adaptation are avoidable damage costs, especially from extreme weather phenomena; new or improved business opportunities; savings compared with alternative adaptation solutions; and a better quality of life. Costs have been calculated including setting up and maintaining the nature-based solutions (or ecosystems), as well as opportunity costs (i.e. accounting for what else could have been done with the same investment) (Doswald et al., 2014). Systematic cost–benefit analyses and reporting of results are important for increasing the interest, and thereby investment, in nature-based solutions for disaster risk management and climate change adaptation, and for increasing the use of long-term funding and public–private partnerships in the set-up and maintenance of them (Kabisch et al., 2016).

Economic actors such as industries, fishermen or farmers act in competition with each other in which the lowest possible price for their products is main incentive to dominate the market. In the competition for the lowest price, also the reputation of the company and quality of the product play a role and environmental protection incentives can be found in this area. For extractive industries, such as mining, drilling or timber-producing companies the incentives on reputation and product quality are of less importance since these companies tend to create products not sold at the consumer market. Working behind the scenes their main incentive is shareholder value and market dominance due to low pricing and delivery guarantees.

The current economic model cannot provide appropriate incentives to protect ecosystem services from extractive behaviour of these types of economic activities. Therefore, as long as the political model as mentioned before does not create explicit incentives to contain expansive behaviour of "economical actors behind the scenes", utmost care must be taken with regard to their proposals. Before mining companies are allowed to extract material from the subsoil a "landscape repair fund" must be instantiated into which a fixed percentage of the profit should be transferred, such funds must be free of links to the company in order to avoid the fund to be ripped when the company goes bankrupt. Disaster repair funds can also be instantiated for oil extraction activities and chemical factory activities, potentially leading to disasters that damage ecosystem services apart from loss of life. The latter often taken care of by legislation whilst damage to the ecosystem services is not taken care of.

Responsibilities in the economic value chain, in which many providers together create one final product, should be made more explicit. This can be done by labelling the full origin of a product using understandable, not legalistic, language. Such labelling, and especially its certification, comes however with a cost. The earlier mentioned "commons"; air, fresh water, soil, subsoil, landscapes, and sea with its seafood lack a clear price and custodian in our economic model. If damaged or altered no consequences are faced by the party that caused the reduction on the functioning of the ES. In order to make a level playground, economic actors need international enforced rules allowing having comparable expenses in taking care of the "commons". With various freshwater regulations, in which industry is allowed to extract water, provided it is delivered back with the same composition and temperature to the river, is probably the best example of functioning policies protecting a part of the commons.

For the commons with an unbounded geographical scope such as the sea and the air, such policies are lacking or only partial successful up to now. Often pricing is proposed, such as CO2 pricing. The pricing can however only be successful if the acquired funds are used to restore the composition of the air to its initial state. Elsewise altering the composition of the atmosphere becomes a privilege for the more prosperous economical parties leading to further exacerbation of an already unequal economic playground.

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The economic benefits of climate change adaptation are avoidable damage costs, especially from extreme weather phenomena, new or improved business opportunities, savings compared to alternative adaptation solutions and income from subsidies. Costs have been calculated from setting up and maintaining the nature-based solutions (or ecosystems), as well as from opportunity costs (i.e. also accounting for what else could have been done with the same investment) (Doswald et al., 2014). Systematic cost-benefit analyses and reporting of results are important for increasing the interest, and thereby investment, toward nature-based solutions for disaster risk management and climate change adaptation, and for increasing the use of long-term funding and public-private partnerships in the setup and maintenance (Kabisch, et al., 2016).

9.3 Long-term incentives for households

In DRR, households play a marginal role if we focus on their impact. However, in households, new ideas are tried out and motivation can be shared with household members or neighbourhoods.

Actions for households to take with respect to DRR and ecosystem-based solutions can be confusing. To keep a house cool during heatwaves, it might be advised to plant trees close to the house to provide shade, while a wildfire protection scheme might urge that all trees close to the house should be cut down. Besides the confusing message, neither measure, if taken in isolation by only one household, will have a significant impact on the exposure to either disaster. The latter obstacle – the fact that the work of one family in isolation has no significant impact – can be demotivational, leading to inactivity on even minor aspects of environmental awareness such as separating litter or maintaining a green garden.

It is therefore important to give individual citizens the tools to make an impact on DRR and ecosystem services. The most obvious measure is to involve citizens at the level of a neighbourhood in the planting of trees and the design of green spaces in their immediate living and working environment. Such actions will lead to better knowledge of the immediate environment, which can be essential during the onset of a disaster. Apart from that, if people are involved in decision-making they will feel responsible for the well-being of the ES, leading them to give assistance during, for example, a period of drought. Recent studies such as that of Santoro et al. (2019) have demonstrated that, in flood risk management, approaches based on physical phenomena are not enough and they should be integrated with household actions. To that end, facilitating a dialogue to reconcile differences of opinion and promote the social acceptance of nature-based solutions is essential.

9.4 Incentives for civil protection

Civil protection agencies have to choose between contradictory measures, alleviating different disasters by choosing the most appropriate measure. Their way of working can ideally lead to localised advice, thanks to their knowledge of the area, to be complemented with scientific knowledge on the complex functioning of ecosystems.

Civil protection agencies have hitherto focused on the aftermath of a disaster; they work to be on the right spot as quickly as possible with the right aid workers.

Preparations beforehand are limited to preparation of supplies and evacuation routes. Incentives for civil protection agencies are straightforward: once the risk of disasters caused by extreme weather events or industrial activities with potential hazardous impacts on ecosystem services is reduced, they can allocate more funds to other protection measures, ranging from cybersecurity to preventing disasters related to criminal behaviour. With limited funding and a wide range of potential disasters, they always benefit from reduced exposure.

Legislation for compensating an EU Member State after a disaster has taken place is linked to measures being taken to reduce the risk of repetition of the same disaster. Civil protection agencies are probably the best organisations to assess locally how far measures taken are beneficial to DRR.

The main problem for civil protection agencies and the way they work in relation to ES and DRR is that DRR by enhancing or restoring ecosystem services will yield softer figures on quantitative risk. For grey solutions, such as dykes, an engineering company can give a hard number of how many times in 1 000 years the dyke will be flooded. For a river allowed to meander again, such figures are absent; the river is to a certain extent even expected to flood the area.

Furthermore, measures related to ES and DRR can be contradictory. The example of heatwaves, wildfires and tree planting, above, is clearly contradictory. The recently introduced policy in Portugal to clear trees up to 4 m from the road, in order to preserve an escape route during wildfires, is similar. The cleared area next to the road will regrow with dry grasses that catch fire much more easily than a tall tree trunk with no under-storey. Roads and trees are anyway part of a complex debate in which a tree is considered an impact risk but it is also known that car drivers slow down on a road with trees compared with a road lying in an open landscape, thus reducing the impact risk themselves.

For civil protection authorities it is therefore of the utmost importance to acquire knowledge of the landscape of the area to protect so that all measures can be compared for their local impact. Civil protection exercises should include an ES component, improving the knowledge of ES in the area and potential losses associated with hazards. Projects such as RECONECT could be used as examples (see Section 1).

9.5 Legal instruments to protect ecosystem services

The long-term sustainability of ecosystem services depends not entirely on the extensive EU environmental laws available but also on the Member States' capacity to adapt and mitigate natural and human-made disasters.

Humans have degraded natural conditions and amplified environmental problems since the Palaeolithic era, and have faced repeated environmental crises since then, which can be divided into three categories: (1) those caused by purely natural conditions, (2) those caused or aggravated by human activity and (3) those arising from increasing human demand for sources of energy (Bentley, 2013). The capacity of an ecosystem to cope with a disaster (human-made or natural) is limited. There is a degradation threshold that, when passed, the system cannot recover from; subsequently it threatens the stability of the society, which can no longer benefit from the ecosystem services. A well-known historical example is the Easter Islanders who cut down the last tree, and rats (an invasive species) ate the trees' seeds before they could regerminate.

The main ecosystem service of the trees on the island was the provision of wood to build canoes. Once the wood was run out, the population was trapped on the island without access to fishing. The ecological catastrophe triggered civil war and social collapse.

How can we make the ecosystem work with us and not against us? As stated in Section 6, well-managed ecosystems and restoration efforts can avoid ecosystem collapse and can support various dimensions of disaster risk management. Regulations and legislation tools need to be designed to avoid risk to the population or the environment. Subsequently, the state has to enforce such regulations, a task often blurred by changing priorities. Pressure groups such as Client Earth bring cases against authorities they consider not bold enough in protecting the long-term interests of society, while using the legislation created by the state.

An exhaustive list of the EU's legal tools (directives, regulations, decisions) addressing ecosystem degradation would be out of the scope of this book, but some of them are listed here: the Water Framework Directive, the habitats and birds directives, the Environmental Impact Assessment Directive, the Strategic Environmental Assessment Directive, the seventh environmental action programme and the resource efficiency roadmap. Further non-binding strategies have been agreed on, such as the biodiversity strategy, the forest strategy and the adaptation strategy.

The Institute for European Environmental Policy estimates that the body of EU environmental law amounts to well over 500 directives, regulations and decisions. Nevertheless, the Earth's condition in Europe and worldwide has continued to deteriorate since 1997 (UN Environment, 2019). Without changes, the situation looks bleak for all of its inhabitants; we are talking about a global issue of catastrophic dimensions. It is partly in our nature to react to an event instead of working on preparation and mitigation.

For example, metal mining, in particular, results in waste (tailings) that may contain dangerous chemicals and heavy metals, which need to be stored safely in heaps or ponds behind retention dams. The subsequent collapse of such tailings dams, e.g. in Baia Mare, Romania, in 2000 (European Commission, 2000; UNEP and OCHA, 2000) or in Aznalcóllar, Spain, in 1998 (Hudson-Edwards et al., 2003), and the resulting environmental and socioeconomic consequences have led to the adoption or amendment of EU legislation to ensure the safe management of mining waste.

Part of this post-event legislative reaction was the Extractive Waste Directive (EU, 2006), which complements the Seveso Directive on the control of major accident hazards (EU, 2012). In addition to these legal instruments, the Environmental Liability Directive (EU, 2004) provides a cross-cutting framework for the protection of environmental assets. It is aimed at the implementation of the polluter-pays principle, whereby a company causing environmental damage is liable and has to take preventive or remedial action and bear all associated costs.

10 Conclusions and key messages

We offer the reader a wrap-up of the main concepts, facts and conclusions extracted from the literature search conducted for this subchapter on ecosystem services relation to DRR, climate change adaptation and reversing land degradation. Meanwhile, we highlight key messages and lessons learned for scientists, decision-makers, practitioners and citizens. We address each societal actor separately; however, human behavioural problems related to the environment require well-organised sectoral cooperation. To pursue that, it is essential to integrate knowledge of ecology, restoration and nature-based solutions into disaster-planning policies, to promote cross-border management and long-term monitoring programmes in which climate change scenarios should be included.

The general messages of the subchapter are:

- The scientific literature supports the view that there is a relation between vulnerability to disasters and ecosystem service degradation. Human activities will be able to reduce the impact and risk of natural disasters if they look for a more integrative, long-term and upscaling approach that brings nature closer to land use planning for DRR. Human activities such as urbanisation, intensive cropping and grazing animals, deforestation or intensive forest management accelerate land degradation and reduce the capmore effectacity of ecosystems to deliver precious services.

- Locating ecosystem functioning in the centre of decision-making, as done by the ecosystem service approach, could assist the decision-making process and ecosystem-based management strategies (Elliff and Kikuchi, 2015).

- Nature-based solutions have been proven a cost-effective tool to prevent and mitigate extreme natural events, thanks to their role in enhancing ecosystem services. However, the real cost of this type of disasters to ecosystem services is much higher than the current assessment predicts. So far, additional efforts have been made, and valuation techniques employed in natural capital accounting could help if they comply with traditional economic accounting to allow consistent integration and analysis with SNA economic accounts.

- It is urgent to work on prevention, not only on reaction. Regulations and legislation tools need to be designed to avoid risk to the population or the environment. Subsequently, the state has to enforce such regulations, a task often blurred by changing priorities in Europe.

- A disaster could trigger long-term effects on ecosystem services that are already damaged or under pressure. Provisioning, cultural and regulating ecosystem services can be substantially affected by disasters. For example, the cooling effect of a forest can be lowered by a pest or during a drought. At the same time, regulating ecosystem services can mitigate disasters as well. During a drought, a forest will hold much more groundwater than adjacent areas without forest cover, providing a higher groundwater table. Human activities such as urbanisation, intensive cropping and grazing animals, deforestation or intensive forest management accelerate land degradation and reduce the capacity of ecosystems to deliver precious services. It can be assumed that damage costs of disasters are higher in the absence of the mitigating functions of ecosystems. Economic impacts of disasters and climate change on ecosystem services have so far been only partially captured. Additional attempts are being made to create a full overview of the economic value of ecosystem services and to understand the economic costs of hazards on ecosystem services.

In addition to this, we can extract the following lessons for specific audiences.

Policymakers

It seems that most legislation is based on post-event reaction and adaptation. Instead, policy frameworks would do better to focus on prevention, thus avoiding the loss of valuable ecosystem services. Following the prevention approach, policy-makers should support nature-based solutions and implement them at a larger scale that contributes to hazard prevention. Meanwhile, reducing grey solutions and substituting them with green infrastructure, when possible, will help prevention and mitigate hazards (e.g. to impact lessening the effect of flooding in urban areas, to preparing large-scale reforestation projects, restore natural grasslands, restore water retention in agro-ecosystems, tree planting in areas suffering recurrent droughts). Policy-makers should promote transboundary agreements between neighbouring countries leading to the implementation of ecosystem-based solutions at a larger scale. Policymakers in the meantime need to learn how to communicate the often complex messages based on scientific findings. To address the degradation of ecosystem services and its consequences, in an effective manner, it would be best for governments to support activities with low impact on biodiversity. Essential to meeting this challenge is the incorporation of natural capital and the ecosystem services it provides into decision-making (Guerry et al., 2015), and these efforts need to be shared and scaled up significantly.

Practitioners

Practitioners are interested in acquiring more knowledge of implementation, monitoring and successful examples of nature-based solutions across Europe. However, there is a shortage of information about successful projects for the non-scientific or non-English-reading community. Civil protection practitioners should receive education and training taking into account knowledge of ecosystem services. One of the main limitations civil protection will need to deal with is that some impacts on ecosystem services are intangible, but still important, and practitioners will require training, learning networks and information sharing to implement a (site-specific) matrix to prioritise the ecosystem services under risk. In order to achieve that, it is essential to build transdisciplinary collaboration between scientists and civil protection practitioners. Guidelines based on successful local cases of nature-based solutions to improve disaster risk management, mitigation and adaptation could be used to overcome limitations and might become possible examples allowing to scale up in other regions. They would therefore remove the onus from policymakers to decide exactly when and where these interventions might be appropriate while keeping irresponsible projects from taking place. Further studies are needed to investigate and quantify the reduction of maintenance cost of nature-based solutions compared to classical grey solutions, and that practitioners should be involved in these cost assessment studies. Private-sector capital can be incentivised to scale up landscape restoration initiatives. To that end, it is essential to have a business plan template derived from successful case studies, making it easier for financiers to step in and contribute to scaling up nature-based solutions and restoration actions.

Scientists

Climate change, but also rural abandonment, among other processes, are game-changers for ecosystem services; nature-based solutions can help divert impacts and shocks, although more research is needed to monitor long-term effects. Climate change scenarios need to understand local ecosystems to anticipate risk and to protect the ecosystem services. We know that damaged ecosystems, especially humid ones such as wetlands, can be restored and, after a while, a reduction in the risk of disaster can be measurable. Ecosystems damaged in dry conditions can be restored as well, but substantially longer times are needed, often greater than the life span of a human being. Understanding how key functions determine ecosystem service supplies and how they depend on and foster biodiversity is crucial in the search for local nature-based solutions. The scientific community should keep on promoting innovation and improving science communication and disseminate the latest scientific findings. Researchers generate information that is often context-specific and hedged in language that prevents the application of their findings and recommendations. Meanwhile, scientists should also ensure that models are tested and replicable under different ecosystem management regimes, across various climatic regions and in different socioeconomic contexts.

Citizens

People are interested in getting informed about the important role ecosystems play in DRR, prevention and mitigation capacity, but they also want to better appreciate the impact of climate change on their environment and livelihoods. Citizen science initiatives using social media could promote collection of data about the impact of hazards on the daily lives of citizens. Citizens play a vital role in implementing nature-based solutions, and it has been widely recognised that the effort of citizens is far more effective if done collectively. Therefore, citizens should find a way to engage with others and to actively participate in decision-making.

We identified shortcomings in the awareness with the named key players in society (scientists, citizens, decision-makers and practitioners) and their perception of the importance of ecosystem services in DRR. We hypothesise that this could be due to a lack of knowledge on the mechanism behind ecosystem services affected by disasters. Furthermore, ecosystem services are often delivered free of cost, leading to a first-come, first-served approach, promoting non-collaboration between societal actors. It is the task of the legislature to protect ecosystem services from this detrimental behaviour.

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Super Case Study

5

COVID-19 emergency

Online Version

Super Case Study 5:

COVID-19 emergency

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CONTENTS

1 Introduction

Despite the experience of previous health and economic crises, the world was significantly unprepared when faced with the coronavirus disease 2019 (COVID-19). The economic impact of COVID-19 was completely unexpected. Moreover, under the current circumstances, the future economic outlook remains largely uncertain, given the difficulty in estimating the economic cost of COVID-19 and the potential dynamics of the recovery.

The pandemic has shown that many health systems lack the necessary mechanisms and materials to respond adequately to how quickly the virus is spreading, and that they have had to rely on societal and economic lateral thinking.

Combating risk is a shared responsibility among institutions and citizens. In times of crises, all parties involved must double their efforts. During the emergency phase, it is essential to fight not only to reduce the impact that has not yet materialised (risk), but also to manage the impact that has occurred.
A clear and coordinated communication strategy for effective risk mitigation is crucial for building trust with citizens in a quickly evolving situation. Furthermore, combating fake news and disinformation can directly help save people's lives.

The COVID-19 crisis also highlighted the divergence in scientific analyses, advice and policy responses due to a lack of harmonised or even standardised approaches for data collection and data analysis, and a lack of modelling tools to analyse hypothetical scenarios and to incorporate real-time data. Uncertainties must be understood as complex constructions of knowledge, materiality, experience, embodiment and practice (Scoones and Stirling, 2020). To efficiently manage a crisis despite such uncertainties, we must be familiar with its components, and this will happen only if the bridge between science and policy is constantly strengthened in peacetime.

Against this background and since the beginning of the crisis, the scientific community has fully committed itself to supporting the competent authorities. This includes not only epidemiological expertise; it was clear from the start that a transdisciplinary approach was also needed, including socioeconomic and data analysis, and social vulnerability assessment, while carefully monitoring the potential growth of other threats such as cybersecurity and disinformation.

We live in a globalised and interconnected world, which requires us to approach crises such as this one in a comprehensive way. Further efforts are needed towards a more coordinated European and global response. The governance of crisis management will have to be reconsidered, as will the way scientific advice is given to and used by policymakers. The long-term science–policy relationship must also be strengthened.

2 Description of the main consequences of the event

The COVID-19 crisis has shown, in an unprecedented way, the EU's fragilities and profound interdependences, both internal and with the rest of the world. It has also shown the need for a coordinated EU response and the importance of solidarity within and among European societies.

2.1 Main consequences on population

The final numbers of this pandemic are still unknown. At the time of writing this chapter (October 2020), the number of fatalities has exceeded 1 000 000 globally ([1]), 23 % of them in the European Union ([2]). The total number of cases in the world is more than 35 million, of which 5.5 million are in Europe. However, these incredibly high numbers are only the tip of the iceberg, since they refer merely to having contracted the novel coronavirus, which is just part of the impact. Unfortunately this pandemic has affected and will affect the whole planet in different ways and with different degrees of severity.

The containment of COVID-19 is a subject for collective action, since the probability of contracting and transmitting the virus depends not only on our own behaviour but also on the behaviour of others. The solution to this problem should therefore be sought at group level (not only at the international or national level, but within localities, workplaces and households) and it is therefore doomed to suffer from the 'tragedy of the commons' (Ostrom et al., 1992), a situation in which individual or national priorities trump the need to preserve our common good, a fair society and a thriving economic system (Lunn et al., 2020).

Governments around the world are adopting different strategies to combat COVID-19, from recommendations on how to wash hands, to quarantines or social distancing. What all these strategies have in common is that public trust is necessary for them to have an effect. Trust in the source of information is central to how people interpret and react to public health messages. The literature on communication of risk during pandemics shows that people with higher levels of trust or confidence in institutions are more likely to accept recommended measures than those with lower levels.

Before the COVID-19 outbreak, around 54 % of Europeans believed their life was fair. However, fairness perceptions varied widely across EU Member States, with southern and eastern Europe displaying substantially lower figures than other EU macro-regions. Similarly, fairness perceptions are lower among unemployed people and lower income groups (d'Hombres et al., 2020). Growing disparities on multiple socioeconomic dimensions have contributed to this sense of unfairness, and are likely to undermine trust in traditional institutions and give rise to political discontent.

In contrast, fairness and inclusiveness have the potential to promote competitiveness and growth. The health and economic effects of the COVID-19 pandemic being borne disproportionally by less well-off people, the current pandemic strengthens the need to address the challenges associated with widening inequalities. The spread of misinformation (including conspiracy theories) and fake news have played a significant role in this pandemic from the start. To ensure we will soon recover from this unprecedented situation, the fight against misinformation, relying on many interventions that are behaviourally informed, is of paramount importance (Box 1).

([1]) *https://coronavirus.jhu.edu/map.html*
([2]) *https://covid-statistics.jrc.ec.europa.eu/QlikDashboard?sheet=multidim*

BOX 1.

Fight against disinformation

The European Commission and the High Representative of the Union for Foreign Affairs and Security Policy have stepped up the fight against coronavirus disinformation (European Commission, 2020a) by proposing a way forward in a Joint Communication (European Commission, 2020b). It sets out the immediate response and concrete actions that can quickly be set in motion to counter the massive wave of false or misleading information, including attempts by foreign forces to influence EU citizens and debates. At the same time, the EU will continue to ensure freedom of expression and support media, independent reporting by which is so crucial during the coronavirus pandemic. The proposed actions will feed into future EU work on disinformation, notably the European Democracy Action Plan and the Digital Services Act.

Biologically, women are not more at risk of COVID-19 than men are, while it seems that men are slightly more affected by the virus (Blaskó, 2020). However, women risk paying a higher price for the crisis than men. This can be in the form of a massive physical and mental (Papadimitriou and Cseres-Gergelyne Blasko, 2020) workload during the crisis that can lead to career disruptions in both the short and the long run, and in extreme cases even in the form of physical suffering.

In a recent UN communication (United Nations Department of Global Communications, 2020), the Secretary-General, António Guterres, noted that the pandemic is having devastating social and economic consequences for women and girls across the world.

Several of the global concerns are valid for Europe. Unless successfully mitigated, this damage could even delay the slow improvements in gender equality. On the other hand, from a European perspective the outbreak has also induced new opportunities, which – if successfully managed – could even provoke some shift towards a more even distribution of unpaid labour between men and women.

The closure of schools and education ([3]) from home with the support of digital technology have created challenges for students and their families. This disruptive situation has revealed several challenges. It has triggered an increase in inequalities in education, due to different access to and availability of devices and educational digital infrastructures, resources and applications on the parts of teachers and students.

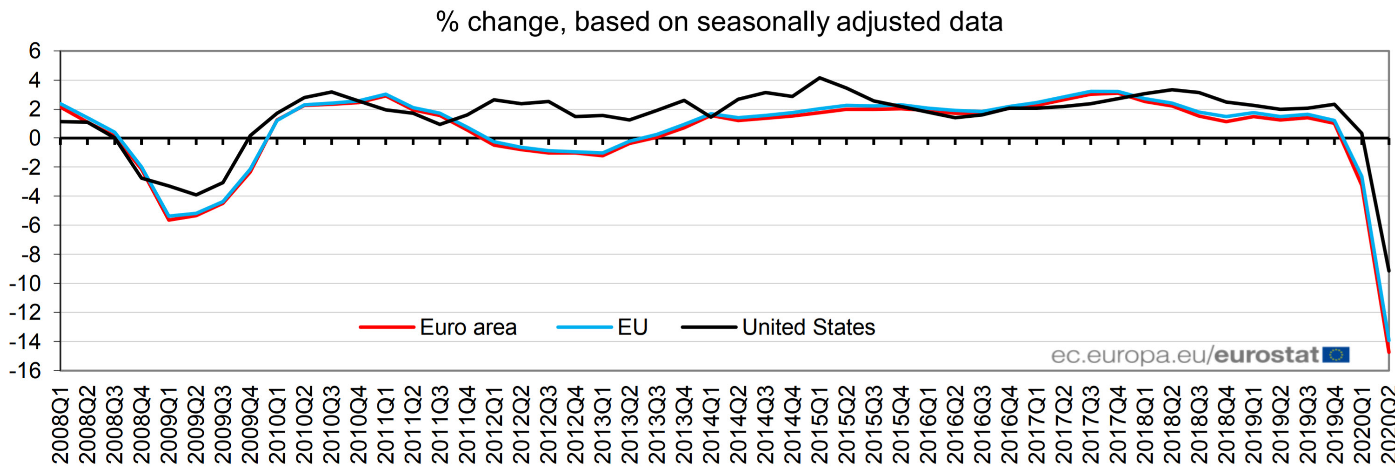
Many schools were not prepared and were lacking digital content and online curricular material to share with students. Teachers, sometimes lacking the necessary digital capabilities, struggled to develop quickly the materials they needed to continue teaching and testing their students online. The differences in digital capabilities apply not only to teachers but also to students. It is already known that around 43 % of the EU population has low or no digital skills.and are likely to undermine trust in traditional institutions and give rise to political discontent.

([3]) *https://ec.europa.eu/jrc/en/research/crosscutting-activities/fairness/fairness-policy-briefs-series#edu_ineq*

2.2 Economic impact of COVID-19: from facts to models

The COVID-19 pandemic has hit the European economy in an unprecedented way since the Second World War (Figure 1). Moreover, the impacts on gross domestic product (GDP) and employment have been far from homogeneous across EU Member States and across economic sectors.

Figure 1. *GDP growth rates over the same quarter of the previous year.* ***Source:*** *Eurostat, 2020.*



The most recent estimates published by Eurostat (2020) reported a decrease in GDP of – 11.8 % in the euro area and of – 11.4 % in the EU as a whole between the first and second quarters of 2020. For employment, the reduction was of – 2.9 % in the euro area and of – 2.7 % in the EU. The first quarter's changes in GDP since the previous quarter were already negative for both the euro area and the EU, but were much less significant, i.e. – 3.7 % in the euro area and – 3.3 % in the EU. Employment slightly decreased during the first quarter of 2020.

During the second quarter ([4]) of 2020, Spain suffered the sharpest reduction in GDP with respect to the previous quarter (– 18.5 %), followed by Croatia (– 14.9 %), Hungary (– 14.5 %), Greece (– 14.0 %), Portugal (– 13.9 %) and France (– 13.8 %) (Figure 2).

Spain and France were already reporting the worst figures during the first quarter ([5]) of 2020 compared with the previous one, although the reductions were more negligible (less than – 5 %). In terms of employment, Spain reported the largest decrease during the second quarter of 2020, – 7.5 % with respect to the previous quarter, followed by Ireland (– 6.1 %), Hungary (– 5.3 %) and Estonia (– 5.1 %).

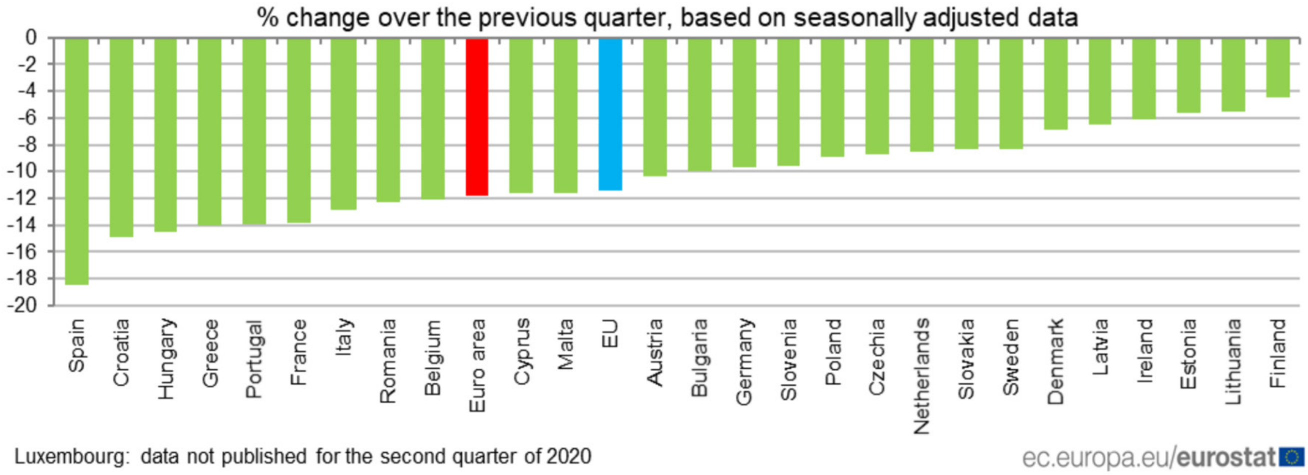
Malta reported the only positive variation (+ 0.6 %). Although these impacts may appear moderate, the declines in terms of hours worked were much more pronounced. Hours worked decreased by – 12.8 % in the euro area and by – 10.7 % in the EU in the second quarter of 2020. The largest declines were in Spain (– 21.4 %), Portugal (– 20.6 %), Greece (– 19.0 %) and Slovakia (– 14.2 %).

([4]) Figures for quarterly GDP volume changes include seasonal and calendar adjustments.
([5]) Data for Slovakia were missing from the Eurostat database, which reported values without calendar adjustments. Luxembourg's data for the second quarter of 2020 had not been published by the time this text was written.

By economic sectors (6) and using gross value added as a proxy for GDP, the wholesale and retail trade, transport, accommodation and food service activities (– 20.8 % in the euro area and – 20.2 % in the EU), and arts, entertainment, recreation and other service activities (– 22.0 % in the euro area and – 23.3 % in the EU) were the sectors most damaged by the COVID-19 pandemic during the second quarter of 2020, followed by professional, science and technical service activities (– 16.3 % in the euro area and – 15.3 % in the EU).

In particular, Spain, Malta and Greece had the biggest reductions in gross value added of wholesale and retail trade, transport, accommodation and food service activities (– 40.4 %, – 37.8 % and – 33.3 %, respectively) in the second quarter of 2020 compared with the previous one. For arts, entertainment, recreation and other service activities, Ireland, Romania and Poland reported the biggest relative reductions in their corresponding gross value added (– 65.5 %, – 52.8 % and – 46.0 %, respectively). Spain (– 28.2 %), Ireland (– 28.2 %) and Greece (– 25.1 %) saw their professional, science and technical service activities reduce their value added the most in the EU during the second quarter of 2020 compared with the previous one.

Figure 2. *Gross domestic product growth rates in the second quarter of 2020.* ***Source****: Eurostat, 2020.*



Regarding employment (7), wholesale and retail trade, transport, accommodation and food service activities (– 5.6 % in the euro area and – 5.1 % in the EU), arts, entertainment, recreation and other service activities (– 4.6 % in the euro area and – 4.5 % in the EU) and professional, science and technical service activities (– 3.8 % in both the euro area and the EU) were the sectors most affected by the COVID-19 pandemic during the second quarter of 2020, compared with the previous quarter. In particular, Ireland, Spain and Austria had the biggest decrease in the employment of the wholesale and retail trade, transport, accommodation and food service activities (– 13.6 %, – 12.7 % and – 8.3 %, respectively) in the second quarter of 2020 compared with the previous one.

For arts, entertainment, recreation and other service activities, Ireland, Spain and Denmark reported the largest drops in their domestic employment (– 18.3 %, – 10.4 % and – 9.6 %, respectively). Hungary (– 13.4 %), Croatia (– 11.9 %) and Ireland (– 11.4 %) reported the largest reductions in their employment in professional, science and technical service activities during the second quarter of 2020 compared with the previous one.

(6) Gross value added (seasonally and calendar adjusted) by economic sectors for the second quarter of 2020 is available for all EU Member States except for Slovakia (without calendar-adjusted values) and Luxembourg (not published yet by the time this text was written).
(7) Data for Czechia, France, Greece, Luxembourg, Malta, Poland, Portugal and Slovakia were missing from the Eurostat database at the time this text was written.

These effects become even worse if we compare them against the same quarter of the previous year, when the EU economy had positive increases. During the second quarter of 2020, GDP fell by – 14.7 % with respect to the second quarter of 2019 in the euro area and by – 13.9 % in the EU. Regarding employment, the number of persons employed in the euro area fell by – 3.1 % in the second quarter of 2020 compared with the second quarter of 2019, and in the EU by – 2.9 %. The quarter-to-quarter rates in the first quarter were – 3.2 % and – 2.7 %, in the euro area and in the EU, respectively, while for employment they were slightly positive for both the euro area and the EU (0.4 %).

Spain is again the EU Member State reporting the worst quarter-to-quarter rate in the second quarter of 2020 (– 7.6 %), followed by Hungary (– 5.6 %), Austria (– 4.0 %), Ireland (– 3.9 %) and Estonia, Italy, and Portugal (– 3.6 %). In the first quarter, figures were still positive but very small. Although the impact on employment in numbers of persons can be considered still moderate thanks to government support schemes, declines in hours worked are much more pronounced. Compared with the same quarter of the previous year, the number of hours worked declined by – 16.6 % in the euro area and by – 13.8 % in the EU. The largest decline occurred in Greece (– 29.8 %), followed by Spain (– 24.6 %), Portugal (– 22.6 %) and Italy (– 20.1 %).

By economic sectors, value added quarter-to-quarter rates between 2019 and 2020 provide a similar picture to that sketched above for quarterly rates compared with the previous quarter. In particular, for the second quarter of 2020, it is noteworthy that the value added of the wholesale and retail trade, transport, accommodation and food service activities in Spain fell by – 46.4 % while for arts, entertainment, recreation and other service activities in Ireland and Romania it fell by – 67.8 % and – 54.3 %, respectively.

The employment effects across economic sectors measured by quarter-to-quarter rates during the first and second quarters of 2020 also provide the same conclusions as described above for quarterly rates compared with the previous quarter.

2.2.2 Development and use of models

The adverse impact of COVID-19 on the EU economy may be worse than that of the 2008–2009 global financial crisis. A multidimensional effort has been made since the onset of the crisis to assess the many aspects of the economic and social impacts of the COVID-19 crisis and of the related containment measures. To capture the impact of the outbreak, epidemiological analysis was coupled with an assessment of social and economic effect, which the scientific community carried out by activating its analytical and modelling capacities. The development and use of economic models has provided an essential contribution to policymaking along many dimensions. This section, without claiming completeness, provides some examples.

While the crisis is ongoing, a timely analysis of the impact of the shock is essential to ensure that policy decisions are taken on the basis of an evidence-based, realistic evaluation of the situation. To this end, the scientific community has repeatedly assessed the macroeconomic impacts at national level, for example looking at the effects of COVID-19-related confinement measures on employment. The Joint Research Centre (JRC) in collaboration with the Directorate-General for Economic and Financial Affairs (DG Economic and Financial Affairs) has developed new monitoring tools (BIG-Nowcast project) that, on the basis of large amounts of big data, allow real-time monitoring of the economic situations of the Member States (European Commission, 2020c).

An important factor in shaping economic policies to tackle the COVID-19 crisis is the correct interpretation of the nature of the crisis and of its impact on different parts of the economy. The COVID-19 pandemic has led to an unprecedented massive economic shock, difficult to capture with standard economic models and forecasting techniques.

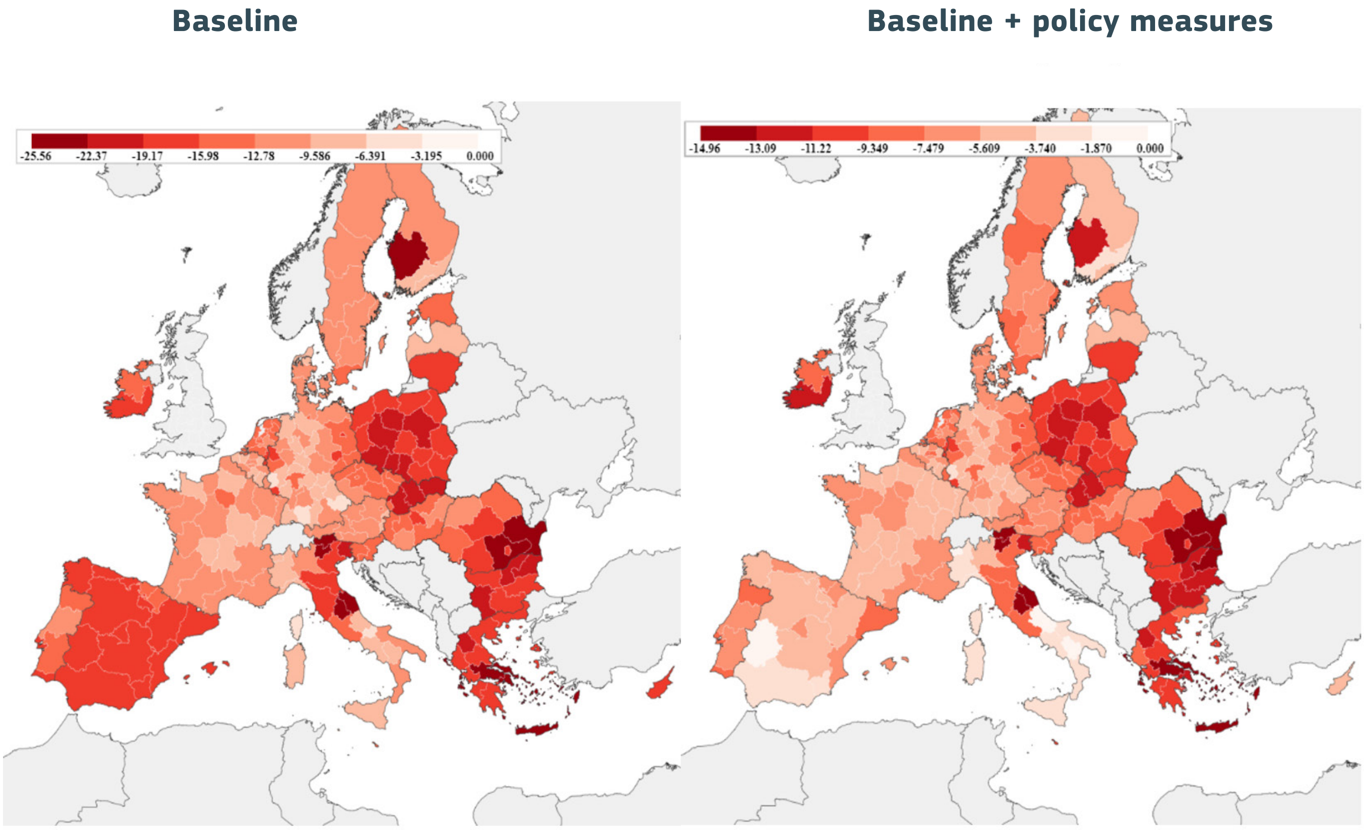
DG Economic and Financial Affairs's QUEST model (which is the global macroeconomic model that the Directorate General for Economic and Financial Affairs (DG ECFIN) of the European Commission uses for macroeconomic policy analysis and research) has been essential to chart the terrain in the preparation of the spring economic forecast (Pfeiffer et al., 2020). Structural models, such as QUEST, provide a consistent and transparent discussion, relying on a clear set of assumptions to tailor model simulations and benchmark the different shocks and policy interventions at play. In addition, the JRC–DG Economic and Financial Affairs Global Multi-country (GM) model is used to decompose the economic spring forecast, to give insight into how the multiple shocks triggered by the COVID-19 pandemic, and planned policy actions, are likely to be transmitted to the economy in 2020–2021.

The global nature of the crisis has highlighted the role of international spillovers and interactions. With the purpose of analysing such interactions on a sectoral basis, the JRC uses its Trade Supply Chain Analysis (Trade-SCAN) tool (Arto et al., 2019; Román et al., 2020) to calculate GDP and employment effects of EU exports following the global demand shocks due to COVID-19. Their results were included in the spring economic forecast (Pfeiffer et al., 2020).

The solution to the COVID-19 crisis is likely to be both local and European, calling for efficient multilevel governance and optimal use of support programmes to speed up short, medium and long-term recovery, and different in different economic sectors. Territorial analysis enables the examination of economic and trade impacts at regional level. While the shock has hit all 267 regions in Europe equally, an uneven regional response is expected, given the different initial endowment and economic characteristics of regions.

Quantifying the territorial/regional economic impacts of the pandemic is essential for policymakers who need to take into account existing trade-offs between public health and support of economic activity. The JRC is contributing to territorial impact assessment of the COVID-19 crisis and associated sectoral economic performance in the context of the different de-escalation proposals. In addition, the uneven impact of the pandemic could be amplified by different policy measures (Figure 3). However, countries will not (be able to) adopt the same set of measures, and at the same magnitude, to tackle the economic effects of the pandemic. The recently announced measures already point to this differentiated response (Anderson, 2020). The Regional Holistic ModeL (Rhomolo) (Conte et al., 2020) allows calculation of the budgetary and personal income implications of the crisis and of the consequent budgetary responses of Member States, on the basis of detailed information provided by micro-data and existing national tax and benefit codes.

Figure 3. *The GDP impact at regional NUTS 2 level under both scenarios.* ***Source:*** *Conte et al., 2020.*



A specific sectoral analysis, looking in particular at the sectors with higher decreases in consumption and investments, has also been conducted. While the analysis includes all sectors, two specific examples are of particular interest in the current juncture. A first strand of work concerns the impacts of exit scenarios on the agri-food sector, and examines not only economic impact but also the more crucial issue of food security. In June 2020 the Commission published the regular short-term outlook for EU agricultural markets.

The report showed that, despite considerable short-term disruptions (e.g. to supply chains, consumption patterns and labour movement), the agriculture sector has responded and adapted constructively to the new circumstances. A second strand concerns some sectors, such as tourism, that have been severely hit. The predicted decline in tourist arrivals in the EU-27 is between 38 % and 68 % in 2020, and between 6.6 million and 11.7 million jobs could be at risk, with very heterogeneous impacts on different Member States (Figure 4) and different areas in the same country.

Figure 4. *Intensity of risk to jobs in tourism-related activities, EU-27*
Source: *Marques Santos et al., 2020..*

The extent to which fiscal measures taken in the EU, including both national and EU-level measures, would help mitigate the social consequences of COVID-19 is difficult to gauge given the uncertainty regarding the impact of this crisis on employment and households´ income. A first preliminary assessment was carried out by JRC (see Almeida et al., 2020), combining information on fiscal policy measures enacted or announced in 2020 and the European Commission forecasts, using the EUROMOD microsimulation model.

The results show that policy interventions are instrumental in cushioning against the early impact of the crisis on inequality and poverty. These results further reinforce the view that large scale policy interventions at the EU-level, in particular through the Recovery plan for Europe, could absorb a significant share of the economic and social shock, especially in countries most directly affected by the crisis and with tight fiscal constraints.

In more detail, the analysis suggests that over the course of 2020, on average, households' disposable income in the EU would fall by -5.9% due to the COVID-19 crisis without discretionary policy measures, and by -3.6% with policy intervention, pointing to a significant cushioning effect of these measures in protecting households against income losses. Furthermore, the impact of the COVID-19 crisis is likely to be highly regressive, with the poorest households´ being the most severely hit.

However, discretionary policy measures are expected to contain the regressive effects of the recession, resulting in a quite homogeneous impact along the income distribution. Poverty, as measured by the at risk of poverty (AROP) rate, would increase significantly, even in presence of policy measures (+1.7pp), although this result depend on whether the poverty line is anchored to its pre-crisis level.

Policy interventions are therefore seen as instrumental in cushioning against the impact of the crisis on inequality and poverty. Additionally, the results suggest that the social impact of the Great Lockdown is likely to be much larger than the one experienced during the 2008/2009 financial crisis, at least for what concerns the immediate impact of the crisis.

2.2.3 Resilience after COVID-19

Following the COVID-19 shock, the social economic assessment also analysed resilience, which is the ability of our society to face the shock in such a way that societal well-being is preserved, leaving no one behind and without compromising the heritage of future generations (Giovannini et al., 2020).

Even though there is no single understanding of the concept of resilience in the scientific literature, the JRC, together with many representatives of Commission Services (Resil.net), has taken stock of the available expertise to create a shared framework for the definition and measurement of several important dimensions of resilience.

BOX 2

SURE: a European instrument for temporary support to mitigate unemployment risks in an emergency

On average, for the EU, the employment lost could represent 2.85 % of total employment, leading to an increase in the number of unemployed people of 37.69 %. Short-term work policies would have the largest budgetary impact, varying on average between 1.16% and 1.27% of EU GDP, depending on the countries covered (given the very preliminary estimates available for some countries).

The Commission has proposed a new instrument for temporary support to mitigate unemployment risks in an emergency (SURE). It will provide financial assistance of up to EUR 100 billion in the form of loans from the EU to affected Member States.

The SURE instrument will be available to Member States that need to mobilise significant financial means to fight the negative economic and social consequences of the coronavirus outbreak on their territory. It will provide financial assistance to Member States to address sudden increases in public expenditure for the preservation of employment. Specifically, the SURE instrument will act as a second line of defence, supporting short-time work schemes and similar measures, to help Member States protect jobs, and thus employees and self-employed people, against the risk of unemployment and loss of income.

The establishment of SURE is a further tangible expression of Union solidarity, whereby the Member States agree to support each other through the Union by making additional financial resources available through loans.

This section provides some examples and outlines several principles for policies that enhance resilience.

During the pandemic, the JRC has applied its resilience framework to assess the vulnerability of Member States to the crisis and their ability to cope with and rebound from it. Dashboards on health, economic and social aspects of the crisis have been developed or expanded and are routinely used to provide a better assessment of the vulnerability and resilience of the Member States to COVID-19.

Euromod, the microsimulation model for the EU, simulates the impact of aggregate employment changes on households' incomes under different scenarios, with particular attention to the most vulnerable strands of the population, and to the increase in poverty. The JRC is also assessing the longer-term impact of the pandemic on employment and education as well as on gender inequalities. By identifying vulnerable groups of households, the analysis helps to target financial assistance – such as existing income support and unemployment measures or the new Support to mitigate unemployment risks in an emergency (SURE) instrument – at the households that are most likely to need it (Box 2).

To give an example, the availability of households' financial buffers, i.e. savings in deposits or in mutual funds that can be easily accessed, has been used to assess the vulnerability of households following lockdown measures and potential income losses. Le Blanc (2020) shows that, in most EU Member States, more than half of the households have liquid savings worth less than 2 months' income. Employees in the retail and tourism (accommodation and food) sectors are particularly vulnerable, as they have less than 1 month's income as a financial buffer. This will most likely affect southern European countries, where tourism constitutes a larger share of GDP. Income support is particularly important for those households that have insufficient financial buffers. These households belong mostly to the lower income groups or younger age groups.

The analysis indicated some lessons learned during the COVID-19 crisis and provided some indications of how to steer the recovery.

The COVID-19 pandemic affects our society at different levels and with different intensities, affecting human and social capital, institutions, communities, the production process, consumption and investment. It first has an impact on people's health and erodes human capital. Containment measures further affect human and social capital by requiring people to stay at home, shutting down non-essential activities and suspending schools.

This may exacerbate loneliness. Institutions are all hit hard. Governments are under pressure to respond to the emergency in the short term. Financial markets are suffering from uncertainty and the repercussions the crisis has on the economy. Many sectors are confronted with a long period of low demand and issues with supply. Consumption has substantially decreased, as households may experience financial distress or prefer not to spend given the uncertain situation. Investment in the vast majority of sectors is shrinking or freezing. Overall, societal well-being is under severe stress. A recovery plan must be comprehensive, acting on all dimensions and at all levels of our society.

Moreover, for a full recovery, policies have to focus on the short run, but also keep in mind the medium term and the opportunity to bounce forward. Whereas, in the acute state of emergency, governments need to focus strongly on actions aimed at prevention and protection, the recovery plans for the medium and longer run need to focus on accelerating a transformation process that can put the EU on a more sustainable economic, social, environmental and institutional path. The opportunity of getting out of the crisis greener, more digital and fairer must not be wasted in the name of urgency.

In line with this forward-looking view, the JRC's approach to tackling societal resilience has led us to suggest a few actions that could be implemented to face the current COVID-19 emergency.

First, policy measures need to rebuild all forms of capital eroded by COVID-19: infrastructural, human and social. This requires better and stronger coordination of sectoral interventions, improvement in the measurement and monitoring of human and social capitals, and the adoption of innovative classifications of public and private expenditures, in accordance with the 'capital-based' policy framework.

Second, redesigning the labour market and upskilling current and future generations are essential to accelerate the transformation. Studies on industrial performance and employment creation are looking at, for instance, how high-growth enterprises have reacted in the crisis and how they were able to respond to COVID-19.

Third, the role of individuals in making crisis management and recovery more or less successful is of the utmost importance. Therefore, we need to design policies that take into account the role and participation of citizens and increase trust in institutions. The societal mood and people's perceptions will play a key role in driving behaviours in the post-lockdown phase. Therefore, it is fundamental that governments and the EU be perceived as institutions able to manage the recovery process. This implies the need to prepare the ground in terms of communication, clearly identifying the messages and tools of such a campaign.

Fourth, the principle of leaving no one behind should remain at the core of the recovery. The health and economic impacts may disproportionately hit different segments of the society, particularly vulnerable groups, and risk magnifying social inequalities. Policy interventions are particularly important for people at the margins of society, who are more vulnerable and often also less resilient.

Fifth, the recovery should focus on identifying opportunities that would allow the EU to improve its well-being and sustainability without using expensive policies. For example, we could reconsider the health systems, re-address the trade-offs between security and privacy, promote a shift towards more sustainable tourism, and make a jump in using digital tools in administration and education practices.

2.3 Main consequences on critical infrastructures

Protective measures imposed by governments around the world to control the spread of the coronavirus have necessitated the temporary closure of thousands of sites and substantial reductions in personnel remaining on site. As these protection measures are relaxed, site operations are restarted. During this time, it is important that all operators of hazardous sites remain mindful of the elevated risks associated with abnormal operations, such as shutdown, start-up and unforeseen staff reductions (JRC, 2020).

For hazardous sites, especially chemical-processing sites and petroleum oil refineries, safe shutdown of operations, maintaining safety during the shutdown period and safe start-up are all keys to surviving the pandemic.

Good corporate governance and risk management are essential. The chances of avoiding an incident, especially a serious accident, can be considerably improved if the operator has a conscious strategy to keep plant safety at the forefront while addressing other pandemic-related concerns. The competent authorities can give support by spreading awareness, establishing measures to monitor the situation and ensuring appropriate preparedness measures are in place.

Nuclear power plants' operators typically have business continuity plans that include pandemic response. These include staged implementation of progressively more stringent measures as the situation demands. Critical personnel required for continued safe operation are identified. Measures already implemented to avoid infection of critical personnel include exclusion of other staff from sites (teleworking where possible).

The pandemic caused by COVID-19 has revealed the vulnerability of the EU's supply production networks of certain critical goods related to the fight against the COVID-19 (Box 3). The effects of such vulnerability spread around the EU, including at national and regional levels.

Therefore, there is a need for the EU to assess the vulnerability of its (essential) supply chains, and to take action to reduce it and ensure resilience. The resilience of the supply chains is a critical ingredient to secure the strategic autonomy of the EU vis-à-vis the rest of the world and guarantee that the EU will maintain its global leadership.

BOX 3

The EU4Health programme

The COVID-19 pandemic has shown the need to significantly boost the EU's preparedness and capability to respond effectively to major cross-border health threats. It has demonstrated in particular that the EU needs:

- more coordination between Member States during a health crisis;
- more capacity at EU level to prepare for and to fight health crises; and
- more investment in health systems to make sure they are ready for the challenges of tomorrow.

The Commission has proposed a new, ambitious stand-alone health programme for the 2021–2027 period: the EU4Health programme, which will make a significant contribution to the post-COVID-19 recovery by making the EU population healthier, strengthening the resilience of health systems and promoting innovation in the health sector. This new programme will also fill the gaps revealed by the COVID-19 crisis and ensure that EU health systems are resilient enough to face new and future health threats. Through the EU4Health programme, the Commission proposes to invest EUR 9.4 billion in strengthening health systems.

The European Commission has developed the pharmaceutical strategy for Europe (European Commission, n.d.a). Coming in the wake of the COVID-19 pandemic, the strategy aims to ensure Europe's supply of safe and affordable medicines to meet patients' needs and support the European pharmaceutical industry to remain an innovator and world leader.

In the domain of health (European Commission, 2019), resilience as a property of health systems recently emerged as a topic of academic discourse not only during the COVID-19 emergency but following the onset of the Ebola epidemic in West Africa ([8]). Another event that triggered the interest of researchers in this topic was the 2008 financial crisis, the knock-on effect of which on public expenditure simultaneously exposed healthcare systems across Europe to ever tighter budget constraints and greater health needs ([9]).

The health workforce will bear the brunt of demographic and epidemiological transitions, and a first demonstration of its impact has been clear during the COVID-19 crisis. Population ageing, changing care demands and digital technologies require a variety of different health workers to acquire the right skills and competences and update them continuously, while coordinating proactively with each other. From the perspective of the health system, there is a need for improved health workforce planning and forecasting, finding innovative solutions through new technologies and organisational changes, such as reinforcing task shifting, to ensure that a certain skill mix can flexibly adapt to foreseen and unforeseen challenges in the future.

([8]) Unexpected delays in the responses to disease outbreaks revealed a number of structural deficiencies, which pressed governments and multilateral organisations to recognise the need to invest in the creation of more resilient health systems.
([9]) Pressure imposed on health systems by fiscal consolidation measures elicited a wide range of responses from policymakers. This revealed significant differences in health systems' susceptibility to economic fluctuations, as well as in their capacity to cope with sudden resource shortages, effectively reconfigure service delivery and, if required, adapt in the face of new circumstances

2.4 Main consequences on the environment

The COVID-19 pandemic has had and is still having a severe worldwide impact, including on the environment, with short- and long-term consequences. In the very short term, the lockdown, adopted in many countries to stop all human activities but the essential ones such as hospitals, pharma industries and food chains, gave rise to an unprecedented situation for the ecosystem. In this unfortunate situation, citizens and scientists observed reduced smog in the cities, low levels of water pollution, increased biodiversity and wildlife repopulation in some human-free areas as consequences of decreased anthropogenic pressure.

At the same time, however, pressure on water resources increased in arid and water resources due to a significant increase of drinking water consumption (UfM, 2020). For populations without handwashing access, immediate improvements in access or alternative strategies are urgently needed, and disparities in handwashing access should be incorporated into COVID-19 forecasting models when applied to low-income countries. Likewise, pollution in coastal areas by disposable masks reminded us about the urgency to address the litter issue (Patrício Silva et al., 2020).

The short-term reduction in some environmental pollutants (in the air, water, etc.) raised awareness of the increasingly urgent need for an early change in the export model for raw materials, and the requirement for international coordination. This crisis has remarkably offered the world a massive test-bed for new and already known possibilities to become greener, more digital and more sustainable.

To assess the negative consequences of this situation, it is reasonable to consider the behaviour of consumers. Analysis of such behaviour can use the 'quality of life' approach, which includes three components: financial well-being (income, wages, etc.); social characteristics (education, health, etc.); and an ecological component (clean environment, ecologically clean products, clean water, recreation, enjoying nature, etc.). Behaviours can also be influenced by fear of exposure to COVID-19; therefore, people could privilege using private vehicles instead of public transport, thus increasing air pollutant emissions. The socioeconomic impacts of the pandemic could have a long-term impact on well-being. The consequent global poverty might influence the resources available to tackle the climate challenge. Poverty could also lead to behaviours that have negative environmental impacts (such as deforestation, land degradation and overfishing) (Diffenbaugh et al., 2020). Policy decisions and investments can support an economic recovery that will sustain the green aspect, as the EU is pursuing with its plan for the EU's green recovery (European Commission, 2020d).

Because of the reduction in transport and change in consumption patterns, daily global CO2 emissions decreased by – 17 % by early April 2020 compared with the mean levels in 2019 and are projected to be up to 7 % less in 2020 than in 2019 (Le Quéré et al., 2020). With such a reduction, total CO^2 global emissions would drop to 2012 levels (Crippa et al., 2019). However, this will not be enough to stop the increase in CO^2 atmospheric concentrations, which will continue to rise even in 2020. The change in concentration needs to be large enough to be distinguishable from natural CO^2 variability caused by vegetation and soil response to seasonal and annual variations of temperature, humidity and soil moisture.

Data from European Environment Agency (EEA) and the JRC (Putaud et al., forthcoming) show how concentrations of nitrogen dioxide (NO2) – a pollutant mainly emitted by road transport – have decreased in many European cities where lockdown measures have been implemented (European Environment Agency, 2020a). However, limited/no improvement was registered for other, more complex, air pollutants (e.g. fine particulate matter), linked not only to traffic but also to other anthropogenic sources such as domestic heating. Although satellite air pollutant maps were analysed particularly at the beginning of the lockdown measures in Europe, and were heavily advertised in the media, such data did not consider meteorological variability between years, which can deeply change air pollution concentrations even without emission reductions.

Although the post-lockdown priority is economic recovery, what was observed during the lockdown could be an opportunity to reflect on anthropogenic pressures and impact on the environment and therefore could act as a catalyst and promote the European Green Deal (European Commission, n.d.b). Thus, urban sewage perceived as a major challenge prior to the crisis, reveals now to be a valuable information source allowing to monitor the presence of the virus in urban settlements (European Commission, 2020e). Extracting and accessing the encoded information stimulates the idea of further digitalisation of the water sector in support to both, public health AND environmental protection (Water Europe, 2020).

The European Green Deal, launched by the European Commission, aims to promote the restoration and preservation of the ecosystem, protecting human, environmental and economic health by embracing innovation and engaging citizens in a more holistic view of life. The investment plan sets out a multiannual EU budget proposal of EUR 1 trillion over the next 10 years (European Commission, 2020f). As part of a plan for recovery from this economic crisis, an additional financial instrument called Next Generation EU, amounting to EUR 750 billion, has been recently proposed by the Commission, framed within well-defined policy targets (European Commission, 2020g).

The long-term consequences of COVID-19 include a new awareness of the place of humans on Earth. The feeling of our civilisation's power over nature has been broken by COVID. Recovery plans need to seize the opportunity to align environmental and climate objectives with society's resilience to current and future shocks. We need to be conscious that environmental health is our health and therefore all health is one, a message already adopted by the Commission regarding antimicrobial resistance (European Environment Agency, 2020b).

Furthermore, the pandemic has brought more attention to zoonotic diseases and the risks of them, which are increasing in frequency because of many factors, among them climate change, ease of access to places that used to be remote, and human and animal movement. Only interdisciplinary and international collaboration will succeed in mitigating the risk. In addition, scientists are also ever more aware that biodiversity may be a source of novel drugs providing potential products for cures or vaccines.

2.5 Main consequences on cultural heritage

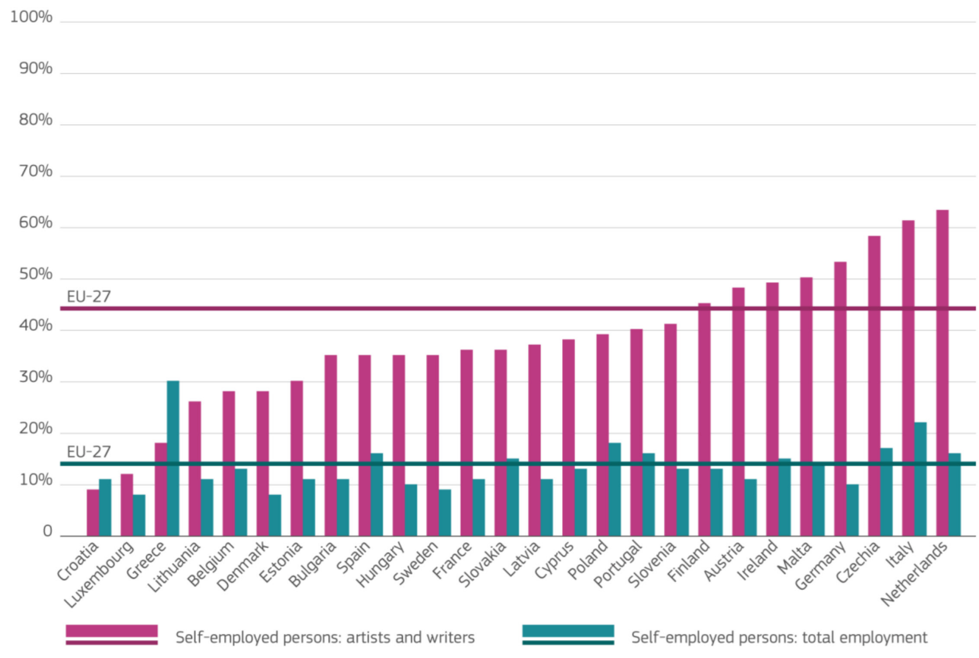
Cultural heritage, both tangible and intangible, is our common wealth – our inheritance from previous generations and our legacy for those to come. It is an irreplaceable repository of knowledge and a valuable resource for economic growth, employment and social cohesion. It enriches the individual lives of hundreds of millions of people, is a source of inspiration for thinkers and artists, and drives our cultural and creative industries. Cultural heritage is a shared resource, and a common good. Like other such goods, it can be vulnerable, as it has been during the COVID-19 crisis. Looking after our heritage is, therefore, our common responsibility (European Commission, 2014).

The coronavirus has made clear that culture does contribute to the social and economic vitality of our societies (Montalto et al., 2020): culture and the strictly connected sector of tourism have been widely recognised as some of the sectors most affected by COVID-19 in terms of lost revenues and Jobs. As a result of this awareness, the World Cities Culture Forum has included fragile cultural work among its nine priority working areas.

This crisis has also accelerated digitalisation processes in the sector, providing a unique opportunity to upscale innovation and the use of online/digital tools to further democratise cultural participation. However, cultural establishments are particularly exposed to the economic consequences of the COVID-19 outbreak, and the crisis has endangered more than 7 million jobs in the cultural and creative sectors.

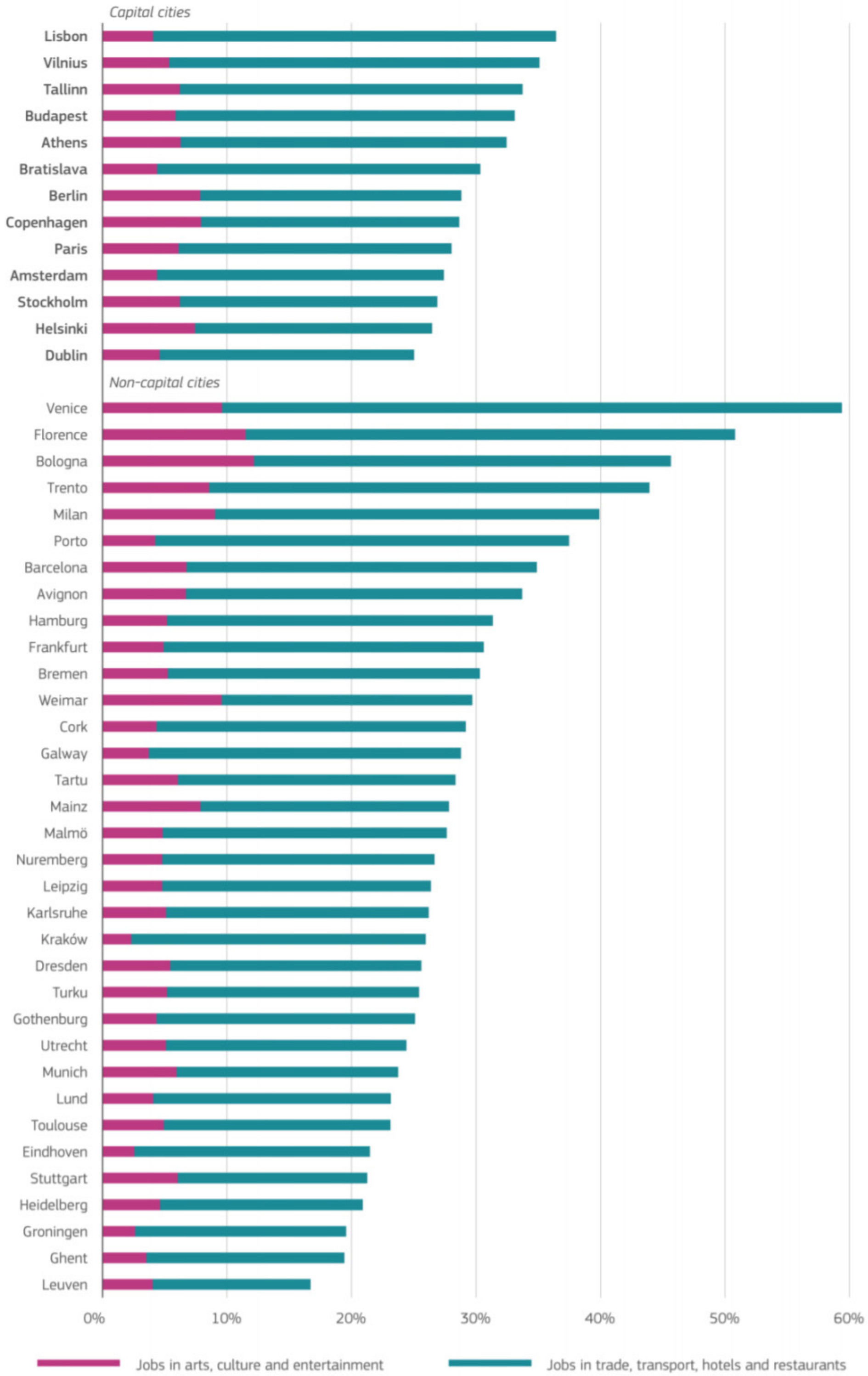
Cultural jobs are particularly at risk because of the sector's high level of structural fragmentation as well as its reliance upon live events and institutions open to the public. Such activities have been mandatorily cancelled/closed to the public in many EU Member States. In addition to that, cultural workers are at risk of major losses of income because they may fall through the cracks of existing social protection systems more than other types of workers: in the 27 EU Member States, on average, 32 % of them are self-employed, compared with 14 % in overall employment (see Figure 5). The percentage of self-employment is much higher among artists and writers (44 %). Non-standard workers such as the self-employed are not only at higher risk of losing their job and/or income, but are also likely to have no alternative sources of income or medical insurances.

Figure 5. *Self-employed persons among artists and writers and in total employment.*
Source: *Montalto et al., 2020.*
Note: *No data available on artists and writers for Romania.*



City-level data from the JRC's Cultural and Creative Cities Monitor (European Commission, n.d.c) show that some medium-sized European cities may be particularly vulnerable to the pandemic owing to the important contribution of culture and tourism to the local job market, while capitals and bigger cities may count on larger and more diversified economies (see Figure 6).

Figure 6. Share of arts and tourism jobs among total jobs **Source**: Montalto et al., 2020.



Medium- and longer-term measures are needed to accompany and support change in cultural institutions and professions, in accordance with long-standing European policy objectives. These include ensuring equal and fair access to culture, guaranteeing fair remuneration of artists and cultural operators, providing access to diverse cultural expressions, beyond mainstream content, and enabling transnational exchanges and cooperation as a driver of innovative ideas but also of new market opportunities. While we must not underestimate the dramatic impact of COVID-19, the pandemic gives us an opportunity to reinvent and widen the scope of cultural work and make the contribution of culture to sustainable and resilient societies much more visible and shared.

3 Lessons learned

During the novel coronavirus crisis, the risk and crisis management communities have been fully mobilised to provide evidence in support of the tasks of crisis management, while at the same time they have started thinking about the aftermath of the crisis.

Now is the time to implement what we have learned during this unprecedented situation. The facts are clear: in the globalised world we live in, any shock is going to affect the rest of the planet because of our existing interdependencies. This pandemic has abruptly highlighted this fact, which was already known but not sufficiently considered. The COVID-19 crisis has been an opportunity to learn from experience.

Our economies, our societies and our environment share common challenges and the only way to overcome them is to join forces across geographical scales, across countries, across economic sectors and across scientific disciplines. Only united and in solidarity with each other will we surmount the crisis to come. The EU has demonstrated the importance of these principles during the negotiations with Member States to establish the funds to be allocated to support the recovery plan.

A multidisciplinary community of scientists has been working on the development of models to predict the development of this crisis to manage it effectively, assess the situations and accordingly proceed with drawing up appropriate exit scenarios able to guarantee an overarching view of the different possibilities and their pros and cons. This is the way forward. This cross-cutting approach motivating scientists from any discipline to share data, results, opinions, etc. should be the new normal.

Social aspects along with the environmental impact of our decisions were not forgotten in this situation. Governments understood more than ever before that citizens' collaboration was crucial to fight against the spread of the virus. Specific effort was required to carefully monitor the situation from the citizens' perspective to understand their fears and concerns in a timely way. This has allowed national and international institutions to better manage the current crisis, since cohesion, solidarity and trust in institutions are vital in crisis time and should be the lymph of the post-pandemic period as well.

Since a pandemic can be fought only if we remain solidary and united, no country or region must be left behind. This lesson should also be applied to other kind of disasters, be they triggered by a virus, a natural hazard, a technological accident or a malevolent act. If we are all interconnected at the global level, every single local hardship should be able to count on receiving a suitable response at the most appropriate geographical scale, which will be the one able to overcome the adversity encountered. To do that, the reinforcement of integrated risk management governance, considering all geographical scales, is required.

4 Challenges and next steps

In the EU, serious cross-border threats to health are defined as life-threatening or otherwise serious hazards to health that spread or present a significant risk of spreading between Member States and may therefore require coordination among national health authorities in terms of response activities. In more detail, the EU legislation (EU, 2013) refers to cross-border threats in cases of (1) threats that are unusual or unexpected for the given place and time, (potentially) cause significant mortality and morbidity in humans, and/or grow or may grow rapidly or exceed or may exceed national capacities; (2) threats that affect or may affect more than one Member State; (3) threats that require or may require coordinated responses at EU level. Strong governance at EU and global levels is still lacking even though the threat and the response have been identified for a long time.

People commonly refer to these threats in terms of events of biological origin (outbreaks, epidemics). However, the legislation clearly states that chemical and environmental events and, in general, events of unknown origin should be considered as well. This is in line with what the World Health Organization (WHO) defined as an all-hazards risk approach in the revised International Health Regulations of 2005 (WHO, 2016), which represent the legally binding agreement defining the rights and obligations of countries in terms of identification of, reporting and response to public health events that may have international consequences. However, scientific communities are still fragmented and more has to be done to build multidisciplinary groups to tackle the complexity of these situations.

A large proportion of Europeans live today in urban settings: cities of different sizes, towns and suburbs, all contexts characterised by high population densities. There has been in recent decades a significant demographic trend from rural to urban areas in addition to intensified regional migration patterns. Consequently, a large proportion of people in Europe live today in close contact, sometimes in overcrowded settings. In addition, there are more opportunities for socialising and meeting in public places than in the past and this represents an increased risk of spread of infectious diseases, especially for those characterised by high human-to-human transmission (e.g. respiratory infections).

The most efficient way to protect our communities is by keeping them continuously informed about potential threats and how to prevent them. Governments and citizens have to trust each other.

Human mobility is one of the most obvious aspects of globalisation and one of the most relevant to pandemics. People today have unprecedented opportunities to move and travel for various purposes, such as tourism and economic migration. Cross-border movements of people are faster and more frequent than at any other time in history, and this is particularly relevant at EU level, as freedom of movement between and residence within Member States is one of the key rights of citizenship.

Therefore, the possibility of cross-border spread of local outbreaks always needs to be considered carefully, and the level of this risk depends on agents involved, disease transmission patterns and national capacities to reduce disease impacts, among other things. Given this, the risk related to an outbreak spread from one country to another is often complex to define and needs to be analysed in detail. Hence, increased collaboration based on shared data and platforms to detect and communicate potential threats early is strongly recommended.

Furthermore, the higher mobility of people worldwide implies an increased risk of new or re-emerging infectious diseases typically observed in other regions appearing in the EU/EEA (European Economic Area). Countries need always to consider the risk of appearance of cases of almost any infectious disease, including the ones that are seldom seen in the region. This implies that alliances to fight against health-related issues need to be made at the global level.

Zoonoses are infectious diseases that are transmitted from vertebrate animals to humans (and vice versa). It is estimated that over 70 % of emerging diseases reported in the last decades are zoonoses that were transmitted to humans from domestic animals, poultry or livestock (FAO, 2011; Brown, 2013; Wang and Crameri, 2014). This pattern of transmission is not new, and the recent increase described has to be put in the context of the human population's uncontrolled growth and the consequent impact on the environment. For example, through intensive agricultural practices including deforestation, livestock grazing and other activities the interaction between animals, humans and wildlife species continues to increase. Protecting our environment and its biodiversity is essential. The health of our planet depends on us as much as we depend on it.

Climate change can have significant implications for human health, both directly and indirectly (ECDC, 2010). Extreme weather events and natural disasters, for example, are already driving the risk of occurrence and further spread of some infections. Another outcome of climate change, however, is more concerning: the changing patterns of transmission of infectious diseases that are spread to humans through vectors from human and animal reservoirs. These variations could significantly affect the risk of occurrence and diffusion of specific diseases that have not been seen in the region for a long time and in some cases have never been documented. The EU Green Deal offers a unique opportunity to reduce the risk of their having an increased impact on health in the future.

There are several examples in the recent past showing how international food trade can easily affect the health of people in Europe (Van de Venter, 2000; Boqvist et al., 2018; WHO, 2020). Food-borne outbreaks of disease have been linked to chemically contaminated food items (through naturally occurring toxins and environmental pollutants) but also to bacterial and viral contamination of food, these lasts leading to outbreaks of infectious diseases. It is important to persist in the introduction of rigorous controls imposed by the international institutions based on commonly agreed standards at global level.

Vaccine hesitancy refers to a reluctance or refusal to vaccinate against vaccine-preventable diseases (VPD) despite the availability of immunisation services (ECDC, n.d.). It is currently considered a complex and context specific phenomenon varying over time, and between places and vaccines, but its role as a public health challenge in terms of the reappearance of cross-border outbreaks has recently been confirmed: WHO includes vaccination hesitancy in its list of the top 10 threats to global health ([10]). Vaccine hesitancy is contributing to declining immunisation rates in several Member States and is therefore increasing the number of VPD outbreaks. Strong collaboration among countries is required in order to assess the current risk and identify common communication challenges to be addressed so as to avoid cross-border spread (European Commission, 2018; ECDC, 2019) ([11]). Once more, citizens' trust in institutions is essential.

The process of detecting, validating, analysing, assessing and investigating signals that may represent a threat to public health is commonly known as epidemic intelligence (EI), especially when referring to events of biological origin (i.e. outbreaks). The aim of EI is the early detection and appropriate assessment of the risk to the human population. In particular when there is an outbreak, this process needs to be implemented rapidly in order to promptly identify potential actions to be considered in response to the event.

([10]) https://www.who.int/news-room/spotlight/ten-threats-to-global-health-in-2019
([11]) https://www.vaccinesafetynet.org/

There are currently several initiatives that are trying to promote more collaborative approaches to all steps of EI at different geographical levels. One of the latest is the 'epidemic intelligence from open source' (EIOS) initiative (Barboza, 2017; Spagnolo et al., 2020; Morgan, n.d.), a project under the leadership of WHO since September 2017 that aims to build a common EI system to be used by a comprehensive network of health experts worldwide.

On 28 March 2019, 15 Member States signed framework contracts for pandemic influenza vaccines under the joint procurement mechanism. By pooling needs and increasing volumes to be procured, the agreement improves Member States' preparedness for the next flu pandemic, ensures equal treatment, guarantees more balanced prices and shows a high level of solidarity between Member States agreeing to share the limited quantity of flu vaccines available in the event of a pandemic. It allows greater exchange of best practices and pooling of expertise, and ensures equal access to all participating Member States. This is the way to proceed to reinforce epidemic preparedness.

EU Member States have expressed interest in joint procurement procedures for the diphtheria anti-toxin and the tuberculin and bacillus Calmette–Guérin vaccines, as well as personal protective equipment, all of which are currently in the preparatory phase.

At the request of Member States, the Commission has proposed a procedure for the exchange of medical countermeasures using the selective exchange mechanism of the early warning and response system. This will allow Member States to offer or request medical countermeasures for bilateral exchange between them. While the overall structure will be agreed and signed off by the Health Security Committee, every exchange will be bilateral, and the terms will be entirely agreed between the Member States themselves.

A combination of tools, technologies, disciplines, approaches and alliances seems to be the most appropriate way to fight against these prevailing threats.

BOX 4.

Re-open EU

The European Commission has launched 'Re-open EU' (European Union, n.d.), a web platform that contains essential information for a safe relaunch of free movement and tourism across Europe, so that people can confidently enjoy their upcoming holidays. The platform will provide real-time information on borders, travel restrictions, public health and safety measures such as physical distancing or the use of facemasks, and other practical information for travellers. Re-open EU is available in the 24 official EU languages.

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Chapter 3

Assets at risk and potential impacts

3.6

Cultural heritage

Online Version

3.6 Cultural heritage

CONTENTS

3.6
Cultural heritage

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1 Introduction

The most widely used measures of disaster impacts are direct losses, which refer to the immediate physical damage to properties, infrastructure, agriculture and human life. Direct losses are mostly defined by monetary damage, fatalities and injuries, and currently dominate all other loss measures due to the tangible nature of physical damage. However, developing the capacity to include indirect losses as well as non-monetized losses into loss estimation is paramount in order to achieve a sound understanding and quantification of the full impact of disasters. In the context of the current chapter, this relates particularly to the damage of non-monetized resources such as cultural heritage assets and the relationship between them and society.

To provide context and frame this issue, concepts related to cultural heritage, cultural significance and cultural value are first addressed. Different types of cultural heritage values are introduced and the conceptual and methodological issues related to the economic quantification of cultural heritage value are also discussed. These concepts are then connected to the issue of disaster impact analysis in cultural heritage, namely to the quantification of the loss in value of damaged cultural heritage. After reviewing current practice in this field, as well as addressing its limitations and the challenges it involves, the development of complimentary tools for a more efficient implementation of disaster risk management in cultural heritage based on disaster impact analysis is also examined. In particular, the chapter discusses the need to put into practice a resilience enhancement chain for cultural heritage connecting three elements: the reduction of disaster impacts in cultural heritage as a way to reduce disaster impacts in multiple sectors of society; the implementation of conservation and maintenance practices to reduce disaster impacts in cultural heritage; the availability of inventory and management systems with adequate information about the existing cultural heritage and about its condition to be able to implement efficient and rational conservation and maintenance practices. These elements are discussed in more detail, highlighting relevant technological advancements that are available.

2 Cultural heritage and cultural heritage value

Most cultural heritage values cannot be quantified in economic terms

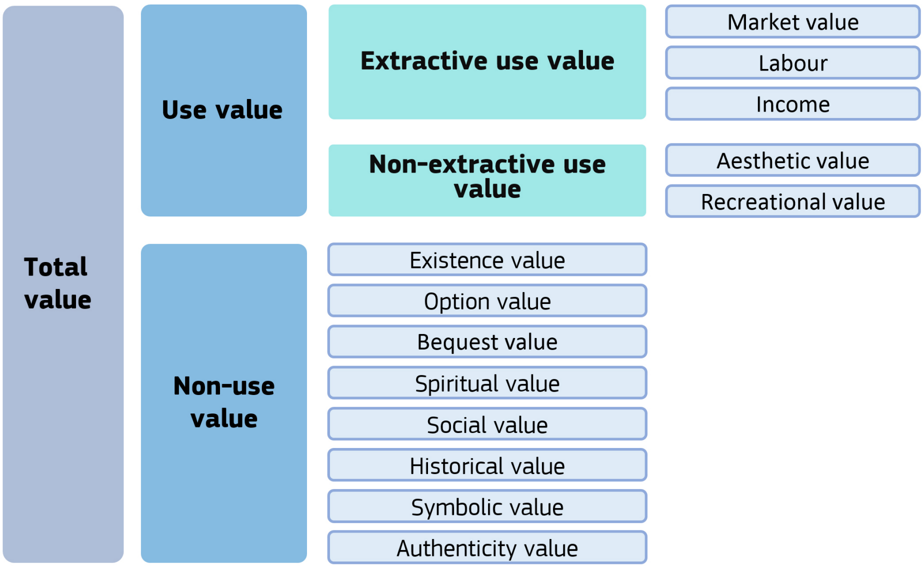
The concept of cultural heritage has evolved over time, reflecting the complex evolution of societies and the changes in their value systems (see for example Jokilehto, 2005; Ahmad, 2006; Vecco, 2010). Cultural heritage bridges past and future, and the term generally refers to assets capable of arousing certain values that lead a given society to consider them heritage (Vecco, 2010). In general, cultural heritage is often divided into the categories shown in Figure 1

Figure 1. *Categories of cultural heritage.* ***Sources****: Authors.*

<table>
<tr><th colspan="3">CULTURAL HERITAGE</th></tr>
<tr><th colspan="2">TANGIBLE HERITAGE</th><th>INTANGIBLE HERITAGE</th></tr>
<tr><td>Immovable</td><td>Movable</td><td rowspan="2">Music,
Oral traditions,
Performing arts,
Rituals,
Crafts, etc.</td></tr>
<tr><td>Monuments,
Archaeological sites,
Historical centres, etc.</td><td>Paintings,
Books,
Sculptures, etc</td></tr>
</table>

Cultural heritage normally embodies a series of values that can be used to determine its significance, which can in turn be used as a proxy to define a level of protection, prioritise resources or inform conservation decision-making. Countries usually establish the cultural significance of cultural heritage using regulatory procedures leading to the listing of assets at various levels of importance. These can range from the UNESCO World Heritage Site designation, for sites of 'outstanding universal value' (UNESCO, 2015), to designations referring to cultural heritage properties that are of interest to local communities only. The level of cultural significance of a particular cultural heritage asset is also usually assigned based on a qualitative assessment, given the inherent subjectivity and qualitative nature of classification criteria. In general, these criteria address (explicitly or implicitly) different types of values, but no universally accepted typology of values is seen to currently exist (see for example Fredheim and Khalaf, 2016, and references therein). In fact, it is important to keep in mind that values are a social construct and, therefore, can change both in time and in space. To illustrate what are possible values, reference is made to those suggested by Vecvagars (2006) based on Serageldin (1999), Throsby (2001) and de la Torre (2002), which are grouped into non-extractive use values and non-use values in Figure 2. By adding the extractive use values, a definition of the total value of a given heritage asset is then obtained.

***Figure 2**. The total value of cultural heritage assets.* ***Sources**: Authors based on Vecvagars, 2006, and references therein.*



After identifying possible types of cultural heritage values, a further step relevant to disaster impact analysis would be to transform these values into an economic valuation. Multiple studies have addressed this issue and several methods have been developed to elicit monetary expressions of cultural values. See Frey (1997), de la Torre (2002), Noonan (2003), Vecvagars (2006), Choi et al. (2010), O'Brien (2010), Carson (2011), Nijkamp (2012), and Holden and Baltà (2012) for extensive reviews of these methods that also discuss their strengths and limitations when applied to cultural heritage. The main drawbacks of these methods include the fact that most of them require significant amounts of data and/or surveys to be carried out among the population, and the fact that results obtained are sensitive to the valuation method that is used and always specific to a certain heritage asset, with little chance of being extrapolated to other assets. A further limitation particularly relevant to disaster impact analysis in cultural heritage is that these methods were not developed to estimate loss in value of damaged cultural heritage assets. The quantification of loss in value introduces an additional level of subjectivity due to the difficulty in estimating losses across the multiple types of values that are embodied in a cultural heritage asset as a result of a certain amount of physical damage in the asset.

3 Disaster impact analysis in cultural heritage

What is the real impact of cultural heritage disaster losses in society?.

3.1 Types of disaster impacts on cultural heritage

Disaster impacts on a physical asset are assessed primarily in terms of the level of damage that was sustained, which means the extent of physical harm that occurred (i.e. from no damage to total destruction). This level of damage is then expected to be later translated into an economic valuation by determining the cost of repairing or replacing the asset. For tangible heritage, this approach can fall short of identifying the full extent of the losses that were sustained, since heritage value is not just the economic value of physical damage, given the intangible nature of non-use and non-extractive use values that may also be affected.

In some cases, a damaged (but not destroyed) heritage asset can be restored to its original value. In other cases, it can lose part or all of its non-use and non-extractive use values (even if it can be physically repaired), or can even generate new values if it is not repaired. In the case of a heritage asset that is destroyed, the situation is simpler, since replacing the asset will seldom be able to represent the totality of its non-use and non-extractive use values (but it can generate new values). Therefore, measuring the level of physical damage undergone by a tangible heritage asset can be used to determine the losses sustained in the non-use and non-extractive use values, but its economic valuation cannot be expected to express the true extent of the losses.

Aside from these direct impacts, cultural heritage damaged by disasters can also generate other types of impacts. These impacts are often called indirect and can include, for example, those connected to the extractive use values of the cultural heritage asset. In this case, damage can lead to the interruption of activities taking place at the asset, which, in turn, can lead to a loss of income generated by the asset, for example in the form of rent (if a site or a building is used for other purposes such as housing or commercial activities) or entrance fees (if people pay to access and visit the asset). In other cases, this interruption of activities can also lead to a situation in which employees who worked at the asset lose their jobs because it was destroyed in the disaster. All these scenarios refer to impacts that can be expressed in economic terms, since the activities involved have market values. However, there are other relevant indirect impacts, for which this economic valuation is much more difficult. For example, losing the recreational value of a given heritage asset (because it was destroyed or cannot be accessed for some time) can have impacts on the well-being of people that are difficult to express in economic terms. Similarly, the loss of the social or spiritual value associated with the heritage asset can have deep social impacts, namely in people's sense of identity, continuity and belonging. This type of impact can also be associated with the loss of cultural landscape, as discussed in the Super Case Study 1 on the earthquakes in Central Italy.

Social impacts can also be seen to depend on the disaster impacts on intangible heritage. For this particular category of cultural heritage, the impacts can be due to the interruption of intangible heritage practices and transmission of traditional knowledge, or to the inability to have access to cultural spaces or places and materials necessary for the practice of intangible cultural expressions.

Wilson and Ballard (2017) establish that disaster impacts on intangible heritage can be expressed by measuring losses in three elements: people (the individuals or communities transmitting intangible heritage), place (the setting and resources necessary for the transmission of intangible heritage) and story (the knowledge, narratives and traditions). Damage to and losses in the first two elements can be more easily quantified (but not expressed in economic terms), but impacts on knowledge and knowledge systems are much more difficult to identify and will depend on the redundancy of the mechanisms by which a given society holds, documents and spreads this knowledge. In any case, quantifying the overall impacts on intangible heritage due to impacts on the individual elements is challenging (Wilson and Ballard, 2017), particularly if there is insufficient information about the intangible heritage that existed prior to a disaster.

The impacts that have been discussed emphasise the systemic interconnectivity between cultural heritage and multiple sectors of society. Furthermore, the negative effects of the referred impacts are expected to lead to equally negative effects on sustainable development, namely on economic sustainability and social sustainability (Nocca, 2017; Mensah, 2019). The significant exposure of cultural heritage to hazards and its simultaneous multi-hazard vulnerability (see for example Stanton-Geddes and Soz, 2017; European Commission, 2018) point to the fact that risk assessments and potential disaster impact analyses need to go beyond the direct effects on the physical heritage assets. Furthermore, integrating cultural heritage protection measures into risk management strategies is, in fact, a way to protect a significant part of the societal system that is at risk, and should be highlighted to change the currently low priority that is given to cultural heritage in risk management planning (European Commission, 2018).

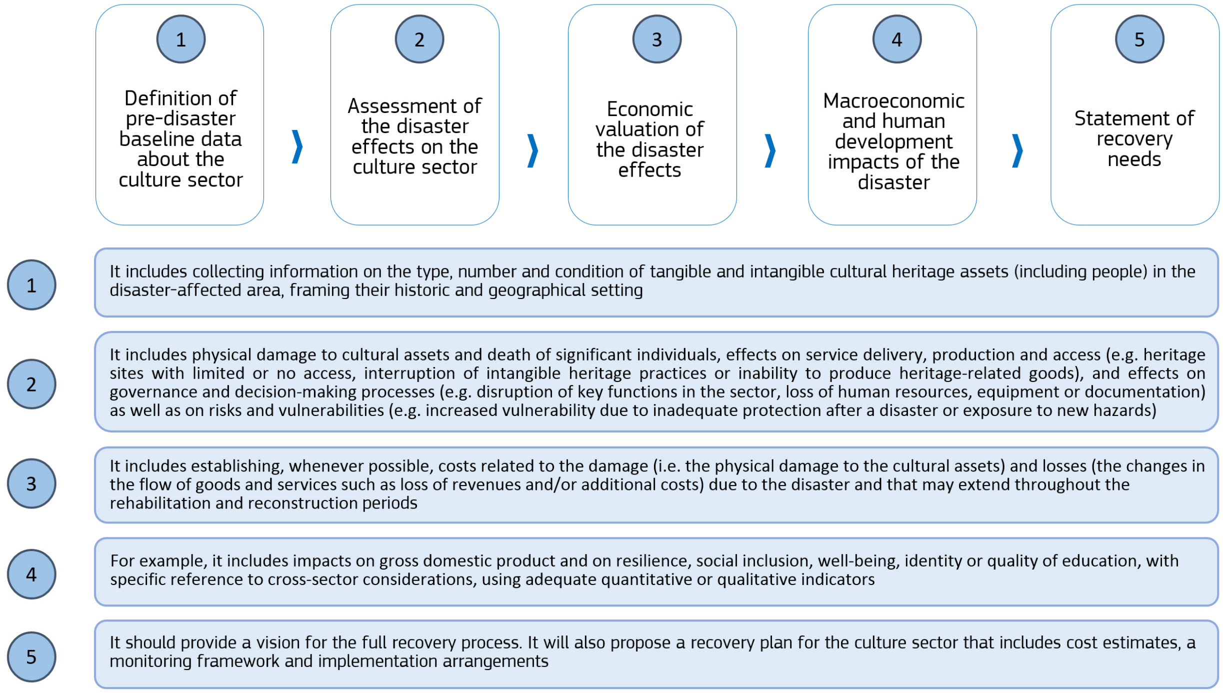
3.2 Existing methodologies for disaster impact analysis in cultural heritage

Given the challenges highlighted in the previous section in identifying and quantifying disaster impacts in cultural heritage, the development of specific methodologies for this purpose has been scarce. Most of the existing developments on this topic are based on the disaster damage and loss assessment (DaLA) methodology established by the Economic Commission for Latin America and the Caribbean (ECLAC) in the 1990s, which was then adapted by Vecvagars (2006) for the specific case of cultural heritage. Currently, the DaLA methodology (ECLAC, 2014) includes a specific section to assess disaster impacts on the cultural heritage sector that covers damage to tangible cultural assets. However, the proposed approach does not fully adhere to the recommendations of Vecvagars (2006).

In 2008, the European Union (EU), the World Bank and the United Nations (UN) Development Group started to develop the Post Disaster Needs Assessment (PDNA) methodology to harmonise existing post-disaster assessment methods. This methodology (PDNA, 2013) provides a framework to determine human recovery needs and to value damages and losses, and combines sector-specific tools developed by UN agencies and the DaLA methodology developed by ECLAC. A PDNA is launched at the request of, and led by, the government of the affected country, with the support of national and international stakeholders. Its fundamental purpose is estimating disaster damage and losses across all sectors of the economy that are affected, as well as recovery, relief, reconstruction and risk management needs (Jones, 2010). It will also provide guidance for developing actionable and sustainable post-disaster short-term and long-term recovery strategies, namely with respect to mobilising the necessary financial and technical resources. Since this procedure appears to have been thought for developing countries, the PDNA outcomes are often also used to launch an appeal for financial aid from other countries and donor agencies (Jeggle and Boggero, 2018).

The PDNA methodology has a chapter dedicated to the culture sector, which covers damage to both tangible and intangible heritage, and in which the approach recommended for quantifying economic impacts accounts for the proposals made by Vecvagars (2006). The chapter also covers losses to repositories of heritage (museums, libraries, archives, etc.) and to cultural and creative industries (i.e. infrastructure, resources and processes for the production, distribution and sale of creative cultural goods). In general, applying the PDNA methodology for the culture sector includes the steps described in Figure 3.

Figure 3. *Steps of the PDNA methodology* ***Source****: Authors*



The existence of the PDNA methodology does not preclude the fact that disaster impact analysis in cultural heritage is also carried out outside this framework in many cases. From the publicly available data that can be found after numerous disasters, most references to damage and loss analyses in cultural heritage assets do not mention that PDNA procedures were implemented. The available information on disaster impacts to cultural heritage assets comes mostly from media-based informal descriptions of damage, from official governmental documents or from technical reports describing damage levels with varying degrees of detail, including cases where more systematic technical damage data collection was implemented based on assessment forms specifically developed for this purpose (for the case of earthquakes, see the forms by MiBAC, 2015).

In some cases, these informal or formal damage descriptions are also complemented with economic information that is mostly related to damage repair or rehabilitation costs of tangible (immovable and movable) heritage assets. With respect to the availability of economic valuations of disaster impacts, reference is made to information related to applications to the European Union Solidarity Fund, which often mention damage and losses to heritage assets. Even though some of these reports state that funding was assigned for the repair of damage to heritage assets (see European Commission, 2012; European Commission, 2017), detailed data are usually not found.

Generally, disaster data on damage and losses related to cultural heritage assets are scarce and often not available at all (Drdácký et al., 2007; European Commission, 2018). This might be because of multiple factors, namely the lack of systematic collection of damage and loss data related to heritage assets that are affected by disasters, the unavailability of an adequate methodology to assess damage to heritage assets in monetary terms (given the multiple values they embody and their impacts on several sectors of society) and the lack of cooperation between the various stakeholders that manage heritage assets (e.g. local, regional or national authorities, civil society institutions such as the Church, or private institutions). Still, factors related to the unwillingness to disclose this type of information due to sensitivity issues should not be discarded as well. As a first step to enhance disaster loss data-sharing practices, reference is made to the Sendai Framework for Disaster Risk Reduction (SFDRR) (UNISDR, 2015) and to the indicators that were identified to measure global progress in its implementation (UNISDR, 2018).

These indicators are expected to measure progress in achieving the global targets of the SFDRR and determine global trends in the reduction of risk and losses. Among these indicators, indicator C-6 refers to the direct economic losses to cultural heritage damaged or destroyed by disasters. This indicator is expected to capture part of the direct economic losses sustained by tangible (immovable and movable) cultural assets. These losses should be divided into repair costs (for damaged assets that can be restored to a pre-disaster situation), the economic value of destroyed assets with a market value and the replacement costs of destroyed assets with no market value.

In addition to this information, this indicator should also collect the number of tangible (immovable and movable) cultural assets that were damaged and destroyed by the disaster. Besides indicator C-6, reference is also made to indicator D-8, which addresses disruptions to other basic services attributed to disasters and can be used to collect relevant data by considering the losses associated with services provided by cultural assets (e.g. religious buildings). Through this indicator, it could then be possible to capture the impact of disasters on human development due to damage to, or loss of, cultural heritage.

3.3 Challenges for disaster impact analysis in cultural heritage

In the light of the previously discussed issues, developing a methodology that can fully capture the true spectrum of economic losses due to damaged or destroyed heritage assets remains the biggest challenge. However, this challenge is not expected to be fully overcome, since the true economic loss due to the destruction of certain heritage assets will never be measurable. Still, developing ways to broaden the level of economic losses that can be measured in terms of damaged or destroyed heritage assets seems feasible. In this context, the current development of methods measuring the economic contribution of activities related to culture and cultural heritage plays a fundamental role.

Research has shown that culture-related activities have a significant impact on economic indicators such as gross domestic product, gross value added and employment (CHCFE, 2015), but these impacts are not readily observable in traditional national accounting systems. Therefore, culture-related data need to be aggregated from the several economic sectors usually defined as industries in national accounting systems. This aggregation is called a Culture Satellite Account (UNESCO, 2009; Throsby, 2015) and measures the economic impacts of culture across the multiple productive sectors of an economy.

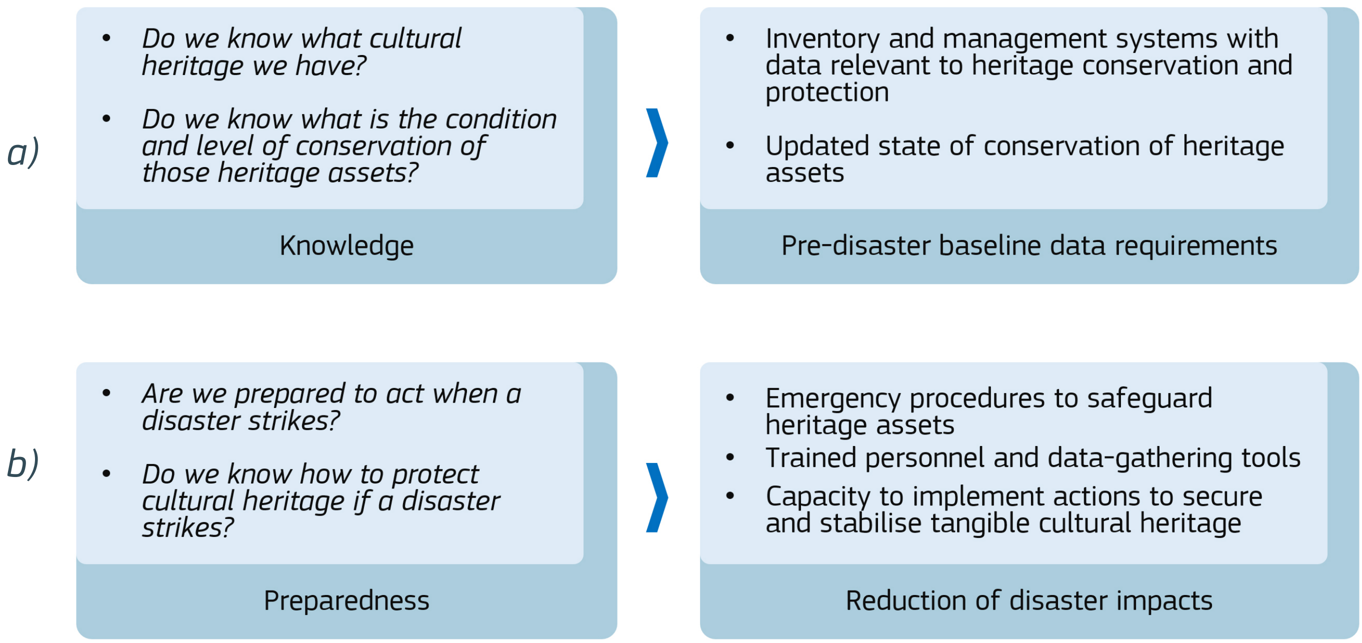
As mentioned before, cultural heritage has also a non-economic impact on several domains of society, namely on social cohesion and community participation, education and knowledge, social identity, well-being and quality of life, and environmental sustainability (see for example CHCFE, 2015, and references cited therein). Although the methods previously referred to for eliciting monetary expressions of cultural values can also be used to monetise the influence of cultural heritage in these domains, their limitations in this case are also those discussed before. However, current trends in analysing the influence of cultural heritage often include non-economic approaches, such as those based on multi-criteria decision analysis or qualitative/semi-quantitative methods (CHCFE, 2015). These approaches need to be ported to the context of disaster impact analysis.

This discussion highlights the fact that developing methods to measure the holistic influence of cultural heritage across the several domains of society is undoubtedly important. Still, it is recalled that, as stated before, measuring value is not the same as measuring loss in value. Therefore, methodological advances in the former need then to be adapted to address the latter. Moreover, the quantification of non-economic losses is not just an issue for the cultural heritage sector, since it has recently become a component of international climate change policy (Hirons et al., 2016; Serdeczny et al., 2016; Tschakert et al., 2017). Thus, developments in this sector may be relevant and applicable to cultural heritage.

Disaster impact analysis in cultural heritage also depends on other factors whose importance is often not highlighted enough. Adequate disaster preparedness is one of those factors and it can be divided into two components. The first one is related to the availability of the previously mentioned baseline data about heritage assets when a disaster strikes (Figure 4a).

The second component is related to the availability of emergency procedures to contain disaster losses in cultural heritage once a disaster strikes (Figure 4b); see for example the case related to radiation contamination referred in the Super Case Study 2 on the Fukushima Daiichi accident. Some of these issues are further discussed next, introducing technological advances that are currently available to assist in addressing these issues.

***Figure 4**. Factors affecting disaster impact analysis: (a) baseline data availability; (b) disaster preparedness* ***Source**: Authors*



4 A resilience enhancement chain for cultural heritage

Enhancing the resilience of cultural heritage can reduce disaster losses in multiple sectors.

The previous sections emphasise the difficulties in defining the full spectrum of impacts resulting from damaged cultural heritage. Still, given that cultural heritage influences multiple sectors of society, increasing our ability to assess these impacts is paramount and will provide hard evidence of the need to enhance its resilience and, consequently, reduce the overall impacts of disasters. Grasping this holistic view of disaster impacts on cultural heritage is the first element in a chain of actions targeting the enhancement of heritage resilience. This first element will then trigger the need for more active implementation of conservation and maintenance practices to improve heritage protection. Consequently, to implement such practices in a more efficient and rational way, updated information and knowledge about the condition of cultural heritage should also be available when needed. This, in turn, triggers the need to have inventory and management systems capable of providing the multidisciplinary information that is necessary.

Among the large spectrum of data these systems should provide, particular attention is given to the importance of having information, as detailed as possible, about certain features of built heritage assets such as their geometry, the construction techniques they involve, the properties of building materials, evolution of and alterations to the assets over time, and damaged or degraded features they may exhibit (ICOMOS, 2003). It is well known that acquiring this information presents several challenges due to the resources it can involve and the complexity of certain heritage assets.

However, this information is vital for performing a realistic assessment of the conservation and/or retrofitting needs in pre-disaster settings, as well as for developing adequate repair and/or reconstruction operations guided by principles highlighting the preservation of authenticity and value in post-disaster scenarios (ICOMOS, 2017). Therefore, in pre-disaster settings, the availability of this information and knowledge will help prioritise conservation and maintenance actions that, in turn, will enhance the resilience potential of cultural heritage and actively contribute to reducing future disaster losses in cultural heritage in a way that is consistent with the anticipatory disaster risk management approach suggested in Subchapter 1.3.

Given that some of the relevant information that should be available in the referred inventory and management systems is expected to change over time, regular monitoring of heritage assets is therefore required, as well as additional resources for this purpose. In light of the continuous technological advances in remote sensing platforms (e.g. the development of multiple types of ground sensors and unmanned aerial vehicles, or the launch of new satellites with multispectral sensors), technology-based monitoring and documentation tools with the ability to feed those systems are becoming increasingly available (see for example Toth and Jóźków, 2016; Yang et al., 2016; Weissgerber et al., 2017; Corsetti et al., 2018; Manfreda et al., 2018; Zhu et al., 2018).

Despite these advances, their impact on fields related to cultural heritage protection is still moderate (see for example Cerra et al., 2016; Frodella et al., 2016; Pavlidis et al., 2017; Pastonchi et al., 2018; Chen et al., 2018; Elfadaly et al., 2018; Giardina et al., 2019) and further research is still needed to develop reliable and operational remote sensing tools that will increase the feasibility and cost-effectiveness of cultural heritage monitoring. Still, resilience metrics, approaches and concepts require further developments at different scales to prioritise the implementation of cultural heritage protection measures as an integral part of the concept of a resilient society (Bocchini et al., 2014; Andretta et al., 2017).

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5 Case studies

Community engagement is essential in post-disaster recovery of damaged cultural heritage.

5.1 The 2011 Lorca earthquake

On 11 May 2011, at 18.47 (local time), an earthquake of magnitude Mw 5.1 hit the city of Lorca in the region of Murcia, Spain. Lorca is a medium-sized city that had a population of about 93 000 in 2011. The city, which sits on both banks of the Guadalentín river and on the hillside of a 9th-century castle, is rich in both tangible (e.g. churches, Roman villas, palaces, a castle and several other monuments) and intangible cultural heritage (e.g. the Holy Week and Easter festivities, the San Clemente festivities, the art of embroidery). The earthquake caused extensive damage to both recent and older constructions in Lorca, along with 9 deaths and 324 people injured. Although earthquakes of such magnitude are expected to cause limited damage, the shallow depth of the hypocentre and its closeness to the city are believed to be the main reasons for the significant damage that occurred (Romão et al., 2013). The main earthquake was preceded by another event of magnitude Mw 4.5, at 17.05 (local time). Although this foreshock was relatively weak, damage to some structures was also reported. Overall, this event damaged nearly 80 % of the buildings to varying extents. The inspection of 7 876 buildings in the city showed that 5 383 had suffered minor or no damage, 1 569 had suffered moderate damage, 664 had suffered moderate to serious damage and 260 had to be demolished. The insured losses due to this earthquake were close to EUR 511 million (CCS, 2019), of which 83.5 % was related to residential buildings and 13.5 % was related to commercial buildings, but estimates of the overall direct and indirect losses are in the order of EUR 1 200 million (Olivas, 2011).

With respect to cultural heritage, damage occurred in monuments and historical constructions (and also in movable heritage assets) (Figure 5). Assessment forms were developed to collect damage data, which were then used to estimate costs for the emergency stabilisation and repair of 74 damaged heritage assets (and also for movable heritage assets). These 74 heritage assets are those listed as Bien de Interés Cultural (a designation equivalent to that of heritage assets with national significance) Grade 1 and Grade 2 that were damaged by the earthquake. The damage and cost data were made publicly available in the 'Plan Director para la Recuperación del Patrimonio Cultural de Lorca (Master Plan for the Recovery of the Cultural Heritage of Lorca) commissioned by the Instituto de Patrimonio Cultural de España (Spanish Cultural Heritage Institute) of the Spanish Ministry of Culture and published in November 2011 (BOE, 2011).

The prompt development of the Master Plan indicates clearly how significant this cultural heritage is for the city's recovery and sustainability and for the well-being of citizens. Most costs were funded by various governmental sectors and programmes (at the national, regional and local levels), the Church and the private sector, highlighting the large multi-sectoral coordination effort that was made to implement the plan for the recovery of cultural heritage. To cope with the disaster, Spain also applied to the European Union Solidarity Fund, from which it received EUR 21.1 million (European Commission, 2012; European Commission, 2013), and was granted a EUR 185 million loan by the European Investment Bank (EIB, 2012), from which nearly EUR 24 million was allocated to the recovery of cultural heritage. The overall cost of immediate protection measures and repair of cultural heritage was estimated to be EUR 47.87 million for the immovable assets and EUR 2.1 million for the movable assets (BOE, 2011). The repair works were overseen by a management commission and a technical commission and were expected to be concluded in 2016. The management commission promoted initiatives supporting the value (namely touristic value), the recovery and the preventative maintenance/conservation of Lorca's cultural heritage, and was in charge of managing resources and funding for these operations. Meanwhile, the technical commission supervised and provided guidance for all the repair works.

Figure 5. *Examples of heritage assets damaged by the Lorca 2011 earthquake.*
Source*: Photos courtesy of Xavier Romão and Esmeralda Paupério.*

Aside from managing the recovery of heritage assets, the Master Plan also included several supporting activities under the section 'Auxiliary Programmes'. One of these activities involved the development of a database to document and collect all the relevant data on the repair actions that were performed across the different heritage assets. Developing this database is in line with the previous remarks addressing the need for inventory and management systems with updated information about heritage assets, and will provide relevant information for developing heritage conservation and maintenance plans, for research on cultural heritage recovery and for risk preparedness related to future disasters.

Other activities of the Auxiliary Programmes involved disseminating information about the heritage recovery process throughout its development, across various media and in special publications targeting different sectors of the local population on topics related to the effects of the earthquake and to the heritage recovery operations. However, some activities were specifically designed to preserve the engagement of the citizens with their cultural heritage during the recovery and to involve them in the recovery process. Reference is made to activities such as exhibitions related to the recovery and repair processes, workshops discussing these processes, with invited talks and practical in situ demonstrations, and guided tours to sites of heritage assets being repaired. The guided tours were created mostly for the local population and were based on the route 'Lorca, abierta por restauración (Lorca, opened due to restoration), developed by the Regional Ministry of Culture and Tourism after the earthquake within the programme 'Lorca El Taller del Tiempo (Lorca, the workshop of time), which had been in place since 2003 to enhance tourism in the region. This new touristic product of the programme was a mixture of cultural tourism and the 'dark tourism' created in the aftermath of the earthquake, with the hallmark that 'visitors would not only connect with the cultural heritage of Lorca, but also with its post-earthquake recovery and all the curiosities about the effects of earthquakes in the city and in the lives of Lorca (AN, 2012). This route was designed to limit the post-earthquake reduction of tourism in the city (Muñoz et al., 2018) and to strengthen a sector already in distress due to the economic crisis that had been affecting Europe since 2008. In 2012, this route won the Excelencias award at the International Tourism Fair and a Global Awards at the World Travel Market (LTDT, 2019), acknowledging it as one of the best tourism initiatives in the world. More details of the economic impacts of these initiatives on the tourism sector can be found in Cebrián (2015).

In January 2017, the repair works were officially concluded and the updated costs were set at EUR 64.35 million (MCD, 2017). These updated costs reflect several changes that were made to the Master Plan between 2011 and 2016 (Barceló de Torres et al., 2016). As a consequence of those changes, the protection level of some of the heritage assets was reorganised and the repair works on Grade 3 heritage assets and on some of the public spaces also damaged by the earthquake were integrated into the Master Plan, following recommendations from the management commission. Overall, the revised Master Plan refers to financial aid to repair and/or rehabilitate 186 heritage assets.

The revised plan also includes a series of actions towards the sustainable management and future protection of Lorca's cultural heritage, and three documents reflecting long-term commitments for the post-disaster sustainability of the city. One document proposes actions to integrate cultural heritage, urbanism, landscape and tourism, fostering the recovery of heritage assets and their economic potential (e.g. for touristic activities and job creation). Another document proposes actions to renew degraded urban areas, and to recover the identity of neighbourhoods and their connection with cultural heritage. The last document proposes a revision of the 'Plan Especial de Protección y Rehabilitación Integral en el sector II del conjunto histórico artístico de Lorca (Special Plan for the Protection and Integral Rehabilitation of sector II of the historical centre of Lorca), promoting improvements in the historical centre to encourage its use as a residential area, and defining a new regulation to manage and protect Lorca's cultural heritage.

Finally, in terms of global effects and lessons learned, it is noted that cultural heritage protection protocols were improved nationwide after this earthquake. In particular, in 2015, Spain published a National Emergency and Risk Management Plan for Cultural Heritage (NERMPCH) (MECD, 2015) to address disaster risk reduction issues for cultural heritage. The main objectives of the NERMPCH are:

- to define measures to protect cultural heritage assets from disasters,
- to define resources and protocols for emergency actions addressing the rescue and safeguard of cultural heritage in case of disasters,
- to design instruments and coordination mechanisms between institutions acting in emergency situations and dealing with the safety of people and assets that integrate concerns with the safeguard of cultural heritage.

Among other practical measures, the NERMPCH recommends the Spanish autonomous regions create cultural heritage emergency management units that, in collaboration with civil protection and cultural heritage institutions, will then develop regional programmes and actions for risk prevention in cultural heritage and for the safeguarding of cultural heritage in emergency scenarios. So far, units of this type have been created in the Spanish regions of Murcia and of Castile and Leon, while Castile-La Mancha, the Canary Islands, Aragon, Extremadura and Asturias are in the process of developing their own.

5.2 Additional remarks with reference to other case studies

As mentioned before, detailed accounts of disaster impacts on cultural heritage assets are, unfortunately, limited. Therefore, the positive effects of measures that are implemented for disaster risk reduction are difficult to determine when certain events recur. To illustrate this issue, reference is made to the impacts of the 2002 and 2013 European floods in Germany.

After the event of 2002, flood risk management measures and policies were implemented and the 2013 flood provided an opportunity to analyse their effectiveness. According to Thieken et al. (2016a), the improvements include greater integration of flood hazards in spatial planning and urban development, an increase in mitigation and preparedness measures for individual properties, more effective flood warnings and disaster response coordination, and more efficient maintenance of flood defence systems.

With respect to cultural heritage, since limited information has been shared about the assets that were affected by both floods, it is difficult to understand what measures were implemented, how effective they were in 2013 and what issues remain to be addressed. Thieken et al. (2016b) refer briefly to some of the impacts of the 2002 and 2013 floods on cultural heritage but highlight that no detailed list of the damaged assets is available. The only piece of information allowing a comparison between the 2002 and 2013 floods' impacts on cultural heritage refers to the Garden Kingdom in Dessau-Wörlitz, which was severely damaged in 2002 but was not affected in 2013 thanks to upgrades in the flood protection system.

Fires are also cases in which the unavailability of detailed information on damage and losses to cultural heritage has a significant influence in our ability to reduce disaster risks and impacts. The significant media coverage of single events such as the fires in the National Museum of Brazil (2018) and Notre Dame Cathedral (2019) hides the fact that fires in heritage assets are unfortunately too common. In the United Kingdom alone (one of the few European countries where data on fires in heritage assets are collected and shared) there were 164 fires recorded in heritage buildings between January and April 2019 (HEFP, 2019).

Still, for many of these fires, the available information is insufficient for developing deeper analyses and studies that may provide adequate knowledge to propose fire risk mitigation measures. As an example, reference is made to the fact that many fires occur during maintenance or renovation activities in heritage buildings, but information about the real causes of those fires is usually too limited to adequately support the development of safety procedures that could be implemented when these activities are being carried out.

In sum, these two examples highlight the need to establish robust systems and methods for collecting disaster damage and loss data for cultural heritage. Currently, one critical aspect is that this lack of data is responsible for a biased view of the real effects of hazards on heritage assets, a situation that is further intensified in scenarios involving cascading hazards (when one hazard triggers another hazard) or coupled hazards (when one hazard changes the conditions for the occurrence of another hazard at a later time).

Simultaneously, it leads to risk assessments that underestimate the potential consequences of future events. Globally, these issues underline the importance of understanding risk, as mentioned in Subchapter 1.2, in order to achieve effective disaster risk management.

6 Conclusions and key messages

This subchapter discusses several issues related to disaster impact assessment in the cultural heritage sector, reviewing existing methodologies and challenges, but also emphasising the importance of widening the scope of current practice. Regarding the latter, two aspects should be addressed: capturing a larger spectrum of economic impacts (e.g. indirect losses in other sectors) and capturing non-economic impacts on society (e.g. impacts on social identity and cohesion or on well-being). The development of Culture Satellite Accounts can provide data for the former, while methods discussed by CHCFE (2015) or others possibly developed in the field of climate change policy could help with the latter. Given the holistic influence of cultural heritage in society, the subchapter also highlights the importance of overcoming these challenges to underpin a chain of actions that should be implemented to enhance the resilience of cultural heritage as a way to increase the overall resilience of societies to disasters. The main components of this chain of actions are discussed, highlighting how advances in remote sensing technologies can provide important data for heritage inventory and management systems.

Disaster impact assessment in cultural heritage and post-disaster recovery management is illustrated for the case of the 2011 earthquake in Lorca. The available information from this event indicates that the promptly developed detailed post-event survey of the damage to the heritage assets and the coordination between local, regional and national authorities, the Church and the private sector were paramount for developing and implementing the recovery plan for cultural heritage. Aside from addressing the repair of damaged heritage assets, the plan also included several actions targeting citizen participation and engagement in the heritage recovery process, highlighting the importance given by stakeholders to the connection between the cultural heritage and the citizens. Despite these significant improvements, namely progress towards developing a city-wide strategy addressing its post-disaster sustainability that includes the sustainable management and protection of cultural heritage, the attention to other relevant hazards (e.g. floods or landslides) or climate change adaptation measures appears to be limited and should be addressed in the short term.

Finally, since detailed examples as the Lorca case are, unfortunately, limited, the need to define disaster data collection systems and methods to overcome this issue is highlighted. Two additional examples are presented to illustrate the fact that this lack of data may bias our current view of the real effects of hazards on cultural heritage. This aspect is further intensified in situations that may involve cascading hazards or coupled hazards for which there is currently no relevant information (e.g. information indicating that the impacts of an event are more intense due to the occurrence of a prior event), thus requiring special attention and resources. Furthermore, these issues also limit our ability to identify empirical risk factors and validate risk models that will allow us to estimate more realistically the consequences of future events on heritage assets.

Policymakers, practitioners and scientists

There is a need to significantly improve disaster data collection in the cultural heritage sector. Awareness must be raised regarding the importance of sharing this data and adequate methods and standards should be developed to facilitate data collection. Furthermore, the scope of current disaster impact assessment practice should be widened in order to capture a larger spectrum of economic impacts (e.g. indirect losses in other sectors) and non-economic impacts in society (e.g. impacts on social identity and cohesion, well-being).

Policymakers and practitioners

Developing an immediate and detailed post-disaster survey of the damage to cultural heritage assets and ensuring an adequate coordination between local, regional and national authorities, the private sector and other relevant stakeholders are key elements for developing and implementing a successful recovery plan for the cultural heritage sector.

Practitioners and scientists

Account must be taken of the need for further development of conventions on multi-stakeholder collaborations to support a systematic exchange of information, expertise and results. The identification of internal and external interdependencies suggested in new continuity management standards such as ISO 22301:2019 and NFPA 2019/1600 could be the first step in this process. However, new steps are needed in terms of legislation and policies to support the development of a holistic collaborative framework and introduce better accountability and compliance requirements. Some open questions remain, associated with the quantification of cascading impacts triggered by the disruptions of EMFIs. At the time of writing, it is not possible to access any quantitative information on losses and damages that could have been avoided if EMFIs had been completely efficient. These data could be used to develop some better cost–benefit analyses to support decision-makers. Clearly, this approach is merely a first step in a longer process of improvement and evolution that should involve EU legislation and policies.

Policymakers and citizens

The role of individual citizens is another element that can be explored to improve the status quo. For example, the literature recommends defining what to communicate and how to do it (Alexander, 2016; Lindell et al., 2007), but there is a lack of understanding of what procedures would be most useful if emergency facilities were disrupted. In line with the SFDRR (UNISDR, 2015), it could be useful to develop better involvement with local communities and stakeholders. Indeed, civil society could represent an essential asset for coordinating emergency efforts, and developing basic training for the population on cascading scenarios could be one of the tools for improving societal resilience (Royal Academy of Engineering, 2016).

ACKNOWLEDGEMENTS
The lead author and the first contributing author would like to acknowledge the financial support from POCI-01-0145-FEDER-030469 - RIACT – Risk Indicators for the Analysis of Cultural heritage under Threat, by FEDER through COMPETE2020 - Programa Operacional Competitividade e Internacionalização (POCI) and by national funds through FCT - Fundação para a Ciência e a Tecnologia, and the financial support from Base Funding - UIDB/04708/2020 of CONSTRUCT - Instituto de I&D em Estruturas e Construções, by national funds through FCT/MCTES (PIDDAC).

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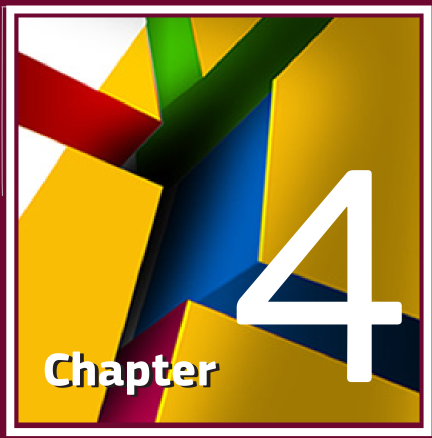

Communicating disaster risk among all

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Boersma, K., Martelli, C., Bruinen de Bruin, Y., Vetere Arellano, A.L., Claassen, L., Pickl, S., 'Communicating risk among all', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

4 Communicating risk among all

CONTENTS

Introduction

This chapter, 'Communicating risk among all', is focused on a specific aspect of risk management: how to link and integrate territories and communities ever better in facing challenges, reacting to shocks, anticipating them and learning from experiences by means of two-way risk communication. The object of this chapter is to show how good, granular and effective communication plays a paramount role in strengthening cohesion between all the stakeholders involved in order to deal with the risks in their territories.

To achieve this goal, it is not enough to produce content and data: what is needed is a comprehensive shared knowledge system, able to support, communicate widely and be understood by all the actors involved and exposed to risks.

It is worth noting that we are finalising this chapter during the COVID-19 pandemic emergency: it has been impossible not to reread our contents from the perspective of what is ongoing. In this very moment we are experiencing, with a strength perhaps never experienced before, the systemic nature of our communities, the limits of some of our institutional organisations, and the role of social networks and technology.

Communication has played, as foreseen, a massive role in the overall situation, both for good and for bad. What we are now observing is that the communication dimensional axes that we are experiencing are the ones that have been explored in this chapter: institutions, communities and technology.

The concept of complexity is at the root of all the contents of this chapter, recognising that territories and communities are networks made by a plurality of actors and stakeholders, mutually interrelated by processes and relationships, and sharing, alongside their differences, the same risk. The idea informing this chapter is that the only answer to the network of risks is the network made by an informed and proactive territory.

This objective cannot be taken for granted: our societies, communities and institutions, even if deeply interconnected in the face of the risk, are historically organised in a hierarchical and sectoral way, to assure specialisation and clear responsibilities in governance processes. Nevertheless, this aspect may hamper the efficiency of response to risks. This chapter, on the basis of case studies, good practice examples and the discussion of past experiences, deals with methodologies, instruments and strategies to overcome this hierarchical and sectoral approach and achieve a complex environment based on efficient communication.

This chapter addresses convergent objectives: how to create the conditions in which nodes in communication networks are able to connect to one another (subchapter 4.1), how to involve stakeholders and sustain their capacity to perceive themselves as essential nodes in the network (subchapter 4.2) and how to take advantage of technology to realise this environment (subchapter 4.3).

The concept of complexity has been explored and applied in many of its dimensions. This chapter considers complexity not merely a network, but a system, with a certain number of specific properties. The first one is about keeping the separation paths among the nodes as short as possible. This aspect is dealt with in subchapter 4.1, where the different approaches to linking actors, sectors and governance levels are presented and discussed.

The chapter also shows that installing linking paths among the nodes of the network is not enough if they are not kept alive and participating. This aspect is, in particular, discussed in subchapter 4.2, in which the question of how to overcome the classical hierarchical governance structure in the context of more bottom-up and participative governance is addressed. That part of the chapter is, in fact, about a governance approach for transforming a community in a real complex network: the management of different points of view and interests or the recognising of clustering phenomena that may provide advantages for designing efficient processes for participation through social media or, as we are experiencing now, for blocking the propagation of false information.

Besides the more political, organisational and structural approaches discussed in the first two subchapters, subchapter 4.3 looks in particular at the technical feasibility conditions.

It is quite tricky to succeed in providing an exhaustive and updated discussion of the state of the art in this field: in these very days, for instance, we are witnessing, hour after hour, the emergence of new proposals for instruments and communication assets to face the present challenges.

The chapter, anyhow, discusses the fact that technology, information and communication science is not only about instruments, but about methods and design approaches, essential to realising complex information and communication networks.

4.1 Linking actors, sectors and governance levels

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1 Introduction to risk governance and its challenges

The challenges of good governance in addressing the many risks affecting society can only be addressed via a process of effective communication between stakeholders working together to build trust, common understanding and alignment in an open, timely and problem-solving mode.

Our modern societies are fast evolving, interconnected, volatile, uncertain, complex and ambiguous, thus making risk governance a significant challenge at the interface between policy, science and practice, depicted in several models (Luc Hoffmann Institute, 2017). Despite risk prevention efforts by many stakeholders, disasters still remind us of our vulnerability to all kinds of hazards ([1]) (IPCC, 2019; WEF, 2019). Moreover, several controversies have highlighted failures of risk management and governance, as shown in this subchapter. The increase in misinformation through social media (Lewandowsky et al., 2017), politicisation of science (Deming, 2005; Jasanoff, 2005; Davies, 2019) and organised ignorance (Frickel and Vincent, 2007; Knowles, 2014; Wieland, 2017) to manufacture doubt and confusion have started eroding the public's trust in scientists and experts (tobacco, climate change, vaccines, etc.). The control of risk and crisis communication is much harder when social media tend to be the first to communicate relevant and fake news. Against this background, can we benefit from past lessons, good practices and insights from science to rebuild trust by using effective communication processes to enhance risk governance?

Interconnected and dynamic hazards and risks require the participation of all relevant actors tackling shared problems in a collaborative and communicative manner (Walker et al., 2010; IRGC, 2018). This continuous inclusive process accommodates competing interests and priorities from both formal institutions and informal arrangements that people and institutions either have agreed to or perceive to be in their interest (Commission on Global Governance, 1995; UN-Habitat, 2009). It is against this background that the second priority of the Sendai framework for disaster risk reduction (United Nations, 2015), i.e. to strengthen the process of disaster risk governance, has been established.

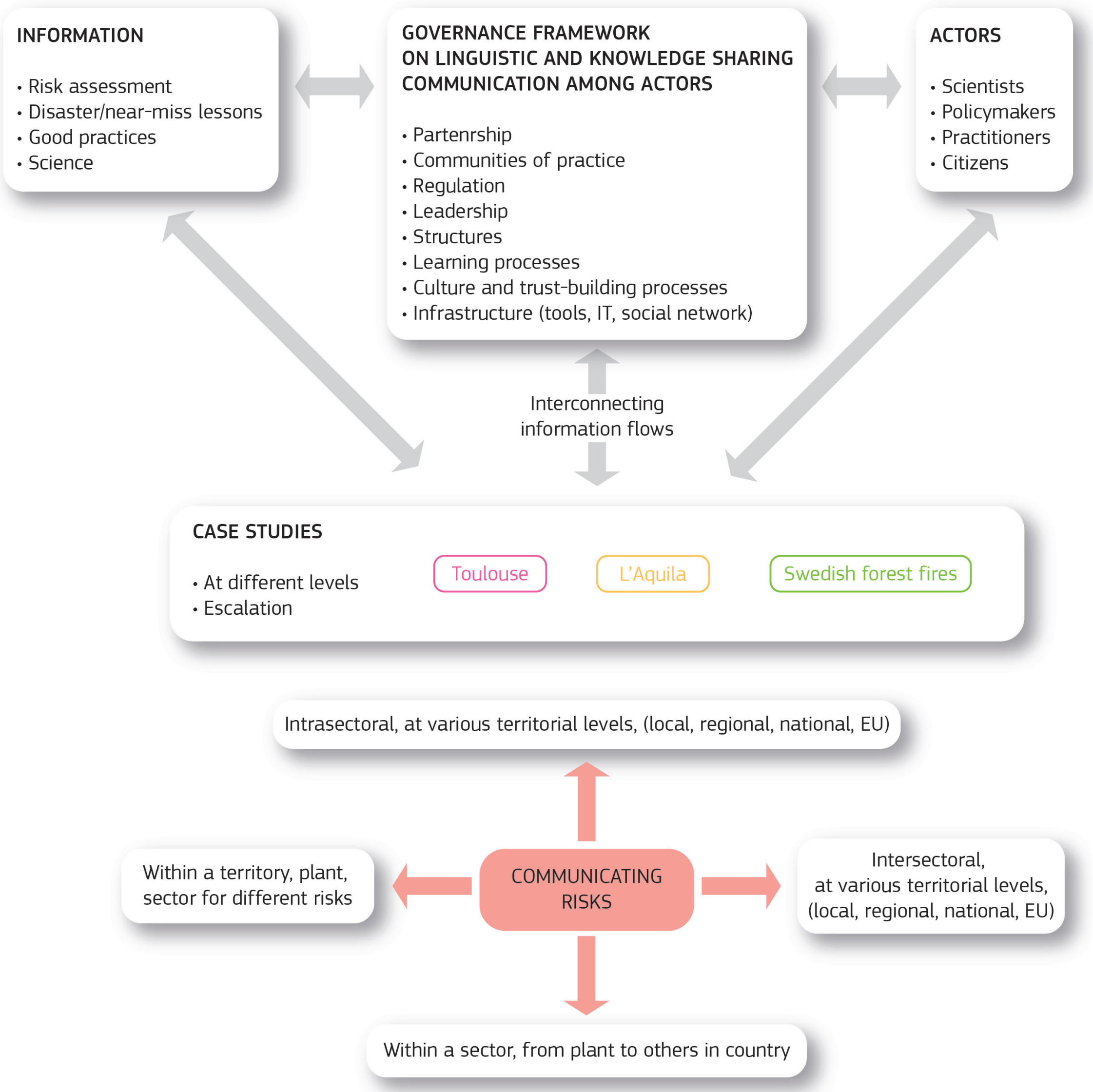
To achieve good governance in multi-stakeholder situations is very challenging (Keping, 2018). It requires knowing how to evaluate, plan, implement and maintain risk management measures, along with appropriately deciding who should be involved and who is excluded (Renn, 2008; Di Nucci et al., 2017). This consists of processes that foster openness to democratic learning across different sectors, among varied stakeholders (decision-makers, scientists, practitioners and citizens), and between different levels of society (international, national, regional and local) (Tompkins et al., 2008), while seeking to collaborate and communicate effectively with each other in an open, inclusive, fact-finding, problem-solving and trust-building manner. Furthermore, a multidisciplinary approach should be promoted, by drawing on more varied skills, knowledge and resources (both human and financial) (Paton, 2007; Walker et al., 2010), thus promoting trust, communication and collaboration among and between various actors (Wachinger and Renn, 2010; Kuhlicke et al., 2012; Di Nucci et al., 2017).

([1]) Hazards can be known, emerging and/or rapidly increasing in frequency because of climate change or contact with (remaining) nature/wildlife, new technological developments, etc

PG ensures that all stakeholders affected by a given risk, or who can influence the decision-making process, work together towards a common goal (Mees et al., 2016; Begg, 2018). Collaborative processes can be designed according to different criteria: scale, psychological impact, societal concern, knowledge of the target group etc. For example, differing values when deciding about long-term radioactive waste storage (Di Nucci et al., 2017) sometimes result in stakeholders rejecting a common goal.

If a balance of power is achieved and articulated with communication, PG is beneficial in many ways, such as in promoting social learning (Pahl-Wostl et al., 2013), active citizenship, community empowerment, and improved acceptance and quality of decisions (Webler et al., 1995; Chambers, 2002; Paton, 2007; Walker et al., 2010; Featherstone et al., 2012).

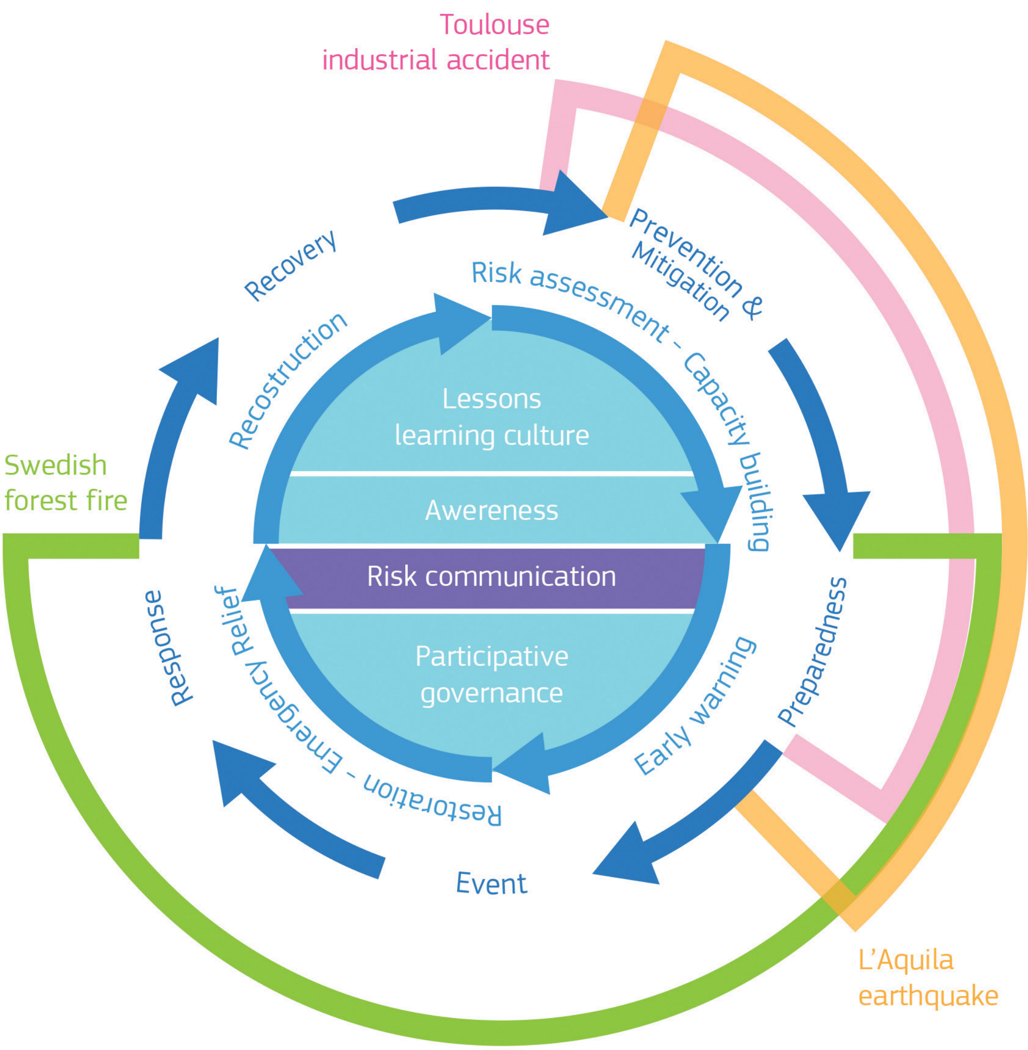
Figure 1 *When communicating risks, the complexity related to interconnected aspects of information flows should be considered*
Source: *Authors.*



This subchapter aims to showcase governance and communication-related experiences and good practices, especially resulting from lessons learned from selected past events. Figure 1 portrays an analytical framework encompassing various complex and interconnected aspects of information flows, processes and actors.

Risk communication is dependent on many aspects, such as perception of probabilities and various cultural, institutional and situational factors (Pidgeon et al., 2003; Kahan et al., 2009). These aspects are further described in subchapters 4.2 and 4.3. Furthermore, where identified, good practices at different governance levels and different disaster management phases (see Figure 2) are presented in the tables found in Section 5 of this subchapter. The importance of risk and uncertainty perception and communication is highlighted in Section 2. Trust building is the development of long-term partnerships between scientific risk assessors, practitioners and policy communities (Section 3). Partnerships take centre stage in Section 4, while Section 5 briefly describes three disaster case studies, along with related lessons learned and management gaps. Section 6 provides some conclusions. The concept of complexity, in terms of risks and answers, underpins all chapter contents.

Figure 2. *Events analysed with evidence of good practices mapped onto the disaster risk management cycle, modified from BEH & UNU-EHS (2016)**. Source:** modified from Vetere Arellano et al., 2004.*



2 Governance, risk perception and communication despite complexity and uncertainty

Clarify risk and uncertainty communication objectives, along with roles and responsibilities before, during and after a crisis.

Disaster risk governance and communication require a variety of stakeholders (national, regional and local authorities, rescue services, scientists, media, the public, etc.) with different skills to work together (Renn, 2015). Understanding the way each stakeholder perceives risk knowledge is essential for effective risk communication (Terpstra et al., 2017). To implement targeted risk communication processes, a clear and shared perception of both hazard and its likelihood of occurrence is required, as well as an understanding of potential impacts (Shreve et al., 2016). Especially for low-probability, high-consequence events and potential 'black swans' (Taleb, 2007), i.e. a rare outlier event of high impact that could have been foreseen, but was not perceived, the uncertainties associated with risk assessment and decision-making processes should be transparently communicated to all stakeholders.

These interacting and interlinked processes described above reflect the dynamics of our complex society. As stakeholders have different departure points, the communication among them must be an iterative process to converge towards a common understanding (Bourrier and Bider, 2018). Divergence may occur when, for example, citizens may decide not to act on risk assessment results if they deem them unreliable (because of trust issues resulting from political incidents or perceived personal gain), or when knowledge claims are tested in different contexts (Jasanoff, 2005; Eiser et al., 2015). Similarly, decision-makers and citizens may want to know how a risk assessment was carried out, including its outcome, while scientists may make assumptions about citizens' risk perception and behaviour. Thus, understanding the complexity of social and behavioural dynamics is important in the management of risk (Donovan et al., 2014, Donovan and Oppenheimer, 2014; Kusev et al., 2017).

The three case studies described in Section 5 illustrate the complexity, ambiguity and uncertainty of risk assessment, awareness and communication, especially when scientific knowledge faces limits (properties of off-specification ammonium nitrate fertilisers polluted by other chemicals in the Toulouse accident; interpretation of small shocks in the L'Aquila earthquake), or when changes in stakeholders' behaviours are needed as a result of insights into plausible future scenarios (shift to a more resilience-oriented approach in forest fire risk management in Sweden) (see Tables 1 and 4).

Awareness of potential biases and possible opposing values among actors is essential when communicating risks and uncertainties. Knowledge of these values and biases makes communication more effective. Another communication aspect to consider is context-sensitive framing: communication should be framed in dialogue with the intended audience, so that terms and vocabulary are clearly defined, and uncertainty (Stirling, 2007; Spiegelhalter and Riesch, 2011; Doyle et al., 2014; Doyle et al., 2019) is clearly communicated. The example of the Swedish forest fires exemplifies this (see Table 4). The rescue service provided information to the public using different types of media, while the police had face-to-face discussions with the affected civilians when evacuation became critical (Myndigheten för samhällsskydd och beredskap, 2018). Furthermore, scientists and practitioners are not always trained in probabilistic thinking, making the use of expert judgement difficult (Donovan et al., 2017).

Managing information between institutions is a challenge requiring reflexivity in framing and using visuals (O'Neill and Nicholson-Cole, 2009; Kim and Di Salvo, 2010; Charriere et al., 2012). Great care needs to be taken in how probabilities and uncertainties are clearly communicated to different actors, and how vulnerability is characterised and understood (UNDRR, 2019).

Research suggests using different visualisations and communication methods (see subchapter 4.3), as they assist in ensuring that a message is understood (Spiegelhalter et al., 2011). Even where risk assessments are understood, achieving effective actions can be challenging (Wachinger et al., 2013): risk perception is only part of the picture, particularly when people have motives not to take action or are not empowered to do so (Gaillard, 2008). Furthermore, people often prefer information on a given hazard to be certain (Blake, 1995; Covello and Sandman, 2001; Bennett et al., 2010).

According to Juanchich et al. (2017) experts who used the phrase 'I am certain' were judged to be more knowledgeable than experts who said 'it is certain'. The results were reversed if the speaker was a layperson. Certainty is strongly linked to perceived trust (see Section 3); therefore, when communicating uncertainties and statistics, the communicator should be clear about the objectives, acknowledge expert guidance and work closely with the intended audience (Spiegelhalter, 2017)

3 How to build trust for risk communication and governance towards a learning culture

Trust building is a long-term iterative process based on good practices and lessons learned. When there is trust, it becomes the oil that facilitates an effective risk communication culture among diverse stakeholders. Trust is built through systematic sharing of information and inclusive experiences between first responders, crisis coordination centres, scientists, decision-makers, etc. in dedicated fora. A competent leader is needed to moderate this process, acting as a catalyst, steering the group towards a learning culture.

Trust builds and strengthens relationships between stakeholders and influences the success of DRM practices. It relies on governance structures, but also participatory processes and subtle practices for sharing and learning. Trust-building processes should take place in structures that nurture a positive risk culture (see Table 2), and clear leadership is required during interactions between stakeholders (see Table 4), so that stakeholders reach a common understanding of the issues and solutions, and clearly agree on who is responsible for what. The leader's challenge is to foster a just moderation or mediation process in which all stakeholders are able to influence decisions being made and collectively learn from each other. These skill sets are very specific, requiring both theoretical background and significant practical experience. Thus, setting up peer working groups or communities of practice fosters exchanges of good practices and experiences and is useful to collectively formalise lessons learned from case studies (Merad and Carriot, 2013).

Awareness of risk communication models assists in better understanding risk communication processes, enabling the communicator (regardless of role) to respect different perspectives. Owens (2015) suggests four in particular: the technical-rational model, the strategic model, the cognitive model and the co-production model. In short, scientists frequently assume a technical-rational model in which science feeds into policy and then is communicated to the public – but this process is undermined by the social nature of science and of policy. As demonstrated in the L'Aquila case study, assumptions are made about science by all stakeholders, and the interpretation of science also depends on the interpreter. Thus, Jasanoff's (2004) co-production model is a more representative approach to the production of scientific advice: science and social order are produced together.

If there is mistrust and confusion among stakeholders, then that order breaks down. Trust is a relationship: scientists and policymakers also have to trust the public and understand how the public judge knowledge claims and themselves contribute towards knowledge (Pidgeon and Fischhoff, 2011). Furthermore, risk communication does not only involve the hazard: it also involves communicating, discussing and reducing vulnerability, which is a longer-term process (UNDRR, 2019). Public–private partnerships (see Section 4) are another example of where trust-building processes take place.

4 Forming and managing partnerships

Building long-term partnerships is the key to enhancing multidisciplinary collaboration that promotes synergies between scientists, policymakers, practitioners and citizens. Embedding these synergies in stable networks builds trust and makes it possible to exchange information and best practices, education and training, and awareness raising in the area of risk management, governance and communication.

Existing partnerships can facilitate communication based on trust, which is essential for effective disaster risk management across the phases of the disaster risk management cycle (see Figure 2). The very nature of a crisis disturbs networks of actors, with social media accelerating the exchanges. This increases cacophony, which threatens the long-term and fragile trust-building processes. Through partnerships and collaboration, actors can foster learning of different worldviews and values, create common norms and vocabulary across fragmented entities, enhance situational awareness, improve decision-making, access more resources, expand outreach of communication efforts, improve coordination with other efforts, increase effectiveness of emergency management efforts, maintain strong relationships built on mutual understanding and create more resilient communities (FEMA, 2015).

Forming and managing partnerships can happen on multiple levels: local, regional, national and international. Within Europe, cross-border cooperation is well developed in the various disaster risk management phases (see Figure 2):

- the EU macro-regional strategies(2), for the prevention phase
- sharing of lessons learned, such as EMARS(3) and the ARIA Database(4) for the prevention phase, and of research results through research framework programmes, being CORDIS(5) an example for the prevention and preparedness phases;
- joint training and EU coordinated emergency response through the Union Civil Protection Knowledge Network(6) for the preparedness and response phases.

(2) https://ec.europa.eu/regional_policy/en/policy/cooperation/macro-regional-strategies/
(3) https://emars.jrc.ec.europa.eu
(4) https://www.aria.developpement-durable.gouv.fr/the-barpi/the-aria-database/?lang=en
(5) https://cordis.europa.eu/
(6) https://ec.europa.eu/echo/what/civil-protection/experts-training-and-exchange_en

Regional cooperation or cooperation around shared or common risks enables better preparedness for disasters through the sharing of experiences, approaches and resources. Partnerships can also be formed outside existing EU frameworks; for example, in 1992, countries around the Baltic Sea established together the Council of the Baltic Sea States, which is a regional intergovernmental organisation working on safety, security and sustainability, active in the area of civil protection and emergency response.

Over the last decade there has been a worldwide boom in public–private partnerships (PPPs), aimed at improving emergency/disaster risk management and the resilience of essential services provided by critical infrastructure systems. PPPs have become increasingly recognised among both practitioners and scholars as an integral part of strengthening resilience (Busch and Givens, 2013), bringing together stakeholders to share knowledge and best practices geared to effectively carrying out DRM (Kapucu, 2006; UNISDR, 2012). An in-depth study of seven successful PPPs identified five common characteristics (Trucco and Petrenj, 2017):

1. a continuous improvement strategy;
2. enhancement of information sharing between the public and private stakeholders;
3. the importance of working together before, during and after an event;
4. the important prevention activity of understanding/modelling risks and vulnerabilities; and
5. using exercises as the most common practice to enhance awareness and trust and to build an interorganisational collaboration culture between public and private stakeholders.

An example of a successful temporary PPP in the aftermath of the Toulouse disaster is briefly portrayed in Table 2. There are various guidelines on setting up a public–private partnership (see UNISDR and ADPC, 2007; UNICRI, 2010; ENISA, 2011; TISP, 2011).

Partnerships are also important between governance levels. Examples are Swedish local police working with three regional authorities (see Table 4); Member States working together with the EU (see Tables 2, 3 and 4); and local public and private sectors working together with the French government at the national level (see Table 2). Furthermore, the analysis of the role of norms that shape informal and formal agreements, is fundamental in a partnership and is a social phenomenon that spreads among partners through communication (Fazio, 1990; Kincaid, 2004).

Communication structures are practical guidance frameworks geared to assist partners to hold constructive discussions, manage conflicts and make decisions. Open discussions allow partners to share and gain knowledge together, resulting in the development of effective coalitions. Such a trust-building approach (see Section 3) results in empowering partners to take ownership and share responsibilities. Evidence of this can be observed after the Toulouse accident (see Table 2).

5 Case studies

Disaster case studies help us better understand failures in risk governance and communication processes. They are also an opportunity to learn; to follow up on actions taken after insights and knowledge are gained; and to transfer these to more generic concerns, to other sectors and to other levels of governance.

This section briefly describes three case studies: the Toulouse ammonium nitrate disaster, the L'Aquila earthquake and the Swedish forest fires. Table 1 summarises key points related to the three case studies below.

Table 1. *Summary of selected case studies* ***Source:*** *Authors.*

Date	Hazard type	Location	Damages	Degree of domino effect	Reason to show
21-set-01	Industrial installation explosion	AZF fertilizer plant, Toulouse, France	31 deaths and 10 000 injured 27 000 houses and flats destroyed EUR 1.5 million to EUR 2.5 million of damages (Barthélémy et al., 2001; ARIA, 2007; Dechy and Mouilleau, 2004; Dechy et al., 2004, 2005; Lenoble and Durand, 2011; Merad and Trump, 2018)	High potential. Although no notable domino effect took place, consequences could have been much worse due to the many chemical storage tanks nearby (ARIA, 2007)	Good example where lessons learned changed legislation at national and EU levels
06-apr-09	Earthquake with aspects of natural disaster triggering technological disaster	L'Aquila, Italy	309 deaths and 67 000 displaced 100 000 buildings destroyed	High. Earthquake disrupted critical infrastructures: industrial, electric, water, waste, etc. (Kongar et al., 2015)	Good example of failure in risk governance with high potential for improvement
May to July 2018	Forest fires	Across Sweden	1 death Several hundreds of people evacuated from home 25 000 hectares of forest burnt Forest owners suffered the most severe losses (Myndigheten för samhällsskydd och beredskap, 2018)	High potential. There was concern that forest fires could affect electricity networks (OECD, 2019)	Good practice at EU level and climate change effect on forest fire management

2.1 Toulouse ammonium nitrate disaster, France (2001)

On 21 September 2001, a disaster occurred in a fertiliser plant (AZote Fertilisant -AZF) situated 3 km from the town centre of Toulouse, France, due to an explosion of off-specification ammonium nitrate. The explosion led to significant damage (see Table 1). A series of inquiries provided findings and lessons learned; however, liability has not been assigned, as findings of direct causes are still being challenged. The accident scenario was not included in the Seveso plant safety case report, because of poor understanding of chemical properties among stakeholders. The fertiliser industry supported worst-case scenarios based on a fire rather than an explosion. There were deficiencies in regulations related to urban planning control. Historical co-development of industries and cities (a sevenfold increase in Toulouse's population in the 20th century) caused increased potential for exposure. Since the 1980s, efforts to reduce risks by land use planning had not been enforced retroactively for The inhabitants and workers were not involved in the negotiations between plants and regulators.

Lessons learned showed that the explosion resulted from several failures in risk assessment, management, governance, control and regulation. After the event, several regulation changes occurred in France (Dechy and Mouilleau, 2004; Dechy et al., 2004, 2005; Salvi et al., 2005; Merad et al., 2008; Taveau, 2010; Lenoble and Durand, 2011; Dechy et al., 2018), which also had ripple effects across Europe, especially regarding improved land use planning (Cozzani et al., 2006) and governance with stakeholder involvement. In addition, AZF raised a existing houses. concern about the safe storage of ammonium-nitrate-based fertilisers in manufacturing plants. In fact, changes were also inserted into the proposed directive relating to fertilisers (EU, 2003). In particular, a detonation test was made mandatory for ammonium nitrate fertiliser (straight or compound ([7]) with a high (28 %) nitrogen content (Marlair and Kordek, 2005). Table 2 provides a summary of examples of good practice, the corresponding governance level and the related disaster risk management phase. The management gaps identified were an oversimplified interpretation of the Seveso II Directive (EU, 2012), resulting in lax land use management planning; inadequate risk assessment methodology implementation; and inadequate investment of resources for inspections (OECD, 2003

Table 2**. Examples of good practice resulting from Toulouse accident.* ***Source: *Authors.*

Risk communication and/or participatory process good practice evidence	Governance level outreach	Disaster risk management phase showcased
Governance, risk perception, complexity (Section 2)		
The disaster enhanced multiple debates in French society and amongst decision-makers, resulting in a law that changed to increase local stakeholders' involvement in co-designing French technological risk prevention strategies and measures (Salvi et al., 2005); develop specific tools to address the complexity of technological risk prevention; clarify procedure to determine safety distances for land use planning; provide new methodlogy for modelling worst case scenarios, shifting from deterministic to semi-probabilistic approach when carrying out risk assessment (Lenoble and Durand, 2011; INERIS, 2019).	National	Prevention
The EU legislative amendment process of Seveso II Directive was delayed by the European Parliament to include lessons learned from the Toulouse accident. In particular, storage control was reinforced together with technical measures on land use planning regarding buildings and transport routes, and disclosure of operator and establishment information. The amendment to the Seveso II Directive finally entered into force on 16 December 2003. The rules on land use planning and operator and establishment information were changed throughout Europe (Vierendeels et al., 2011).	EU	Prevention
Trust-building & lessons learning processes (Section 3)		
Law No 2003-699 established local committees for information and dialogue (CLICs) , thus involving local stakeholders in the risk prevention decision-making process. The law also fosters CLIC participation in drawing up and implementing technological risk prevention plans, which allows them to be part of the urban planning process related to hazardous plants, promoting the creation of a risk culture (Salvi et al., 2005; Merad et al., 2008, Merad and Dechy, 2011).	Local	Prevention & preparedness
The amendment of Seveso II resulted from a participative process. A specific workshop was organised by the Joint Research Centre on ammonium nitrate (30 January to 1 February 2002), where Member States, industry, specialists from research organisations and the European Commission came together (Wood and Mitchison, 2002). The outcomes of the workshop contributed to developing amendment proposals addressing lessons learned from those two accidents (European Commission, 2003). In addition, findings and recommendations of Seveso technical working groups were reported to the Committee of Competent Authorities and the Council working groups (Vierendeels et al., 2011).	EU	Prevention & preparedness
Forming and managing partnerships (Section 4)		
After the Toulouse accident, the French National Institute for Industrial Environment and Risks provided scientific and technical support to decision-makers within the participative process of engaging with public and private sectors to co-design the evolution of the French technological risk prevention strategies and measures (Salvi et al., 2005).	National & local	Prevention & preparedness

(7) Straight fertilisers supply only one primary plant nutrients, i.e. nitrogen (N) or phosphorus (P) or potassium (K). Compound fertilisers contain

2.2 L'Aquila earthquake, Italy (2009)

In March 2009, L'Aquila experienced over 100 tremors (Imperiale and Vanclay, 2018). Local tradition and inaccurate predictions (using radon gas emissions) of a bigger earthquake by a local technician unsettled the inhabitants. On 31 March 2009, a meeting of the Major Risks Commission (civil protection expert advisory body) took place. The meeting conclusions stated that 'There is no reason to say that a sequence of small magnitude events can be considered a predictor of a strong event'. However, a civil defence official communicated that 'The scientific community tells us there is no danger, because there is an ongoing discharge of energy. The situation looks favourable.' This inadequate message resulted in the downgrading of the earthquake from a low-probability event to a no-probability event. The L'Aquila earthquake occurred in the early morning of 6 April with a moment magnitude (Mw) of 6.3, followed by a 6-month period of smaller-magnitude events (see also Table 1). Subsequently, a series of high-profile court cases against both the scientists and civil defence officials led to extensive debates on risk mismanagement, motivation of the key actors involved, and accusations of false reassurances and manslaughter.

Table 3. *Examples of good practice resulting from L'Aquila earthquake.* ***Source:*** *Authors.*

Risk communication and/or participatory process good practice evidence	Governance level outreach	Disaster risk management phase showcased
Governance, risk perception, complexity (Section 2)		
The earthquake and subsequent trials led to substantial and ongoing reflection on the role of scientists and officials in disaster risk management, and particularly in communication. Communication and management tools for high levels of uncertainty are also important. These could include alert levels and advice on preparedness and temporary evacuation. It has also led to calls for a national-level response to enhance local-level work, to ensure that civil protection teams have adequate resources to protect people and are not pressurised into false reassurances. Resources to ensure that seismic codes are upheld are also important and need to be driven at the national level.	National	Prevention
A challenge from the earthquake and trials is that experts may be afraid to provide scientific advice under high levels of uncertainty, particularly where the consequences of the event might be severe. The 2019 Science Advice for Policy by European Academies report to the European Commission on 'Making sense of science for policy under conditions of complexity and uncertainty' concludes that scientists do need to be sensitive to various biases and interests in the request for and provision of advice, and that values and conventions also affect advice. Furthermore, citizens and stakeholders should contribute to the process. Many of these conclusions would have ensured a very different outcome in 2009 (SAPEA, 2019).	EU	Prevention
Trust-building & lessons learning processes (Section 3)		
The committee meeting before the earthquake was closed to the public and the resutls were relayed to the public by an official, rather than explained by the scientists themselves. The scientist did not then correct the miscommunication, but were initially trusted because of their seniority. This attempt at a strategic approach (taking science as informing the policy that the officials wanted) backfired because it was motivated by a desire to reassure citizens rather than to represent the uncertainty coherently and trust the public to manage it. In addition, vulnerability was completely ignored at L'Aquila – all the focus was on hazard, rather than managing the structural problems that meant that seismic codes were not adhered to, local knowledge was not understood and people were not adequately supported.	Local	Prevention & preparedness

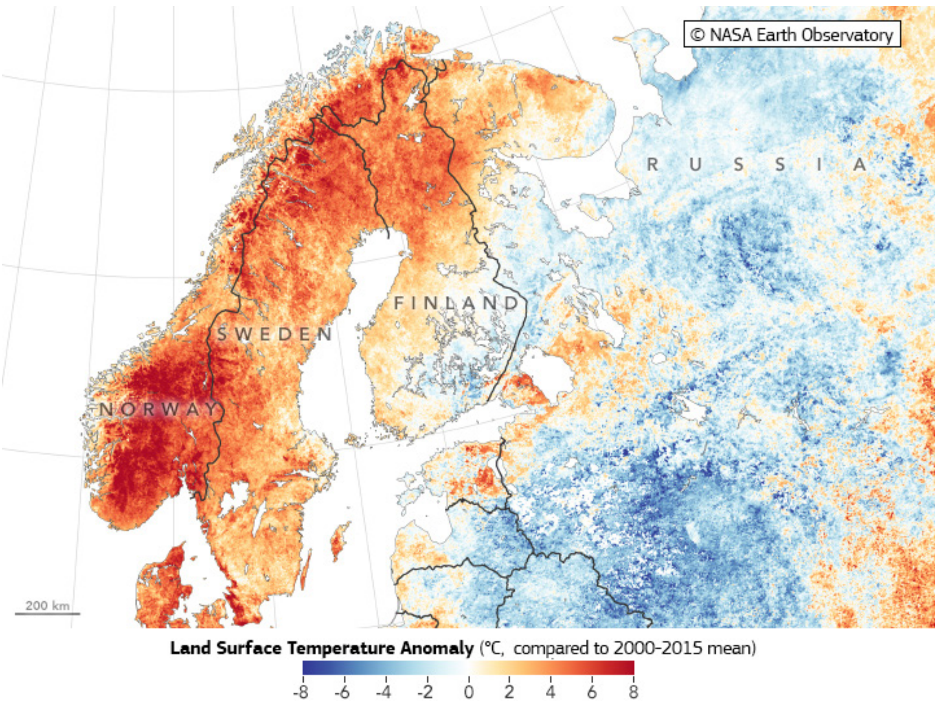
Lessons learned from this event include the following: natural and social scientists need to work together in communicating risk and in understanding social dynamics in situations of anxiety and unrest; holistic preparation (e.g. seismic building code enforcement) should be enforced; local knowledge should be considered alongside scientific knowledge; and one needs to be aware of dangers related to politically motivated risk communication (Alexander, 2010; Scolobig et al., 2014; Donovan and Oppenheimer, 2012; Benessia and De Marchi, 2017). Table 3 gives evidences of good practice, the corresponding governance level and the related disaster risk management phase. The management gaps identified were in the recovery phase: focus on finding a quick housing problem solution resulting in inadequate spatial planning for siting new settlements; poor coordination between government agencies and community networks; and incompetent change management implementation resulting in a missed opportunity to make L'Aquila more resilient (Contreras et al., 2017).

2.3 Forest fires, Sweden (2018)

In 2018, an exceptionally long heatwave (see Figure 3) exacerbated the burning of a total of 25 000 hectares of forest in Sweden, 10 times the annual figure. Three of the biggest fires, resulting in about 7 000 firefighting operations, were caused by human activities and lightning strikes (Myndigheten för samhällsskydd och beredskap, 2018). There were no casualties; in some areas people were evacuated while in others they were asked to close their windows against the smoke.

Lessons learned have been very useful in preparing for the 2019 wildfires and in confirming the need for knowledge for forest management to prevent fire in the context of climate change (Sandahl, 2019; Wickberg, 2019).

Figure 3. *Land surface temperature anomaly in Nordic countries (1-15 July 2018).*
Source: *NASA Earth Observatory, 2018*



They have also inspired the design of a Horizon 2020 knowledge transfer project, PyroLife ([8]), that aims to raise further awareness on the need to change management paradigms from fire resistance to landscape resilience. In addition, the use of information systems with alerts through the telecommunications network and support from other European countries to counter large-scale disasters has been effective (see also Table 4). Management gaps identified by a government report were a slow and overcautious reaction to fires, poor risk assessment, poor training of volunteers and the delayed deployment of helicopters (Engberg, 2019).

(8) https://cordis.europa.eu/project/id/860787

Table 4. *Evidences of good practice resulting from the Swedish forest.* ***Source:*** *Authors.*

Risk communication and/or participatory process good practice evidence	Governance level outreach	Disaster risk management phase showcased
Governance, risk perception, complexity (Section 2)		
The earthquake and subsequent trials led to substantial and ongoing reflection on the role of scientists and officials in disaster risk management, and particularly in communication. Communication and management tools for high levels of uncertainty are also important. These could include alert levels and advice on preparedness and temporary evacuation. It has also led to calls for a national-level response to enhance local-level work, to ensure that civil protection teams have adequate resources to protect people and are not pressurised into false reassurances. Resources to ensure that seismic codes are upheld are also important and need to be driven at the national level.	National	Prevention
A challenge from the earthquake and trials is that experts may be afraid to provide scientific advice under high levels of uncertainty, particularly where the consequences of the event might be severe. The 2019 Science Advice for Policy by European Academies report to the European Commission on 'Making sense of science for policy under conditions of complexity and uncertainty' concludes that scientists do need to be sensitive to various biases and interests in the request for and provision of advice, and that values and conventions also affect advice. Furthermore, citizens and stakeholders should contribute to the process. Many of these conclusions would have ensured a very different outcome in 2009 (SAPEA, 2019).	EU	Prevention
Trust-building & lessons learning processes (Section 3)		
The committee meeting before the earthquake was closed to the public and the resutls were relayed to the public by an official, rather than explained by the scientists themselves. The scientist did not then correct the miscommunication, but were initially trusted because of their seniority. This attempt at a strategic approach (taking science as informing the policy that the officials wanted) backfired because it was motivated by a desire to reassure citizens rather than to represent the uncertainty coherently and trust the public to manage it. In addition, vulnerability was completely ignored at L'Aquila – all the focus was on hazard, rather than managing the structural problems that meant that seismic codes were not adhered to, local knowledge was not understood and people were not adequately supported.	Local	Prevention & preparedness

6 Conclusions and key messages

It is vital to clarify risk and uncertainty communication objectives, along with roles and responsibilities before, during and after a crisis. Ad hoc committees should be set up, already prepared for when a crisis disrupts the stakeholders' lives, as should public–private partnerships. Stakeholders should already have an action plan and related checklist. Dedicated information exchange should already be up and running to provide a continuous basis for information and experience exchanges, along with enhancing a learning culture.

Building trusted partnerships in disaster risk management should enhance multidisciplinary continuous collaboration, timely actions and interventions, embedding synergies between stakeholders especially across risk domains and silos, sectors and territories in networks. These networks foster information exchange, increase operational effectiveness and share the financial burden of the development, identification, promotion and exchange of best practices, education and training, while raising awareness in the area of disaster risk governance and communication.

Policymakers

Disaster risk governance entails having a clear vision, systematic plans, competence, guidance and coordination across different sectors, as well as participation of relevant stakeholders at all governance levels. It should demonstrate social benefits and enhance legitimacy; have a clear approach on effective risk and uncertainty communication, inclusive of all stakeholders with respect to diversity and insularity of sectors, and be carried out across governance levels and during the entire disaster risk management cycle (see Figure 2). Risk messages should be renewed accordingly in line with changing actors, evolving risks and governance changes. Clear role designation and recognition of value are essential while respecting multiple stakeholders' responsibilities, multiple audiences' involvement and appropriate reflection time.

Practitioners

Disaster case studies are key to better understanding failures in risk governance and communication processes. Several disasters and recent crises described in this subchapter remind us that being aware and understanding the possible impact of the words, numbers and figures used to communicate certainties, effects, probabilities and uncertainties to different audiences, comprising policymakers, scientists, practitioners and citizens, is also a key to trust building.

Scientists

Risk communication should offer insights into interconnected processes, highlighting the importance of stakeholder inclusiveness; trust building and mutual learning; forming and managing partnerships with a long-term perspective; and fostering a resilient society through norms and communication structures.

Citizens

Active involvement of citizens is crucial. Members of the public should be part of ad hoc groups at various levels. There is a need to develop a citizens' education and awareness process so that citizens will quickly follow mitigation measures imposed for safety (Bruinen de Bruin et al., 2020).

In some ways, society is still not well prepared in coping with disasters. The current COVID-19 outbreak is witness to this unpreparedness. Many countries worldwide were caught off guard by this event. DRM should continue its evolutionary path towards a more anticipatory and resilience-driven culture, systematically embedding the full DRM cycle, ensuring effective interconnections between actors and processes. As part of this, risk communication strategies should evolve accordingly, focusing on geographical alignment and based on multilevel governance. The aftermath of every event remains a great opportunity to redesign and upgrade strategies incorporating lessons learned, including foresight activities for early warning, also taking stock of new communication technologies that involve the public in this process, whose inclusion will allow better customisation of risk and uncertainty messages, increase awareness and trust, and improve resilience and foresight capability in DRM.

4.2 Citizen participation and public awareness

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Claassen, L., Sapountzaki, K., Scolobig, A., Perko, T., Górski, S., Kaźmierczak, D., Anson, S., Carnelli, F., Bossu, R., Sousa Oliveira, C., Laurikainen, H., 'Citizen participation and public awareness', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Why citizens need to participate in disaster risk management

Over the past few decades, decision-making in disaster risk management (DRM) has witnessed a transition from a predominantly top-down, command and control style of management to the encouragement of citizen participation. Already in 1992, the Rio Declaration (UN, 1992) called for civic society participation in decisions about the environment based on the assumption that involving citizens and including their perspectives in risk decisions empowers them, raises awareness, and encourages preparedness, ownership and responsibility. In addition, citizen engagement may be employed to better anticipate social conflicts, overcome decision deadlocks, improve the policy effectiveness, credibility and legitimacy of projects, avoid delays in the implementation of decisions and increase decision acceptance (Fiorino, 1990; De Marchi, 2003, 2015; Rosenberg, 2007; Ryfe, 2005; Renn, 2008; Reed, 2008; Smith, 2009)

New policies and regulations have been set up at the national, regional and local levels in several EU member states. Examples include the strategic national framework on community resilience([1]) in the United Kingdom, the 'Room for the river' programme in the Netherlands([2]) and household adaptation measures in Germany([3]). In the implementation of policies, participation may come in several forms such as engagement in formal decision-making processes, in campaigns for increasing risk awareness and preparedness, or in consultative public hearings, forums and deliberative processes. Opportunities for citizen participation are also emerging thanks to new and affordable (consumer) technologies; for example, with the help of social media, crowdsourced, self-organised approaches to disaster relief and risk reduction can be fast and effective.

2 Citizen participation; concepts and context

To build more resilient communities, we need bottom-up approaches in which the public is actually involved in risk assessment, preparedness measures, emergency plans etc. at all levels of disaster risk management.

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The participation of stakeholders in DRM is a prerequisite of resilient communities. Such communities have the knowledge and ability to prevent, forecast, prepare for, resist, reduce, accommodate, adapt to, transform and recover from the impact of an event in a timely and efficient manner (Paton and Johnston, 2017). However, stakeholders are a very dynamic, diverse group, differing in the ways and times in which they are affected, and the magnitude of the impacts. This diversity can generate conflicts in decisions about DRM. Disagreements about e.g. ´what solution to adopt to reduce risk´ may become problematic for practitioners who have to implement decisions in the short term, under the pressure of hazards increasing in frequency and severity (EEA, 2017). Although DRM can be improved by the participation of stakeholders of all sectors, in this subchapter we specifically focus on the participation of citizens.

Within DRM, the terms 'citizens', 'the public', community' and 'stakeholders' in combination with 'involvement', 'engagement', 'participation', 'empowerment' and 'resilience' are often used seemingly interchangeably. While these combinations are all generally used to indicate a process through which citizens contribute to risk management, they have distinct meanings and convey different insights into the process they seek to describe (Rowe and Frewer, 2005).

([1]) www.Resiliencefirst.org
([2]) www.ruimtevoorderivier.nl
([3]) www.umweltbundesamt.de

Here, we use the term 'citizens' in a rather broad sense, as members of the entire potentially affected population or community. In this sense, citizens include students, tourists and others. As citizens have a personal interest in the outcomes of policy decisions, they are also stakeholders in DRM. Other stakeholders are media, businesses, community or civil society organisations, interest groups and (local) government representatives.

Citizen participation is the process in which citizens are involved in the decision-making that affects them. The frequency, purpose, and depth of participation can vary widely (see Figure 1).

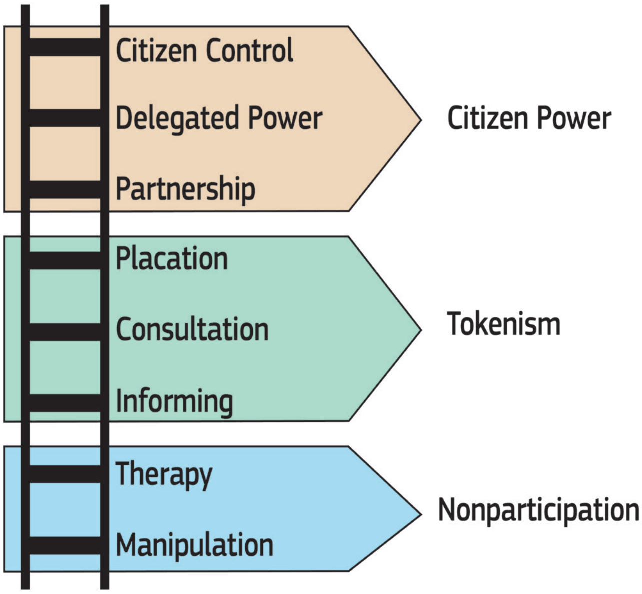


***Figure 1**: The Participation Ladder*
***Source**: Authors based on Arnstein, 1969.*

The metaphor of a ladder is used to represent interactions differing in the degree of participation. At the bottom of the ladder are the interactions between individuals and policy makers in which citizens are manipulated into thinking that public participation is in progress rather than giving them an actual say in procedures.

Tokenism in the middle of the ladder represent interactions in which citizens are consulted and have a (symbolic) voice in the policy process, but no actual means to influence policy. Actual participation only occurs in the interactions at the top of the ladder.

2.1 The institutional context

In the second half of the 20th century, many European countries institutionalised the processes and practices of disaster management (Fiorino, 1990; Coppola, 2006). Within the institutions, which were provided with intellectual, financial and technical resources, the focus was initially on characterising risk by better understanding the probabilities and consequences of hazards and on the systematisation of management processes and practices. It was typically based on technical capacities and expertise, with a centralised and hierarchical model. Under this traditional top-down approach, responsibility rested almost exclusively on organisational shoulders and the public was perceived as a passive receiver of technical information on risk assessment, preparedness measures, emergency plans, etc. (restricted to the lower bars of the participation ladder).

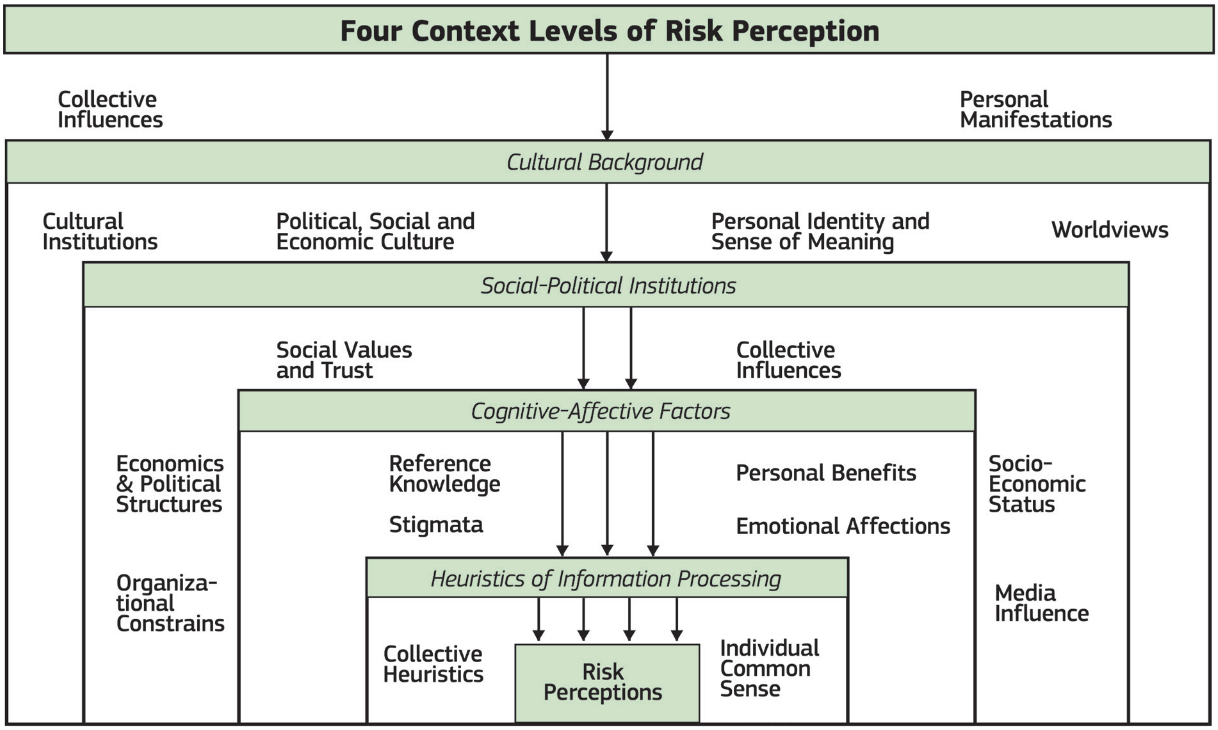
Since the development of DRM, the focus has moved towards more integrated, inclusive, bottom-up approaches in research, education and policymaking, shifting (some) of the responsibilities for DRM to citizens and the community at large. United Nations programmes and world conferences on disaster reduction contributed greatly to dissemination of knowledge and implementation of policies with their publications and campaigns (UNISDR, 2005, 2015). Within the EU, an integrated (disaster) risk management system has been established, with cooperating but autonomously operating offices. These offices share their expertise with authorities, and finance advisory missions in areas that are prone to disaster. Policy developments with respect to climate change (e.g. on mitigation and adaptation) have also contributed to raising awareness. A global network of humanitarian organisations and non-governmental organisations (NGOs), such as the Red Cross and Greenpeace, have sparked actions to empower citizens and communities around the world and facilitated the exchange and dissemination of relevant educational, awareness-raising and technical materials. The World Bank attracted funds to set up a global facility for disaster reduction and recovery, providing guidance and financial resources to support projects by governments, private-sector institutions and NGOs. Associations working for the private sector, local governments, unions, churches, and civil movements and initiatives (e.g. climate activists) have developed specific networks and undertaken activities to promote and facilitate DRM with their own members. It is important to recognise that these developments were assisted, albeit unfortunately, by the occurrence of highly visible disaster events raising public awareness.

2.2 Determinants of public awareness and preparedness

It is important for citizens, groups and communities to be aware of risks and prioritise them, because that activates responses to mitigate or prepare for certain prioritised risks and determines the amount of resources and effort people are willing to contribute. However, they may also translate into lack of action on non-prioritised risk, e.g. when risks are perceived as acceptable. Risk perception research in the domain of disaster risks has shown that the disaster risk awareness and preparedness of potentially affected citizens, groups and communities do not only depend on the likelihood and potential consequences of a hazard.

Various sociocognitive/cultural models to explain individual risk perceptions have been suggested (e.g. Kahnemann and Tversky, 1979; Slovic 1987, 2000; Kasperson et al., 1988; Thompson, 1990; Pidgeon et al., 2003). These models, grounded in disciplines such as psychology, anthropology or sociology, regard several important personal and interpersonal factors that influence risk perceptions as relevant, including systematic and heuristic biases in information processing, affective responses, knowledge and personal benefits, perceived controllability, trust in institutions, media attention, cultural views and institutions (see Figure 2).

Figure 2: *Factors influencing the public's awareness of disaster risk.* ***Source****: Renn and Rohrmann, 2000.*



While there is a robust body of knowledge explaining people's risk perception, there are limited insights and experimental evidence concerning effective communication, preparedness and engagement strategies to motivate different people and social groups to prepare for catastrophes (Weyrich et al., 2020). See Box 1 as an example.

BOX 1

Good practice example: Flood risk management in Stroud, South West England

Stroud in South West England is located in a lowland landscape in which the River Frome flows. This area was strongly hit by the 2007 floods. Widespread flooding occurred after sustained periods of rainfall and subsequent increased groundwater levels/flow causing increased baseflow combined with increased runoff response from land areas. Following this, a 3-year project called Rural Sustainable Drainage System, led by the local government, was carried out in 2014.

Working with NGOs, landowners and farmers, many successful interventions were initiated by reaching consensus, defining how to best implement the mitigation scheme and building the works. During this process, the different actors assessed, characterised, evaluated and managed risk. They were all bearers of different kinds of knowledge, which interacted at the local level, driven by relationships among actors and between actors and water catchments. In terms of lesson learned, this case points to how considering local knowledge in risk management can act on risk awareness. Flood risk management was developed by walking, talking, doing and flooding: the flowing of water turned into a socio-political element of risk governance by enhancing or weakening the relationships among the different actors.

3 Approaches to involve citizens in disaster risk management

We should involve citizens by consulting and empowering them to participate in the decision making process, and by tailoring management systems to their needs

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There are three essential pathways to involve the community in DRM:

- Consult community representatives to complement scientific knowledge with the knowledge and practices that exist within the community and to establish partnerships during the development of strategies and regulations, local plans and projects, assigning roles and tasks. Direct feedback about local needs and capabilities also helps to align the national strategies with the actual needs of a community.

- Empower citizens within the community, raising public awareness, educating people about the risk and providing them with the tools, skills, motivation and confidence to participate and to maintain involvement. This is especially needed for marginalised and vulnerable groups (e.g. poor, disabled, illiterate and elderly people and ethnic minorities), as unequal power relations, and lack of information, access to resources, awareness of rights, opportunity and capacity, constrain the motivation and ability to participate or hold decision-makers to account.

- Tailor disaster risk management systems to the needs of users. This means investing in people-centred, simple and low-cost, multi-hazard, multi-sector, multi-channel hazard-monitoring telecommunication and warning systems, risk communication mechanisms and social technologies through a participatory process.

The efficient involvement of citizens requires a mix of considerations depending on the setting and phase (before or after the hazard materialises) (Box 2). Many of the threats generated by natural forces and human influences are unpredictable, complex and not only co-occurring but permeating (e.g. an earthquake threat in a densely populated area with poor housing). The severity can range from imperceptible to crushing and the scope can extend from personal through local, regional, national and global to cosmic. Feasible and effective risk management requires collective resources and the cooperation of governmental and non-governmental institutions, communities and individual citizens on all administrative levels throughout the full DRM cycle.

BOX 2

Good practice example: 'building back better' after the Faial Earthquake in Azores (1998)

In 1998, an earthquake took place, accompanied with hurricanes, large sea waves, heavy rains and landslides, causing tremendous impacts on housing, school buildings, lifelines and monumental structures on the islands of Faial and Pico (Zonno et al., 2009; Oliveira et al., 2011). During the reconstruction process, a huge effort was made to 'build back better'(UNISDR, 2015, p23): analyse the building stock (building by building) and provide building advice, such as the use of wire mesh to enclose poor-quality masonry walls and not replacing old timber floors by heavy reinforced concrete floors. New rules for urban planning were also implemented (e.g. avoid fault traces and proximity to cliffs). Public sessions were organised to involve citizens in the whole process, discussing solutions with technicians and eventually influencing final solutions. The media (local newspapers) took a very important role criticising when the works did not progress more rapidly. The creation of an office for the population to communicate their worries was also very effective in resolving many conflicts. Although at the end of the reconstruction phase citizens became more reluctant to accept some of the recommendations (e.g. to keep the wooden floors), the reconstruction was achieved at relatively low cost for citizens and with considerable support from them.

risk reduction (including policy areas such as environmental management, land use planning and building codes). However, they also present several challenges. Besides the need to guarantee the minimum ethical standards of informative, open, inclusive and collaborative processes, a critical issue is whether or not citizens really want to participate, to be more empowered and to share more responsibility with local authorities. Some research findings indicate that residents often do not feel involved in the process of DRM, do not adopt precautionary measures to protect their households and prefer to maintain top-down models of responsibility (De Marchi et al., 2007; Kuhlicke et al., 2011). Whether this is because individuals do not have the required knowledge or are not willing to take the opportunities they are given by authorities, or because authorities devolve power but can never relinquish it such that individuals become sufficiently empowered, or because of a combination of all three causes, is unclear. Other barriers to effective participation may be related to insufficient time, wrong reciprocal expectations between citizens and local authorities, emergence of conflicts between public and private interests or lack of resources at the local level (Scolobig et al., 2015; Pelling, 2007). In addition, there are challenges to providing an accurate representation of diverse stakeholder perspectives, translating qualitative information into technical quantitative options, using new technologies for stakeholder engagement or accounting for stakeholders' opposing views in pursuit of a compromise solution (e.g. stakeholders may question expert risk assessments or oppose the implementation of measures) (Preuner et al., 2017).

Command, control and coordination of risk information flows embrace technical, spatial and social layers in every local, regional and global system at the same time. Interpersonal communication is performed through dynamic and non-hierarchical network structures and triggered by advanced and decreasing costs of information and communication technology tools and consumer technology. Information and communication technology tools are also increasingly used for scientific purposes in citizen science initiatives, which aim to generate societal transformation through the increased risk awareness of the participants.

3.1 Functions of citizen participation

he participation of citizens in the process of DRM should take place in all its phases; in particular, in two-way information flows. As citizens are at the core of social, economic and political life, crisis situations should not limit their role to being the powerless subjects of rescue operations.

Thanks to the wide availability of the information and affordable technology, citizen involvement is available for any interested member of the community (real or virtual) manifesting itself in the functions of monitoring and detecting hazards, the dissemination of information and raising the alarm. Citizens may also participate in operations and planning aimed at executing or preparing for preventative measures, protective actions and rescue operations, and at mitigating its consequences and contribute to ensuring the continuity of DRM. And, finally, citizens should be involved in education aimed at individuals, local communities and NGOs, which are vital stakeholders in the DRM process. Education covers the transfer of knowledge and experience gained during emergencies (lessons learned), and the development and maintenance of social skills and competences in order to support the desired behaviour in crisis situations.

These functions can be exercised throughout the process by consulting and working closely with individuals, local communities and volunteers. For example, in Poland, voluntary fire brigades cooperating with the state fire service and other rescue organisations, as well as local authorities, also undertake prevention measures by informing and educating local communities about a broad spectrum of hazards and environmental protection to build social resilience against natural and human-made threats.

3.2 Risk communication strategies

In the context of natural disasters, the systematic conceptualisation and practice of risk communication started in the 1980s (Kasperson, 2005). Although it was initially used for one-way information flows aimed at raising public awareness (by means of forecasts, warnings and disaster messages), it has since developed as an integral part of every stage of risk assessment, management and reduction. Risk communication in this broader sense is defined as 'the exchange of information with the goal to maintain or improve risk understanding, affect risk perception and/or equip people to act appropriately in response to an identified risk' (US DHS, 2008, p.26). It is not only an essential part of emergency communication but also takes place before and in the aftermath of disasters to learn lessons (OECD, 2016). As such, risk communication may inform policymaking processes, make policy implementation smooth, empower and reassure the public while ensuring a satisfactory awareness level, and build trust in governmental institutions and the information provided by them (Höppner et al., 2012). Consequently, the key requirement today is a shift from a top-down style of risk communication towards dialogue and exchange of information, aiming for a culture of safety where awareness of risk and the adoption of risk-reducing measures are part of daily life (Twigg, 2015).

Risk communication strategies need to meet the following criteria.

- They must be planned autonomously and applied on a ongoing basis.

- They must involve a wide range of actors (e.g. public authorities, scientists, NGOs, international organisations, the media) to take into account a diversity of risk perceptions and vulnerabilities (Box 3). Those leading the process should enjoy public confidence. Whereas communications from an untrusted source heighten fear of hazards and risks (Ropeik, 2009), leading to unwanted effects, people's empowerment and the adoption of two-way communication with agencies promote trust (Eiser et al., 2012). Ideally, people should act simultaneously as both sources and recipients of messages.

BOX 3

Good practice example: clubs for civil protection at schools

Risk education at schools can lead to more accurate risk perceptions and ensures cross-cultural and more inclusive risk communication. Children are believed to be more receptive to environmental ethics and new ideas; students can influence the wider community through their peers and parents (Twigg, 2015). The creation of clubs for civil protection at secondary school level (15–18 years) is one way to reach this age range. This strategy is adopted in Greece, where the Earthquake Planning and Protection Organization has set about training school teachers to raise their awareness and point to ways of teaching pupils about risk issues ([4]).

- They must cover a wide range of hazards and risks (natural forces and human influences, domestic and transboundary, known and anticipated, emerging from cascading effects, etc.), classified into local potential disasters to address the hazards, vulnerabilities and needs of the locality (Cutter et al., 2003). In that sense, all key hazards and threats are listed in the United Kingdom's National Risk Register, which is a public resource for individuals and organisations to be better informed and prepared for emergencies. In Portugal, few councils on the south coast provide provide information to people on beaches during the holiday season on what to do in the few minutes they can get to evacuate in the event of a tsunami warning.

- They must fulfil a wide range of purposes and functions: education and training, inducing behavioural changes, raising confidence in the institutions and management, and public participation in risk-related decisions. In practice, this means a focus on tangible factors rather than uncontrollable threats and on issues that are relevant to the community context, addressing the issues of vulnerability reduction and resilience enhancement within the scope of community development (Paton and Johnston, 2017).

- They must support a sustained communication process using appropriate sources, media/channels, mode and tools of communication in which the content and style of messages are tailored to the cognitive and psychological needs of users. This requires different approaches for minorities, men and women, children

([4]) *http://www.oasp.gr/*

and elderly people, locals and migrants and so on (Khan, 2012). Ideal solutions include sets of media complementing one another – e.g. printed public information including hazard and risk maps, print and broadcast media (newspapers, TV, radio), the internet, films and video, public signs, events and activities, and social media – and mass media messages complemented by interpersonal communication (Box 4).

BOX 4

Good practice examples: support material for communication

- The members of the project Effective Education for Disaster Risk Reduction – Learning Matters have uploaded a video entitled 'How levee wars are making floods worse' (EDU4drr, 2018). The video displays some difficult-to-comprehend issues such as risk perception, risk transfer, risk complexity and risk scale.
- The EU project 'Know your city, reduce seismic risk through non-structural elements' (KnowRISK, 2016) promotes the engagement of school students, citizens and businesses with social and earthquake researchers to disseminate important issues and tools for reducing non-structural seismic damage.

It should be noted that there is no perfect medium, tool or style of communication; the most appropriate are those that the target audience is receptive to (Twigg, 2015). Communication with the poorest, most marginalised and most vulnerable groups is the major challenge because of accessibility barriers such as illiteracy, disability, cultural marginalisation, displacement, physical remoteness, social isolation and lack of access to modern technologies (internet, social media, mobile phones, etc.). The most important channels for these groups are their own social networks.

3.3 Use of social media

Social media are interactive (web-based, computer-assisted) communications between individuals, and organisations consisting of the sharing of text, audio, photographic and video files on (micro)blogs, social networks and forums, and the collaborative creation of documents (using wikis) (Balana, 2012; Alexander, 2014).

In DRM, social media can disseminate warnings and practical interactive information on how to respond (e.g. with public warning systems such as BE-alert in Belgium, NL-alert in the Netherlands and War-Cat in Germany), directly identify disaster-affected individuals' conditions and locations, send and receive requests for help or assistance, monitor what people are thinking and doing, and discuss causes, implications and responsibility for events (Box 5). In many disasters, the first responders are the citizens who employ their social networks through social media to create social cohesion and mobilise social capital in the form of skills, volunteering, appeals for financial donations and crowdsourcing.

Moreover, the more they are used, the more popular they become, encouraging users to contribute to them. This can help to detect disasters, inform risk assessment, improve reactions to events, better tailor communications to the needs of the affected individuals and the general public, raise awareness, and improve preparedness and participation in policy decisions.

Many factors currently hinder the effective incorporation of social media in risk and emergency management practices. Warning systems, for example, can disseminate useful information, but citizens and stakeholders need to know what to do and have a clear idea of possible threats that are missed by the system. Often,

BOX 5

Good practice example: LastQuake

LastQuake is a simple, affordable multichannel rapid information system that may contribute to immediate global seismic risk reduction. It offers timely, geotargeted information (e.g. safety checks and safety tips to describe behaviours to be encouraged or avoided after violent tremors) in regions where an earthquake is felt. It is based on internet technologies and social media (websites, Twitter, a quakebot using the messaging app Telegram, and a smartphone app) providing rapid tremor detection (between a few tens of seconds and a couple of minutes), derived from the analysis of indirect information, i.e. internet and social media searches by eyewitnesses eager to find out the cause of the tremor. It also collects eyewitnesses' information about the degree of shaking being felt and possible damage incurred. The data from eyewitnesses using the LastQuake website([5]) or app are comparable to real-time seismic sensors. These data are fed back into the ongoing information product, which, in turn, attracts more eyewitnesses through a viral spread (Bossu et al., 2018).

an overwhelming amount of information but also allow the exchange of conflicting, inaccurate and potential harmful information, and it can be difficult to evaluate the credibility and validity of the content (Goolsby, 2010; Kaplan and Haenlein, 2010). It should also be noted that, although false information is often rapidly corrected by knowledgeable people, in many cases experts and authorities are also partly responsible for the confusion by asserting contradicting viewpoints. Moreover, potential ethical dilemmas, such as breaches of privacy, lack of informed consent, social vulnerability because of the digital divide, and the possibility of misuse by commercial entities interested in surveillance (see Maxmen, 2019), can discourage agencies from fully exploring the potential of social media.

Despite the challenges, incorporation of social media into pre-existing emergency management and risk reduction systems is inevitable. Public officials need to consider how to align them with peer-to-peer information exchange and to develop new conceptualisations of the information production and dissemination functions for disaster response. In doing this, they also need to coordinate with the large tech companies to deal with uncertainties, probabilities, privacy and partial information.

Practitioners working in institutions such as civil protection services and emergency warning systems should develop efficient strategies for adapting to the changing reality of social media and the emerging use of consumer technology by investing in simple and low-cost, people-centred technology but also ensuring that they have robust plans to tackle any ethical dilemmas that social media and technology usage may produce in the future.

Scientists play an important role in requiring a better understanding of the determinants public awareness and preparedness. However, more (participatory) research is needed on effective communication, preparedness and engagement strategies to motivate different people and social groups.

As for citizens themselves, they need to become more aware that they are not merely passive subjects in DRM, they share the responsibility for building resilient communities and timely responses, by taking part in policy making, preparing for potential disasters, improve disaster response by employing their social networks, and learn from adversity by building back better.

([5]) *www.emsc-csem.org/#2*

4 Case study: community resilience case in a rural area – power outages in Kainuu, Finland

As a result of climate change, the average temperature in Finland is rising (Ruosteenoja et al., 2016). In particular, the snow loads on tree crowns are projected to increase (Lehtonen et al., 2016), causing power cuts when trees fall on power lines. Rural areas have also faced depopulation and an increase in the proportion of ageing inhabitants, thus becoming more vulnerable to disruptions. For example, it is a challenge to recruit new members to voluntary fire brigades, the key organisations providing emergency services in rural areas.

In 2013, the Finnish National Rescue Association initiated the regional programme Our Safe Village in collaboration with local village associations and local fire departments to strengthen inhabitants' preparedness and safety skills. It provides safety training in collaboration with a local fire department and produces local safety plans describing risk assessment and mitigation tasks in collaboration with inhabitants.

By the turn of 2017–2018, many villages in the sparsely populated region of Kainuu had taken part in the programme. This proved to be useful when a major disruption occurred because of heavy snowfall, causing trees to fall on power lines, and approximately 6 000 households were without power supply, some for up to 5 days. A survey carried out after the event showed that most households seemed prepared for power outages; houses were kept warm by using fires, and inhabitants had stored food and other supplies.

Around half of the respondents had received help from, or given help to, relatives or neighbours during the disruption. Aid provided by local communities exceeded the support received from the rescue services, which underlines the importance of social networks and willingness to help in the villages. More than half of respondents reported that levels of trust in neighbours and also in authorities, especially the fire department, had increased owing to the experience of disruption.

In the future, Safe Village programmes could include more detailed action plans on how to distribute information during disruptions. Information sharing between community members and rescue departments during the disruption also needs to be enhanced. Re-evaluation of safety plans and promoting preparedness in villages is a long-term task, which might suffer from a lack of continuity. To overcome this challenge, voluntary Safe Village coordinators have established a network in which lessons learned and best practices are shared.

Lessons learned show that citizens and local communities can efficiently improve inhabitants' preparedness and can be helpful in a disruption. Risk awareness and citizen participation can be enhanced through community resilience projects like Our Safe Village. However, to raise citizens' awareness, local communities need long-term programmes and preparedness models that encourage inhabitants to participate.

Continuity can be enhanced by building inclusive networks. Strengthening communication and collaboration between citizens and authorities at the local level is vital to achieving a successful and long-lasting outcome.

5 Conclusion and key messages

Genuine citizen participation is a prerequisite of resilient communities. Involving citizens and including their perspectives in risk decisions at all levels of DRM empowers them, raises awareness and encourages preparedness, ownership and responsibility. In addition, citizen engagement may be employed to better anticipate social conflicts, overcome decision deadlocks, improve the policy effectiveness, credibility and legitimisation of projects, avoid delays in the implementation of decisions and increase acceptance of them. The involvement of citizens should be an inclusive, collaborative, informative, transparent and open process.

The future of DRM will probably see the rationalisation and use of new and more inclusive bottom-up legislation, organisational structures, methodologies and technology for consulting and empowering citizens, and tailoring management systems to their specific needs. This will present several challenges that emergency planners and managers must necessarily face. Citizens may lack the knowledge and abilities or not be willing to take the opportunities they are given by authorities. Other challenges are related to the overwhelming amount of potentially inaccurate information, insufficient time, lack of resources, biased representation of diverse stakeholder perspectives, wrong reciprocal expectations and conflicts between citizens, local authorities and private enterprises.

Policymakers

For policymakers at both the national and the local level, this implies that they need to put more effort into actively and sustainedly involving a representative cross-section of all stakeholders, including citizens, in policy decisions, for example by facilitating and encouraging bottom-up initiatives and partnerships.

Practitioners

Practitioners working in institutions such as civil protection services and emergency warning systems should develop efficient strategies for adapting to the changing reality of social media and the emerging use of consumer technology by investing in simple and low-cost, people-centred technology but also ensuring that they have robust plans to tackle any ethical dilemmas that social media and technology usage may produce in the future.

Scientists

Scientists play an important role in improving understanding of what drives public awareness and preparedness. However, more (participatory) research is needed on effective communication, preparedness and engagement strategies to motivate different people and social groups.

Citizens

As for citizens themselves, they need to become more aware that they are not merely passive subjects in DRM; they share the responsibility for building resilient communities and timely responses, by taking part in policy-making, preparing for potential disasters, improving disaster response by employing their social networks .and learning from adversity by building back better.

4.3

Integrating tools for prevention and response communication systems

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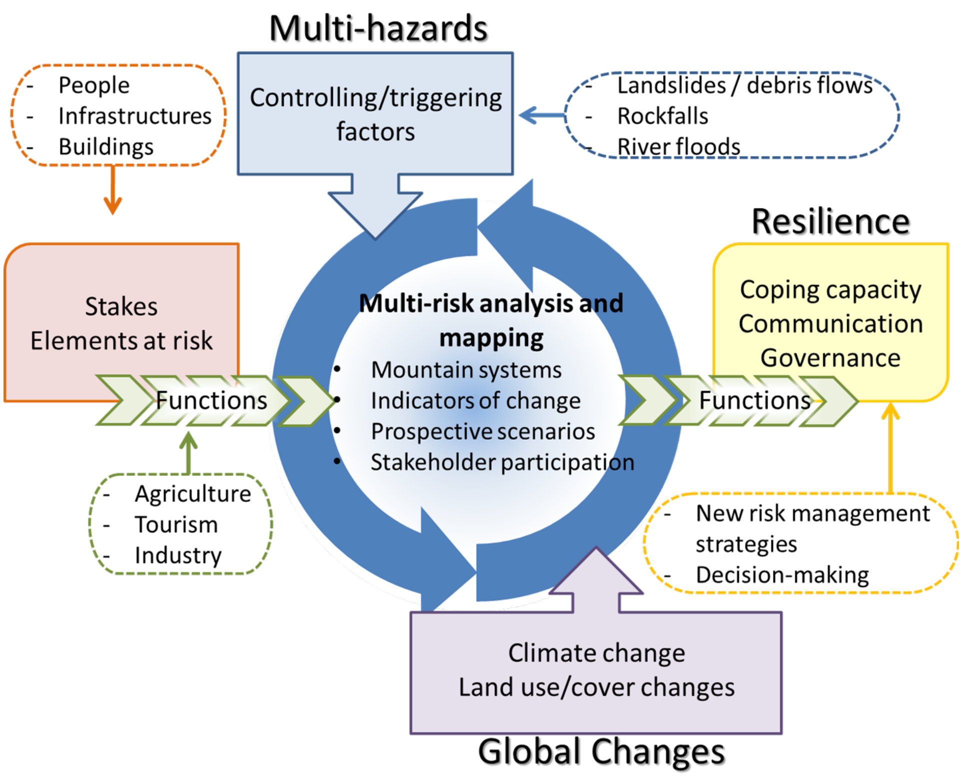
Pickl, S., Grandjean, G., Kolmann, P., Stručić, M., Musacchio, G., Rossi, C., 'Integrating tools for prevention and response communication systems', in: Casajus Valles, A., Marin Ferrer, M., Poljanšek, K., Clark, I. (eds.), Science for Disaster Risk Management 2020: acting today, protecting tomorrow, EUR 30183 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

1 Introduction: high-level initiative for a comprehensive and integrative approach

For an integrative comprehensive approach concerning the four target groups for risk communication – policy-makers, practitioners, scientists and citizens – it is necessary to have shared, possibly wide, knowledge, which will ensure consistency of the message to the society. The previous subchapter offers a glimpse into the related and interconnected processes and highlights the importance of the following: addressing the complexity of various audiences, building trust, forming and managing partnerships with a long-term perspective, and fostering a resilient society through norms and communication structures. Therefore, risk communication includes activities aiming at quickly providing information on, for example, the possible impacts of hazards (CDC, 2018) and disaster events. It naturally requires a joint strategy for the collection and aggregation of knowledge and data, especially in the context of big data and visual analytics. The special role of modern information technology solutions will play a significant role in increasing the accuracy of forecasts, and the certainty and speed of decisions processes, which is already a necessity in modern times of big data and digitisation. This subchapter will focus on a first step of the innovative integration aspect within an agile prevention and response process.

In general, strategies for risk reduction follow more and more an integrative knowledge approach (especially taking into account physical adaptation, but also economic and social impacts). Before we develop such a holistic framework in answer to the existing gaps, we will start with the requirements of short-term proactive adaptation plans. The initial phase consists of multi-risk analysis and mapping (Figure 1).

Figure 1. *Illustration of a multi-risk analysis and mapping* **Source**: *Grandjean et al. (2018).*



Many vulnerable areas in Europe (for instance the specific regions described in the SAMCO platform case study) are also subject to various socioeconomic activities that have undergone deep changes over the last century with the development of our modern societies (Huber et al., 2005).

They therefore reinforce the need to implement short-term proactive adaptation plans (IPCC, 2007), which might be characterised as taking the following into account:

1. the influence of climate (changes) on the frequency of hazards (slopes' stability, rockfalls, floods, landslides at different spatial and temporal scales;
2. the evolution of risks: if early warning systems can take into account climate variability, it remains difficult to assess the effect of these changes on long-term risk occurrences;
3. the interaction between the main economic, social and political actors, to identify adaptation scenarios, to make risk reduction strategies more appropriate.

To address these general communication problems mentioned above, efforts must be driven by multidisciplinary research (see Figure 1) covering the physical, social and economic aspects of those regions, and integrating the perspectives of development from global to local scales (Klein et al., 2004; Birkman, 2006; Commission of the European Communities, 2009), towards a practical communicating platform for resilience assessment with opportunities for some reachback functionalities (Raap et al., 2017).

2 Examples

2.1 Emilia 2012: different perceptions and missing communication

Initiatives such as the Sendai framework for disaster risk reduction (UNISDR, 2015) consider such a risk communication framework an essential component of building effective resilience (Kar and Cochran, 2019). These central tasks will be embedded in certain innovative platforms as part of an integrative approach combining the technical and social perspectives.

An example of different perceptions and missing communication is the 2012 Emilia earthquakes. In May 2012, two major earthquakes occurred in north Italy. They became known as the 2012 Emilia earthquakes. This seismic sequence (Ioannou et al., 2012; Mucciarelli and Liberatore, 2014) significantly affected housing, lives and the economy of local communities, which had a false perception/awareness of the risks they were exposed to. Based on this case study (and related ones), we will focus on the following four key aspects.

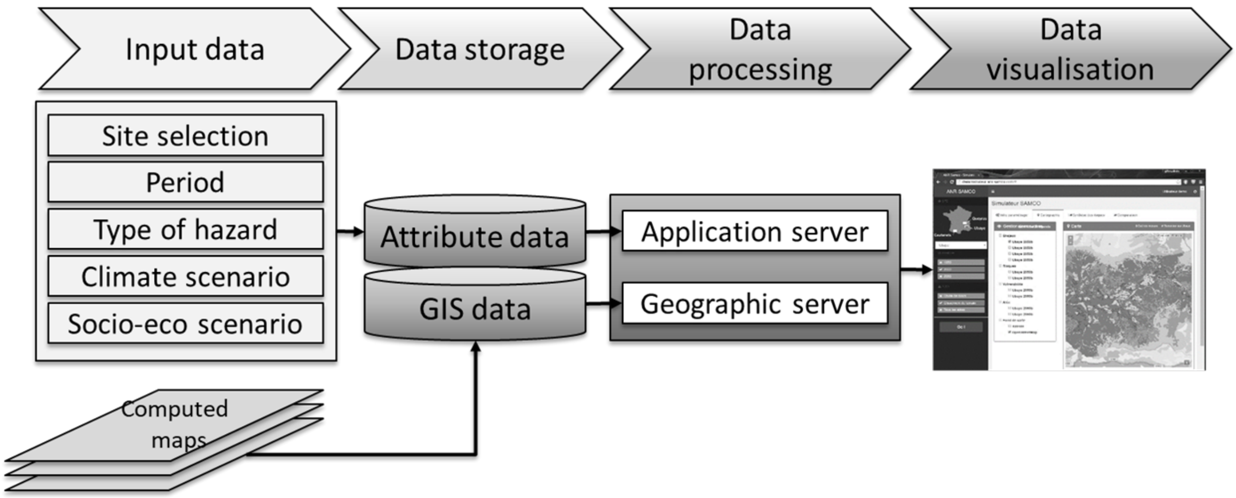
1. Central message: the European dimension. Non-structural damage can be caused by moderate earthquakes, which are very frequent in various parts of Europe.
2. Gaps in risk communication. These are especially prevalent before the event and in the emergency phase.
3. Innovative solutions. The use of information technology enables communication on selected topics using various media (e.g. face to face, internet, digital, paper) targeting diverse stakeholders.
4. Learning cycles: the lesson learned. The emphasis is on special tools, practices and learning cycles.

2.2 SAMCO Platform: A Proactive Comprehensive Resilience Framework and Society Adaptation for Coping with Special Risks in a Global Change Context

In the specific context mentioned in the previous section, the ANR SAMCO project plays an integral role by developing a special proactive resilience framework to enhance the overall resilience of societies to the impacts, especially in relation to risks observable in the EU ([1]). The strength and originality of the SAMCO project (Society Adaptation for coping with Mountain risks in a global change Context) will be to combine different techniques, methodologies and models (multi-hazard assessment, risk evolution in time, vulnerability functional analysis and governance strategies) and to gather various interdisciplinary expertise in earth sciences, environmental sciences and social sciences (SAMCO, 2019).

This is achieved by developing a conceptual, methodological and comprehensive knowledge framework bringing together expert advice on natural sciences and social sciences. To define and identify the role of the different actors involved in risk management (local authorities, consulting companies, researchers, etc.), this tool has been developed thanks to an innovative reachback architecture (Raap et al., 2017) allowing the multi-geohazard risk scenarios to be computed and evaluated numerically according to different socioeconomic pathways. This web-based platform is based on a complete visual chain representation of open-source components from the data storage to the user interface, as shown in Figure 2.

Figure 2. *The SAMCO platform conceptual architecture.* ***Source****: Grandjean et al., 2018*



Other platforms also stress the anticipation approach, which will be discussed in the next subsection.The SAMCO platform presented provides a practical example of identifying general key community resilience factors (e.g. response capacity) to provide risk management strategies adapted to the possible effects of global changes. In the next subsection we continue with a special focus on learning.

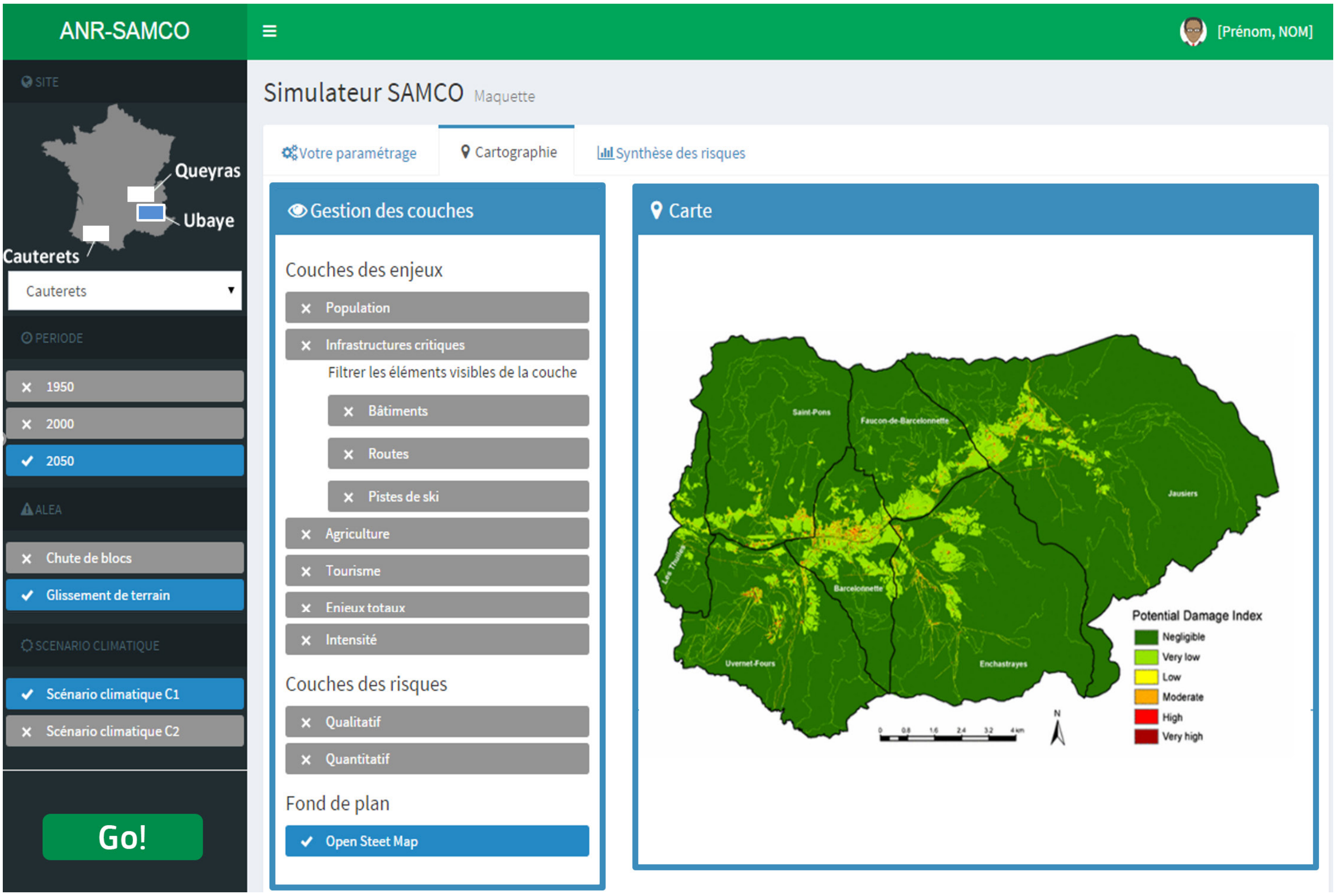
([1]) *There are other innovative platforms besides the SAMCO platform, e.g. the Disaster Risk Management Knowledge Centre Risk Data Hub from the Joint Research Centre (European Commission, 2020).*

2.3 LCMS platform: Network-Centric Anticipation, Learning and Data Delivery

The platform LCMS([2]) (Landelijk Crisismanagement System - National Crisis Management System) is presented here as an example showing the network-centric approach that will be elaborated in detail in this section. The LCMS is used both at municipal and regional level by the teams in charge of risk management supporting decision-making during response of large crises, linking different teams working on it. It is used by public bodies in charge of risk management and by other partners like regional water authorities, the Dutch Ministry of Infrastructure and Water Management and the Royal Military Police (IFV, n.d.).

In general, network-centric infrastructure (NCI) comprises all the networks, knowledge, communications and information management applications required to assure delivery of data/information (optimally) to the right place at the right time in the right format. The SAMCO platform also delivers such a network-centric approach, which aims to develop a set of methodological tools to improve the resilience of complex areas coping with global changes, as shown in Figure 3.

Figure 3. *Visual analytics of the SAMCO web platform showing the critical elements at risk*
Source*: Grandjean et al., 2018*



(2) https://www.lcms.nl/about-lcms

These tools, designed to measure the resilience of ecosystems and societies in three case studies (the French areas of Cauterets, Queyras and Ubaye), were implemented in a web platform allowing the evaluation of impacts in the different scenarios.

This has allowed a new approach to anticipation, knowledge handling, learning and data delivery, which are central to this communication chapter. The only structured way in which citizens can effectively contact authorities to request clarifications or issue new reports is through a specific telephone number (112 in most EU Member States, 911 in the United States), which can get completely congested and unusable in large-scale emergencies. For example, when Hurricane Harvey hit Houston, Texas, in 2017, official emergency channels were overloaded, and so were the capacities of formal responders.

For this reason, in large-scale emergencies in Europe, authorities now urge the public to use social media especially, as part of the NCI, to contact their families, to avoid overloading phone lines. We provide below a set of recommendations related to the implementation of an effective public warning system (PWS), presenting them as key takeaways, and dividing them into four sections: organisational best practices, system architecture, technical standards and guidelines on styling.

Such recommendations are meant to help decision-makers in planning the development of an up-to-date PWS. The suggestion is to create in advance, train and support a public warning communication group (PWCG), which is a dedicated group of people in charge of designing and assessing the strategy and the handling of inbound and outbound information and warnings. Article 110 of Directive (EU) 2018/1972 (EU, 2018) states a future challenge for Member States in the European Union about location-based warning in regard to such PWSs.

An effective PWS must be capable of delivering effective early warning in a timely manner and reaching all affected populations while informing the relevant public authorities involved in the emergency management cycle. This includes those belonging to neighbouring countries in cases of cross-border emergencies. The mission of the group is to effectively convey and disseminate the appropriate information to the appropriate recipients through the most suitable channels and to verify the impact of the communication strategy.

3 Public warning communication group concept (PWCG)

It is important to dedicate human resources to the design and management of public warning communications.

The three case studies demonstrate the necessity of and requirements for the concept of a PWCG.

According to Rossi et al. (2018), the PWCG should include some specific roles, such as a crisis communication manager, a user experience and graphic specialist (visual analytics perspective), a social media specialist, a communication engineer and a legal consultant. This will help the decision-making process in each disaster risk management (DRM) phase, which has to be based on the real social structure, including an accurate knowledge of the human resources available to the territory.

The community mapping must monitor formal groups, local population, trained staff in social and health services, productive bodies, informal groups, transients, commuters, local media and other groups. For each of the above groups, information about the relevant persons and their preferred communication channels (e.g. phone, email, social media) has to be collected, kept up to date and used in the alerting strategy.

An effective public warning communication strategy has to exploit the multi-channel capabilities of the PWS infrastructure according to the technical standards and the audience characteristics. The definition of such a strategy has to be coordinated by the PWCG but it can also involve different stakeholders, agencies, local communities and group leaders, who can help in the definition of multi-hazard scenarios and the associated target audience, the mapping of the systems and channels to be used in the identified cases, and the main communication procedures to be followed.

After consolidating the above, communication experts and the PWCG will then design the informative resources needed to cover and serve all DRM phases, the different channels managed by the PWS and the population segments, in compliance with the standards; iteratively test the resources created, with selected representatives of the audience groups; and integrate the feedback collected in order to optimise the initial designs. It is critical to warn the public carefully, concisely and clearly to avoid panic (or negative escalation).

To summarise this, we propose a special centralised system as a specific communication tool in the following paragraphs.

A dissemination plan considering different scenarios and the media selected is necessary when designing such a communication tool. This communication tool should be a centralised system that enables two-way communication, e.g. by creating a mobile application that allows citizens to provide selected information and feedback. In order to keep the channels up to date with relevant information and tips, different flexible information strategies should be integrated.

Furthermore, periodic training of the operators through practical exercises in the use of the PWS systems and in the techniques and tools is recommended. The target audiences should be educated on the topics of risk awareness, prevention and the possible ways of using certain reachback functionalities (Haynes et al. 2008) to cooperate and support the official authorities in cases of approaching or ongoing crisis.

Such an architecture can guarantee assessment of the timeliness, effectiveness and impact of the PWS with the flexible communication strategy that is under consideration.

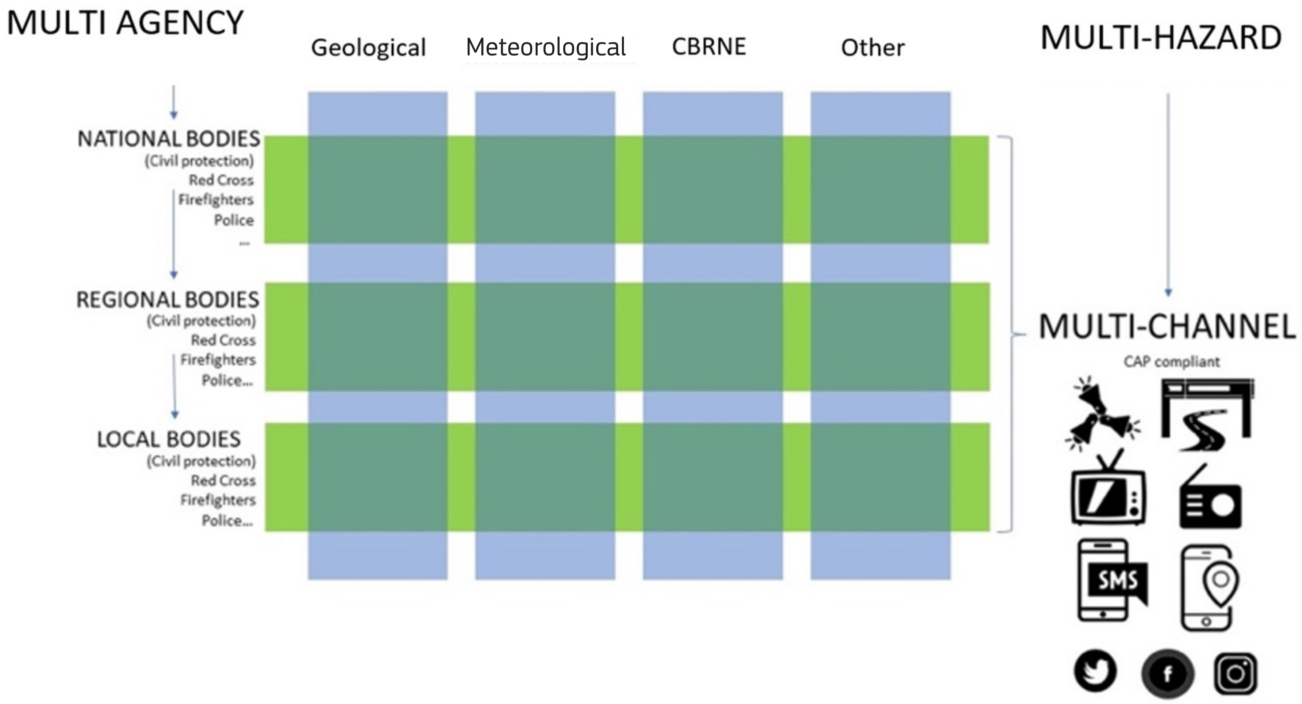
In the next section some technical and functional specifications are described.

4 Centralised communication tool

The suggested approach, developed in the last subsection, is now to build a flexible agile centralised system, which integrates all alert messages to be sent by the authorities through the internet, in a unique and secure gateway to which multiple subsystems can be connected in order to read and spread the alert messages.

The PWS design should be included in the technical and functional specification document of the PWS system as presented in Figure 4.

Figure 4. *Suggested PWS approach.* ***Source****: Rossi et al., 2018.*
Note*: CAP, Common Alerting Protocol (CAP, 2019); CBRNE, Chemical, Biological, Radiological, Nuclear and Explosives.*



4.1 Emergency communications

The central warning system infrastructure (see Figure 5) represents the core of such a complete communication system. As example, the suggested architecture should consist of three main components:

- alerting authorities (AA),
- central warning system infrastructure and
- public warning subsystems.

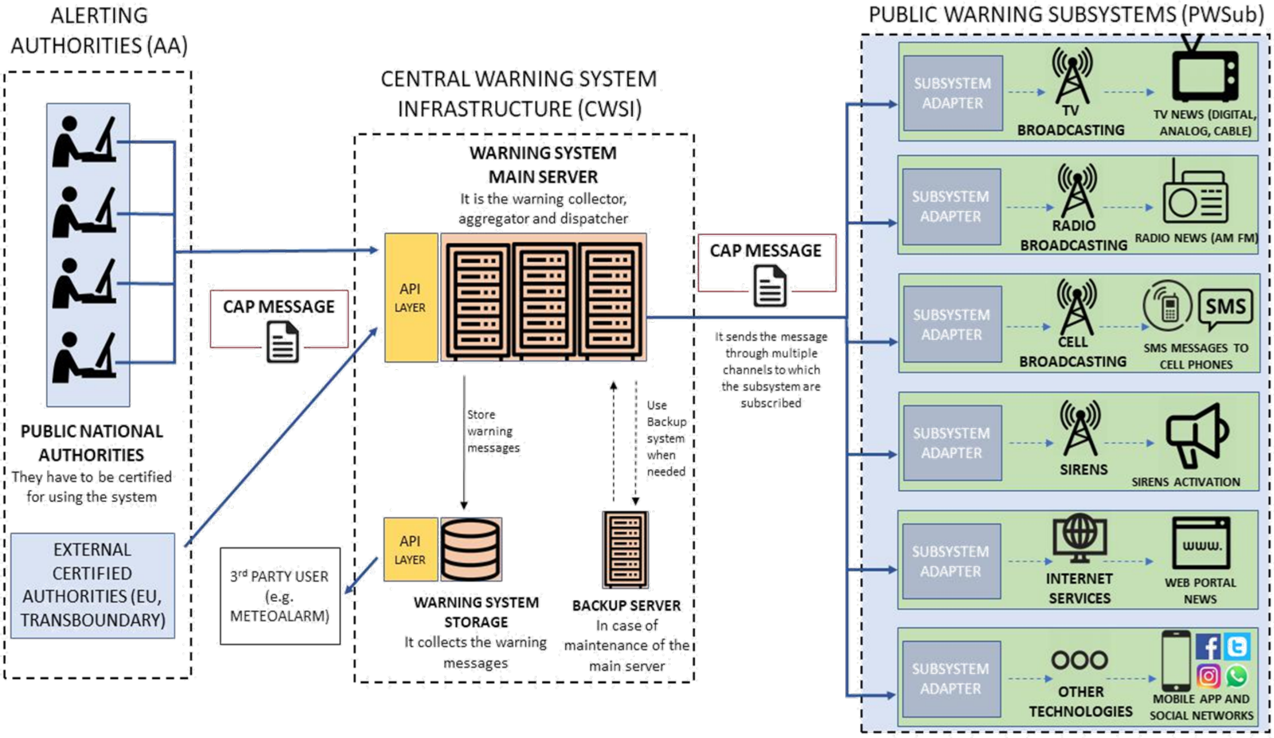


Figure 5*. Suggested PWS architecture.* ***Source****: Rossi et al., 2018.*

4.1.1 Alerting authorities

This component is made up of the public authorities of a country. The authorities can be at the national, regional or local level, depending on the internal regulations on emergency management that cover the specific aspect of communication. Each authority of the AA component must be able to send a message using a standard template, which can be the CAP (Common Alerting Protocol) standard. The AA component should be extendable, allowing new certified authorities to be included in the system when their technology is compliant with the architecture requirements. This customisation feature is crucial, because it gives the possibility of including organisations from other countries. This includes transboundary authorities, whose public warning messages can be useful in the event of cross-border disasters.

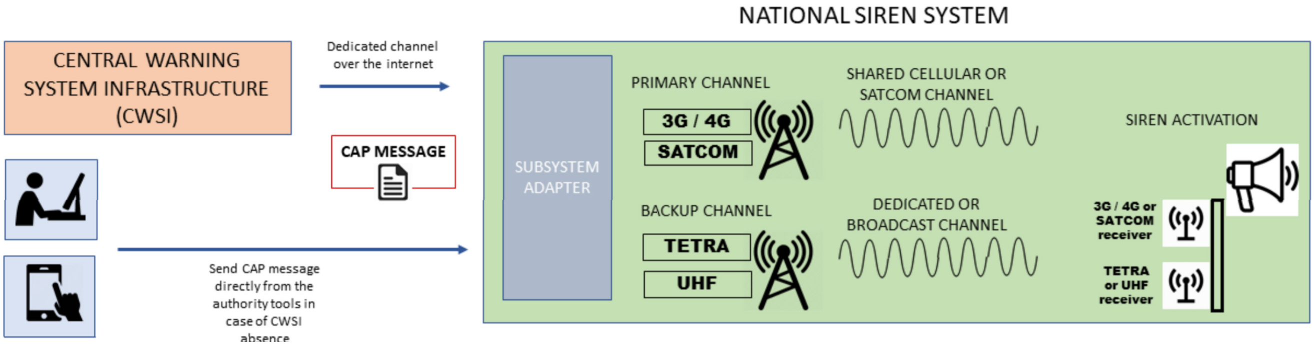
4.1.2 Central Warning System Infrastructure (CWSI)

The CWSI consists regularly of a warning system main server, a warning system storage and a backup server. These three components stand for a multilayer approach which could be easily extended: Different technologies and software solutions might be integrated; app-based solution will become more and more important. The secret of success ought to be in the future a blend of the best attributes of all the existing IT-based decision support system (DSS)-methods.

4.1.3 Public Warning Subsystem

The underlying public warning subsystem contains all the subsystems aiming to disseminate the CAP warning message. Each subsystem should have an adapter, a software component that listens to the dedicated channel for new messages. When the adapter detects a message on its channel, it reads the communication, parses the CAP message in order to filter only the fields that are needed for the technologies to which it is linked, and spreads the message through the network infrastructure to reach the correct recipient (Figure 6); integrating Satellite Communications (SATCOM), Terrestrial Trunked Radio (TETRA) and Ultra-high-frequency (UHF) technologies.

Figure 6: *Public warning subsystem example for sirens* ***Source***: *Rossi et al., 2018.*
Note *: SATCOM (Satellite Communications), TETRA (Terrestrial Trunked Radio), UHF (Ultra-high-frequency)*



4.2 The 'ALL' principle

In order to fill the gaps and to summarise the technical and functional description, we may characterise the PWS by the 'ALL' principle.

The PWS prototype should be designed to be used by ALL agencies involved in DRM across ALL administrations: It should be used for ALL kinds of alerts and across ALL DRM phases. All alerts should be generated at a given URL containing complete information. Furthermore, public warning subsystems should be ALL-owed to be interfaced with the national PWS and be capable of adapting the content to the different media they use. Embedded self-learning activities increase the accuracy of such processes for a future type of an holistic (integrative) service-oriented risk management, which we call risk sensing.

5 Summary: 'risk sensing' as an integrated pre-risk approach

Risk sensing is an innovative expression of risk communication including forecasting, which this subchapter tries to summarise adequately.

We started with special case studies that stand for well-known types of disaster; then we presented a first (national) example of a platform focusing on such disasters. Afterwards we developed an agile architecture that is suitable for an international risk-sensing conceptual framework. It reflects the fact that a comprehensive knowledge approach is only possible and effective if we are able to predict (to 'sense') the relevant risk in a very detailed manner and to communicate it afterwards. Sensing is a special 'pre-risk' approach for all four target groups, using a kind of system-of-systems architecture. Furthermore, this subchapter also suggests using a more standardised approach to presenting events by using a certain knowledge process, graphical tools and visual analytics processes for greater effectiveness in accident investigating, reporting and communicating. Risk sensing allows for the fact that, although there is a high level of uncertainty, the different procedures presented, such as multi-risk analysis, visual analytics, the case studies, the PWGC concept and the centralised communication tool, constitute an integrated knowledge communication process and support an agile architecture to establish prevention and response communication systems.

6 Conclusion and key messages

Subchapter 4.3 can be seen as a direct continuation and summary of subchapters 4.1 and 4.2. The main goal of this report, *Science for Disaster Risk Management 2020*, is to broaden the understanding of current and future risks faced in Europe, stressing the causes and underlying drivers of the exposure and vulnerability of the assets suffering losses. Subchapter 4.3 characterises and emphasises the role of integrating tools for prevention and response communication systems. Such communication tools address the four target audiences in different ways, and altogether they build a risk communication chain.

This holistic approach, which also develops from a national to an international perspective, focuses on this specific risk communication chain (circle) perspective including observation, interpretation, choice, and communication and dissemination, enabling a service-oriented risk assessment (Zuccaro, 2018). Bringing different platforms together and sharing knowledge, information and data might be valuable to generate and communicate consistent and complementary knowledge for policy and practice (EEA, 2017). Therefore we can conclude that the subchapter emphasizes the importance of integrating tools for prevention and response communication systems.

Policymakers

Policymakers should ensure that they provide a full picture and identify a comprehensive approach.

Practitioners

Practitioners should engage with this tool adaptably. Reachback functionalities should build an innovative flexible link between practitioners and scientists.

Scientists

Scientists should develop a risk-sensing approach combining predicting and visual analytics via intelligent platforms on which citizens may participate.

Citizens

Citizens should develop their special relationship with DRM (their sense of it), including risk knowledge, risk awareness and self-protection activities, in a holistic way. They should join the communication platform and challenge policymakers to increase preparedness. This will close the loop.

Conclusions

Adequate risk communication is the keystone to make territories and communities evolve in systems able to challenge complex and multidimensional risk environments.

This chapter, 'Communicating risk among all', reflects on what communication means, and addresses three main questions: how to create trust and conditions that are mutually understandable among all the stakeholders involved; what the role of institutions and governance is; and what contribution technology may provide as part of an overall and shared system of knowledge of risks.

The reflection (subchapter 4.1) starts with the assumption that Interconnected and dynamic hazards and risks require the participation of all the involved actors, facing and defining shared problems in a collaborative and communicative manner, working together to build trust and common understanding in an open and problem-solving mode. The starting point for adequate risk communication is a clear understanding of failures in risk governance and communication processes. Through a selection of relevant case studies, lessons learned have been presented, along with suggestions for follow-up on actions to be taken after insights and knowledge are gained.

Among the main points highlighted are the importance of (1) clarifying risk and uncertainty communication objectives In relation to actors' roles and responsibilities before, during and after a crisis; (2) being aware of potential biases and possible opposing values among actors when communicating risks and uncertainties, as the knowledge of these values and biases makes communication more effective; (3) modelling a context-sensitive communication framework, to empower the dialogue with the intended audience.

This chapters shows that trust building is a fundamental focal point and the oil that facilitates an effective risk communication culture among diverse stakeholders. It provides an in-depth discussion, and presents long-term iterative processes based on good practices and lessons learned. Trust is crucial in risk communication, and is built through systematic sharing of information and experiences between stakeholders moderated by competent leaders acting as a catalyst, steering the group towards a learning culture.

The multidimensionality of risks requires long-term partnerships, which are the key to enhancing multidi sciplinary collaboration to promote synergies between scientists, policymakers, practitioners and citizens. Embedding these synergies in stable networks builds trust and enables the exchange of information and best practices, education and training, and awareness raising in the area of risk management, governance and communication.

All these efforts rely on adequate support from governance and institutions, which then requires the enrichment of their usual hierarchical structures with networking capabilities. To build more resilient communities (subchapter 4.2), bottom-up approaches have to be set up alongside traditional governance approaches. That means that the public should not be perceived as merely a passive receiver of information and decisions, but is actually involved in risk assessment, preparedness measures, emergency plans, etc. at all levels of disaster risk management (DRM).

Hence, citizens ought to be involved in the decision-making process, by tailoring management systems to their needs. The future of DRM will require new and more inclusive bottom-up legislation, new organisational structures, methodologies and technology for consulting, empowering and engaging with citizens.

In this perspective, a paramount role is played by social media: there is, in fact, a strong need for institutions such as civil protection services and emergency warning systems to adapt to the changing reality of social media and the emerging use of consumer technology, and also to ensure that they have robust plans to tackle any ethical dilemmas that social media and technology usage may produce in the future.

Technology for risk communication (addressed in subchapter 4.3) also plays an important role in DRM. In this vein, risk sensing in particular is an innovative solution for risk forecasting and reflects the fact that a comprehensive knowledge approach is only possible and effective if we are able to predict (to 'sense') the relevant risk in a very capillary manner. Sensing indicates now that it is a special risk approach, based on a multipolar sensor setting combined with an integrated knowledge assessment process and intelligent reachback architecture.

Relevant risk-sensing techniques, such as multi-risk analysis, the SAMCO web platform, the public warning communication strategy and the related visual analytics reporting, have been presented and discussed; although still characterised by a high level of uncertainty, risk-sensing procedures constitute an integrated knowledge assessment process and support an agile reachback architecture that might act as an intelligent comprehensive sensor to give deep insight (and early warning) into complex scenarios.

This chapter has thus stressed the importance of adequate, multidimensional, inclusive risk communication, and provided stepping stones and solutions for all actors involved in risk communication. The current experiences that we are all sharing, in particular, are proving in vivo how the network of information and communication may help overcome the network of systemic risk.

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4.1 Linking actors, sectors and governance levels

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4.2 Citizen participation and public awareness

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Super Case Study

6

Education, cultural inclusion and disasters: lessons from Greece, the United Kingdom and Central Europe

Online Version

Super Case Study 6:

Education, cultural inclusion and disasters:

lessons from Greece, the United Kingdom and Central Europe

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CONTENTS

1 Disaster education, culture and communication: a conceptual introduction

The effectiveness of education with regard to training depends on the extent to which education can ensure that cultural concerns are taken into account and reflected in the communicative strategies that disseminate information and knowledge of practices related to disasters.

This introductory part of the chapter will consider the roles of education and cultural inclusion as key resources in preventing, managing and mitigating disasters. Key definitions – of education, culture and communication – will provide a framework for three empirical case studies.

Education and training are traditionally divided into training for the professionals who deal with disasters (such as medical staff, firefighters and the military) and education for the general public. Professional training focuses primarily on the technical tasks and challenges related to particular types of hazards (Hagelsteen and Burke, 2016), which may include training on preventative measures, such as safe and well checks (formerly the home fire safety check, introduced in the United Kingdom in 1999) and consultancy on building regulations. Disaster education for the general public refers both to pedagogical strategies, including school-based initiatives and public-awareness campaigns, and to family and community learning (Preston, 2012; Shaw et al., 2011).

School-based initiatives offer training and training materials to teachers, who in turn raise awareness and preparedness as an ongoing part of their curricula (see Johnson et al., 2014). Such initiatives may also involve visits from professionals, such as firefighters or medical staff, who can assist with matters such as disaster drills. Community education programmes that cannot rely on such administrative structures and often work with volunteers who facilitate emergency response, direct self-assessment of the situation and assist the general public (Shah Alam Khan, 2008; Wisner, 2006).

It is vital to recognise that individuals (professionals and members of the public) are diversely embedded in societal structures through families, communities and professional organisations. This diverse embedding gives rise to distinct risk cultures, as people share various beliefs and values that influence their perception of disasters, their risk behaviours and their knowledge of disasters (Douglas and Wildavsky, 1982). Thus, risk cultures are interrelated with factors such as level of education, age, socioeconomic opportunities, religious beliefs and language skills. Risk cultures therefore relate not just to marginalised social groups, but to different other societal subgroups.

Older generations may have their own cultural background and understanding of the world, which can be different from those of youth cultures. Therefore, in this study we propose a more comprehensive understanding of culture, so that the complexity of risk perspectives and behaviours can be understood from the perspective of this chapter. We therefore propose to divide the risk cultures in relation to disasters into (1) organisational cultures, (2) communities and (3) national cultures.

BOX 1.

Typology of cultures

(1) ***Organisational cultures.*** Typical definitions of culture involve beliefs, values, language, history and attitudes, which are also applied to organisations that support disaster risk reduction, relief and reconstruction. These organisations formulate standards and norms that inform their understanding of safety, risk and disaster management. While such standardisation is a key feature of their operation, it also potentially creates a dangerous barrier to reflecting on how an organisation 'thinks' and 'acts' (see Ramalingam, 2013). This has important consequences on, for instance, how such organisational cultures recognise vulnerability, how they engage with their potential audience and how they deliver their messages and training.

(2) ***Communities.*** Local cultures are increasingly shaped by mobility and diverse lifestyles. It has become easier to move to and settle in other countries, which means that people with diverse cultural backgrounds (and, therefore, distinct understandings of disasters, risks and safety) move around the globe. This poses challenges for intercultural approaches to disaster management. As an instance of the diversity of communities, DiGuiseppi et al. (2002) report that the distribution of free smoke alarms in multiethnic neighbourhoods in London has not reduced injuries. In many cases, the alarms were not installed or maintained, as their value as a safety measure in an urban context was not understood.

Furthermore, societies are made up of subcultures that may include generational cultures, social classes, religious groups and many more, whose members have diverse worldviews. For instance, Harpur et al. (2014) report in a study on fire safety in relation to the elderly that members of the community identified the needs of the elderly for improved safety but felt that it was culturally unacceptable to intervene in another person's life. Similarly, Mitchell et al. (2008) report that the perception of children and young people as passive victims underestimates their potential in preventing and responding to disasters.

(3) ***National culture.*** Finally, cultural values and beliefs at a national or broader geocultural level, which are often supported by accounts in popular culture, affect internal views of disasters, which may relate to history and tradition. They define what is considered to be a disaster and thereby have an impact upon follow-up legislation. For instance, the events of 11 September 2001 had a strong effect on government legislation, policy and education in the United States (for an overview, see Tierney, 2007). Likewise, cultural values shape the view of external disasters and what counts as a disaster through the experience of other nations. For instance, the Fukushima nuclear disaster, in the context of Germany's image of Japan as one of the most technologically advanced nations, led to the shutting down of all nuclear power stations in Germany, as the technology was considered not to be safe. Nation states thus serve as a comparative framework, but this also shows that what counts as a disaster and what is meant by disaster vary according to broad cultural orientations (Birkmann, 2007).

Such cultural perceptions can therefore affect educational needs and training at different levels. For instance, organisational reactions to disasters depend on normative models of decision-making that rely on a chain of command, in which the situation is assessed and an emergency plan is formulated and executed. The more recent literature on organisational learning from disasters has emphasised the need for co-learning, participatory models and experiential learning, strategies that highlight a more interactive communicative approach. This research shows that disasters are situations of great uncertainty, in which decision-making is done in situ based on a more reflexive approach (Childs, 2005; Cohen-Hatlton et al., 2015), which requires communicative training that is more suitable to constant micro-negotiations that are used to clarify ambiguous information in such a situation (Weick, 2010). Restrictions on micro-exchanges to update decision plans have a cascading effect in which small problems grow bigger (Perrow, 1984).

Moreover, research on interactions between organisations and communities demonstrates that such interactions are a key factor in building trust, which has a substantial impact on the perceived capability of authorities and experts to deal with disasters (Wachinger et al., 2013).

At the school and community levels, there is an increasing awareness that simple and didactic top-down approaches, which simply deliver disaster education, must yield to more reflexive and collaborative learning strategies. This has opened new ways of engaging with communities through social media, citizen journalism and blogging, by which local citizens become enmeshed in interactions between 'old media' (TV and radio) and 'new media' (Twitter, WhatsApp). This network of communication is thus able to shape public accounts of the disaster and identify vulnerabilities (see Morgner, 2017).

Finally, at the national level, one cannot simply operate with an approach that assumes that more information, more campaigns and more communication will lead to better preparedness and knowledge. The cultural filters of societal subgroups (including age, gender and socioeconomic status) ensure that such messages are differently interpreted as regards their value and usefulness (Krüger et al., 2015; Otway and Wynne, 1989).

Recognising and understanding the interrelationships between education, culture and communication is crucial in an age of intensified and expanding hazards, increasing exposure and vulnerability, and international migration in a multicultural European context. Based on these conceptual considerations, this chapter will analyse three innovative case studies in Greece, Poland and the United Kingdom that demonstrate the importance of education and cultural inclusion in the prevention and management of disasters.

2 Case study I: multiculturalism and fire incidents

Cultural diversity and migration, and their relationship to fire hazards, as evidenced in the recent and deadly Grenfell Tower fire in London, need more attention and research within a European context of increasing internal and external migration.

Figure 1. *Grenfell Tower block, 4.00, 15 June 2017* ***Source****: Natalie_Oxford, 2017*

On 14 June 2017, a fire broke out in the 24-storey Grenfell Tower block of flats in London (Figure 1). This fire led to 72 deaths and more than 70 others were injured. The majority of the victims had an ethnic minority background, coming from a diverse range of countries, such as Afghanistan, Egypt, Eretria, Lebanon or Sudan (see BBC, 2018). Another example is the deadly Lakanal House fire in 2009, in Southwark, London, which also affected people from different ethnic minorities.

In 2017/18, 334 fire deaths and 7 300 non-fatal casualties were recorded in England (see Home Office, 2017). The estimated total cost of fire for England is on average around GBP 8.3 billion a year (see Department for Communities and Local Government: London, 2011). There is a growing body of evidence that suggests that ethnic minorities are more likely to be affected by fire hazards (see Duncanson et al., 2002; Asgarya et al., 2010). This seems particularly relevant within an EU context, where internal migration between European countries but also from outside EU is ingrained into European institutions. For instance, nearly 10 million people in the United Kingdom were foreign-born and about 40 % came from EU Member States.

To address such cultural factors within a context of fire hazards, a number of public information campaigns have tried to provide a solution. For instance, in 2005 and 2006, the UK Office of the Deputy Prime Minister ran a fire-safety awareness campaign that was promoted at the festivals of Diwali (Hindu), Eid (Muslim) and Chinese New Year. In 2008, as part of the Fire Kills campaign, it was discovered that the Survey of English Housing of 2004–2005 showed that Asian households had a 10 % lower level of smoke alarm ownership than the national average. This prompted an awareness campaign by the ethnic advertising agency Media Moguls, which, also as part of the Fire Kills campaign, produced ads for ethnic newspapers and television channels that were aimed at increasing the number of smoke alarms in selected communities (see Webb and Auckland, 2013).

Similar initiatives have had a more practical focus, trying to increase the number of smoke alarms by giving them out for free. More than 20 000 smoke alarms were installed in a number of multiethnic boroughs in early 2000 in conjunction with the distribution of free educational brochures. However, the research evaluating such initiatives demonstrates that they have little or no impact (see Camit, 2002; DiGuiseppi et al., 2002). No systematic research has been conducted to understand fire behaviour in these boroughs (for instance, why these people have a lower number of fire alarms), but it is assumed that culture plays a role (see Dean et al., 2016).

As a consequence, a research study was conducted in collaboration with the Leicestershire Fire and Rescue Service, supported by the Fire Research and Training Trust, to explore a novel direction. This research looked at all fire incidents ([1]). The initial research showed that more fire incidents as well as more severe fire incidents occurred among black and black British ethnic groups. A more detailed analysis of the composition of households, however, revealed that this finding was true only in households in which black and black British people came from the same ethnic group. Thus, there was a mitigating effect if members of the household came from different countries. This led to the conclusion that it is not culture per se that explains fire incidents but that a relatively homogeneous group in combination with distinct cultural living standards plays a decisive role.

Although education about fire incidents takes place in UK schools, it can safely be assumed that the general population most commonly acquires fire safety knowledge through general integration into British social life. Accounts in popular culture and recommendations by neighbours, friends and professional authorities enable access to relevant information and behaviours. Exclusion from such integration therefore poses the risk that relevant fire safety behaviours and standards will not reach all social groups.

Consequently, a survey and follow-up focus groups were conducted by the Lead Author to understand matters of access and communication in black and black British ethnic groups in Leicester and Leicestershire. The research revealed that a number of African nationalities, i.e. people from Somalia, Zimbabwe and other southern and east African nations (including Kenya and South Africa), strongly clustered in a few areas of the city. Unlike Leicester's South-East Asian population, which arrived over decades, the majority of these arrivals from Africa came within a short timeframe of a few years ([2]). For instance, about 10 000 Somali nationals arrived within a few years around the turn of the millennium, settling in Spinney Hills, Leicester.

Research on the communication patterns within and external to these communities revealed that they had created a social life that was based mainly on personal communication networks with people from the same ethnic groups. Members of the same ethnic groups were granted greater trust than non-members and consequently were the first points of contact in moments of crisis, from small car accidents to dwelling fires. This also meant that knowledge about fire safety depended largely on the knowledge of other members of the same community, creating a gap in terms of knowledge of fire-safety standards outside the community. Moreover, a precarious socioeconomic status meant that fire safety was not a top priority in terms of smoke alarms and other measures. Finally, the high trust in personal networks caused a kind of social sclerosis in the form of a lack of trust in institutional services.

In collaboration with members of the black and black British community, these issues were addressed as follows. Key gatekeepers from the community received basic training on fire safety. Their central role and trustworthiness ensured that the messages they spread would be legitimised and reach future immigrants, ensuring sustainability. Those gatekeepers would join a newly formed equality and diversity board that would serve as a mediator between the fire service and the community, ensuring co-learning on both sides. In collaboration with the Leicestershire Fire and Rescue Service, intercultural awareness training was developed and integrated into the training pathway for firefighters. Recommendations were made to change the data collection practice of the fire service to include demographic information for all types of incidents.

([1]) To overcome the limitation of missing ethnic classifications, it used a large number of fire incidents for which an address was recorded over a period of 4 years (2011–2015). This information was geocoded and correlated with geocoded demographic information (Office for National Statistics, 2011) such as proficiency in English, industry, occupation, multiple ethnic groups, religion, main language, ethnicity, economic activity, country of birth, highest level of qualification and age. The combination of fire incidents and demographic data led to a dataset of 369 562 entries.

([2]) As reported by the National Census 2011 (Office for National Statistics, 2011), 95 % of black Africans arrived after 1981

Because the study focused on the fire service and region of Leicestershire, it is limited in terms of the broader implications that need to be addressed in the future, including the need for public services to be more engaged with new arrivals to enable trust building from the beginning. It is recommended that strategic partnerships be created between fire services and other services, such as the National Health Service and police, but also with universities so that existing data can be better analysed and monitored. Such an early warning system would enable fire services to detect vulnerability at earlier stages. Urban fires do not have a direct link with climate change. However, climate change is considered a motivating factor in international migration.

3 Case study II: Floods in Central Europe as the trigger for building public risk awareness

Trans-national disasters, like floods, pose a particular challenge to cooperation of emergency services across nations due the different cultural and social orientations that direct risk assessment, preparation, response and recovery actions and those are determined by risk awareness.

This case study considers the role of different national cultures from the perspective of a cross-cultural disaster. The focus is on different flood management strategies during the great floods of 1997 and 2010 that affected Czechia, Germany and Poland. Floods in the Danube river basin are also mentioned as events contributing to the development of comprehensive, cross-regional solutions. This case study will demonstrate how these catastrophic events were triggers to improve risk management systems in the area of training and education from a cross-cultural perspective (Raadgever and Hegger, 2018).

The improvement of educational policy embraced, besides defence and engineering, cultural issues within vulnerable territories seen as elements of the regional and cross-border system. The process was streamlined by political, economic and social factors and can serve as an example of cultural inclusion understood as mixing the best problem-solving, creative, innovative and entrepreneurial practices (UNESCO, 2017)

The great flood of 1997 in Central Europe killed over 100 people, destroyed towns and villages, and contaminated the soil over large areas of Czechia, the Oder basin in Germany and Poland (Cowell, 1997; Kundzewicz et al., 1999). As a consequence, the International Commission on the Protection of the Oder against Pollution (ICPO) was established by the governments of the Republic of Poland, the Czech Republic and the Federal Republic of Germany and by the European Community on 26 April 1999 (International Commission for the Protection of the Odra River against Pollution, 2019).

The objective of these initiatives was to provide the best measures against flooding and pollution of the Oder, under the Water Framework Directive (Directive 2000/60/EC), which involved a new narrative of flood management based on expertise and information. The focus of ICPO was to build public awareness by providing updated maps with information about flood risk in the international Odra river basin, presenting information on selected physicochemical and biological parameters about international surface water from the international monitoring stations on the Oder, or creating ICPO-Kids, an educational webpage targeted at the youngest. Furthermore, the maps and databases were designed not only for governmental authorities, but also for e-learning platforms and mobile applications – tools for arising social awareness about flood and creating proper behaviours (Państwowe Gospodarstwo Wodne, Wody Polskie, 2019).

According to the State Fire Service in Poland, the flood of 2010 was one of the worst floods for 250 years, comparable in scale to the great flood of 1997. In 2010 the flood was responsible for 19 fatalities, affected more than 100 000 people and resulted in economic losses of around EUR 3 billion. In total, around 2 000 km^2 of land mass was flooded (about 0.8 % of the total Polish geographical area) (Matczak et al., 2016). This event was also a test of the new system and effectiveness of training within the framework of the BaltFloodCombat (BFC) Module established in 2009 to enhance national flood response capacity, strengthen European rapid response capacity and build multilateral civil protection capacity.

The BFC Module was a rescue module involving firefighters and logistic experts from Estonia, Latvia and Lithuania, co-financed and deployed by the EU Civil Protection Mechanism during the response operations in Poland. They had undergone several training courses, and the 2010 flood in Poland was their first task.

The evaluation results prepared by the Directorate-General for European Civil Protection and Humanitarian Aid Operations (ECHO) were very positive (Walls et al., 2017). The BFC team demonstrated a high level of expertise and was adequately self-sufficient and flexible. After the completion of its mission in 2010, the international BFC staff continued training through the EU Civil Protection Mechanism, which would lead to the deployment of this group during heavy storms in Pomerania (Poland) in August 2017 and in Spain during torrential rains in September 2019 (Jones, 2019).

However, training did not only focus on professional organisations, but included educating the general public's sense of social responsibility and individual initiative, fostered by the transposition of EU legislation (Floods Directive (Directive 2007/60/EC) and Water Framework Directive), which gave new opportunities for non-governmental organisations (NGOs) to act (Morawski, 2014). NGOs possess the expertise and capacity to create relevant short-term and long-term programmes for the general public.

For example, the Polish Scouting and Guiding Association offers its own programmes including Central Bank of Innovation, Active Citizen of the World, Scouts School for Rescuers and Water Education. The level of training and education its members receive allowed them to effectively participate in operations during floods in 1997 and 2010 (Morawski, 2014). Thus, through a range of transnational initiatives, the flood management systems could build cross-border capacities for preparation and response. In addition to this, further initiatives were created to address recovery efforts across different nations.

The International Commission for the Protection of the Danube River (ICPDR), consisting of 14 cooperating states and the European Union, can serve here as a good example. The ICPDR goals are healthy and sustainable river systems, damage-free floods and implementation of the EU Floods Directive in the Danube River Basin ([3]).
However, implementation of the policy of sustainable systems can be hindered by various obstacles.

- Cultural differences (political and administrative approach/solutions). For example, generally accepted ecological solutions promoting green infrastructure are hindered by governance style in a given country, such as a lack of methodology, of a land registry or of access to the land (Spain, Italy, Romania, Slovakia).

- Natural obstacles. Part of the Vistula river is protected under the Natura 2000 programme, which blocks any other activity connected with flood management without prior and individual consultations.

- Lack of information about climate change as a main driver of flood risk, or lack of reference to climate

([3]) The frequency of flooding – 2002, 2006, 2010, 2013, 2014 – justifies the importance of those actions.

change in the flood management plans (Bulgaria, Romania and Slovenia). An example of good practice for climate change education is the ClimateChangePost website, which presents the latest news on climate change and adaptation (ClimateChangePost, 2020; this forum is based on the latest results in scientific journals, and reports by the Intergovernmental Panel on Climate Change and the European Environment Agency).

Risk awareness, which conditions the successful planning of all risk management stages, involves building cultural awareness (ensuring cultural participation, access, and the right to express and interpret culture), which drives all positive incentives and cooperation. And ethnicity is seen as a factor determining flood resilience (Fielding, 2017).

Diversity and inclusion are promoted by the Annual International Danube Days initiative (ICPDR, 2019). It is a cross-border and basin-wide event, which engages governmental, non-governmental and private sector organisations from 14 countries of the basin, which work together to organise river fairs and clean-up actions, conferences and awareness-raising activities, aquatic and sporting challenges, leisure cruises and fun youth events to promote a safer Danube. In spite of different cultures (ethnicities) and histories, people share a desire and responsibility to protect the region.

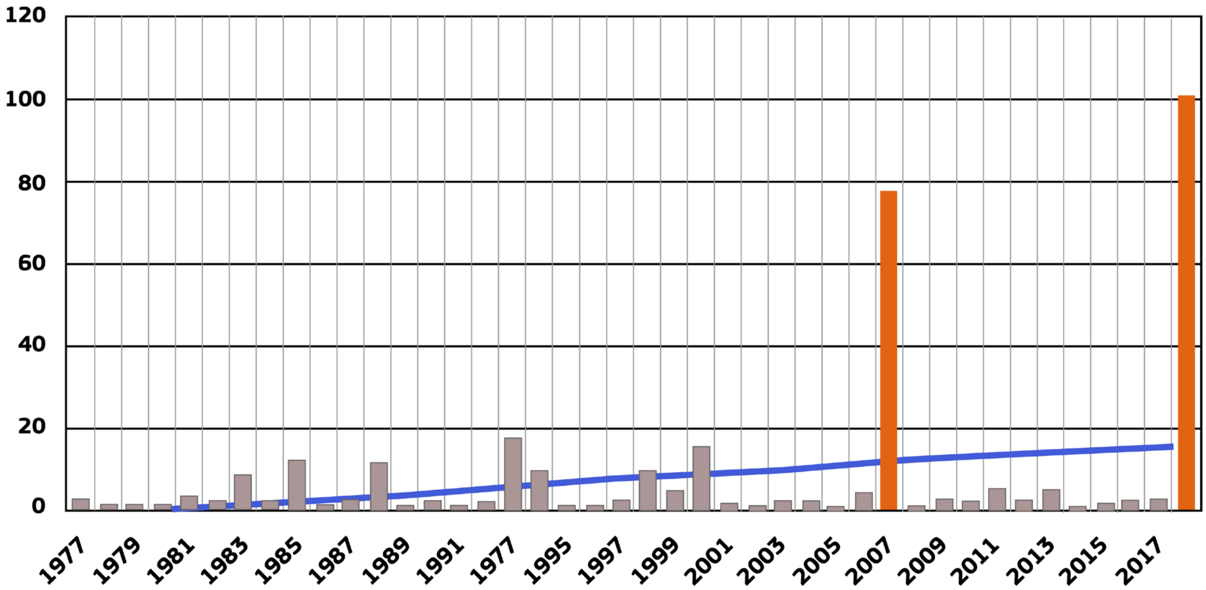
4 Case study III: experiments of cooperation between universities, authorities and school communities for risk education, Greece

Forest fire risk management involves the community exposed and several organisations, each of which has partial knowledge and a distinct risk perception and culture usually focusing on a specific disaster risk management (DRM) phase (prevention or emergency). Bridging the divides and consolidating a culture of prevention is a precondition for success.

Historically, Greece has been exposed to multiple natural and climate-related hazards, predominantly floods, earthquakes, heatwaves and forest fires. Recently, forest fires have become a top-priority hazard and challenge for the country and especially for the responsible institutions and communities in mixed forest and residential areas. The increase in exposure and forest fire disaster risk is probably associated with climate change and the expansion of wildland–urban interface areas since the 1970s, and it is evidenced in the human losses caused by disaster events almost every year since 1977 (Figure 2).

The situation is expected to worsen further in the future as a result of climate change. According to the committee established by the central bank of Greece to report on climate change impacts in Greece (Bank of Greece, 2011), the extremely high risk of wildfire (depending on the humidity of the air, 24-hour total precipitation, air temperature in the middle of the afternoon and the maximum speed of the average wind) will increase by 20 days in the period 2021–2050 and 40 days in 2071–2100 for eastern Greece and slightly less for western Greece. In 2007 and 2018 the country experienced deadly forest fires (84 deaths and financial losses amounting to EUR 3.5 billion in 2007; 102 deaths in Attica alone, the capital region, in 2018) and the public debate on the reasons for the dramatically failed disaster management endeavours is still going on.

Figure 2. *Annual distribution of human deaths due to forest fires in Greece, 1977–2017.*
Source: *GFMC and the Independent Committee of Experts for the investigation of Forest Fire Causes, 2019.*



The national culture concerning forest fires and their management is predominated by an over-emphasis on hazard factors and not on exposure and vulnerability. Consequently, forest fire DRM is considered mostly a matter of the forest fire suppression mechanism and not an issue of prevention, preparedness and sustainability at the community level. This misconception (aligning with tolerance of illegal building development in forest areas) generates difficulties in understanding and cooperation even mutual acceptance in DRM of the institutions responsible for emergency operations on one hand (e.g. Fire Brigade) and those that are involved in prevention and preparedness (e.g. Forest Service, Spatial Planning, Education and Awareness) on the other.

This split of perceptions and knowledge between the organizations involved explains failures in DRM to a great extent (Kalogirou et al, 2011). In particular, Fire Brigade claims the exclusive responsibility of Forest Fire Management setting aside the necessary preventive policies by means of spatial planning and education - awareness institutions. This results in spatial and land use policies undermining whatever efforts for forest protection and forest fire risk reduction, in community unawareness of exposure and vulnerability in wildland urban interface areas and a culture of irresponsibility of citizens regarding forest fire risk mitigation (Sapountzaki et al., 2011).

Changing the culture of organizations and communities toward forest fire prevention assumes, among others, long-term forest fire risk education and training to start at the school level. In 2010, in the context of the EU project Linking civil protection and planning by agreement on objectives (INCA), a team of researchers from Harokopio University of Athens and the Institute of Mediterranean Forest Ecosystems, in collaboration with the regional authorities of Attica, planned and implemented measures to bridge forest fire risk knowledge, cultural and perception gaps between the institutions involved and the general public. Among the measures implemented, there were two successive seminars on forest fire causes, prevention and self-protection for 43 pupils (12–14 years old) of a public school in the municipality of Kalyvia in Attica.

While this seems a purely civil protection measure, it contributes nonetheless to forest fire prevention through the emphasis of the seminars on the land use conflicts behind the causes of the phenomenon (Greiving et al., 2012). Kalyvia was selected as a pilot case because it had had a high record of forest fire disasters owing to its extensive mixed forest and residential areas. The material of the seminars was organised to include information concerning the forest fire phenomenon, causes and impacts, the areas exposed and prevention possibilities; they also gave guidelines for actions to do and not to do for personal safety, in line with the standards/norms set by forest fire management authorities.

PowerPoint presentations and videos were considered the most suitable visual aids to be used for pupils of this age, and these were prepared by the team of scientists and practitioners. Each seminar was preceded and followed by an appropriate questionnaire, which the pupils completed twice (before and after). The questionnaire aimed to (1) address pre- and post-seminar forest fire knowledge and risk perceptions of pupils and teachers, (2) assess the actual effect of the seminars on the school community's initial perceptions and awareness levels, and (3) get feedback for adjustment of the seminars and the overall forest fire risk communication strategy for young people and their community towards a culture of prevention. Statistical processing of the answers has produced the following important findings (Spountzaki and Varympopioutou, 2011).

- The impact of the two seminars has been significant on forest fire risk knowledge but not so significant on sensitivity and perceptions.
- The meaning of prevention remains rather vague in pupils' minds; for example, they consider fire hydrants or firefighting aeroplanes preventative means.
- Pupils' perceptions of forest fire causes are characterised by contradictions. While the majority acknowledge that houses in forests increase the risk of forest fire, most of this group prefer to continue living in the forest rather than in a settlement.
- The majority judged the seminars useful and worth including in routine school curricula. However, they should only be included after scientists and practitioners had aligned their diverse views.
- Pupils have their own imaginative proposals for promptly alerting fire stations. Some proposed audible fire alarm systems to be placed in the forests, while others proposed vigilant forest monitoring

The overall success of the programme was due to the effective cooperation of different organisations involved in forest fire risk prevention and awareness: university and research institutions, a municipality, regional authorities and a school community. The programme succeeded in bridging complementary knowledges and diverse cultures (organisational and societal, including different generations and social classes). The process demonstrated that a knowledge-intensive institution is a necessity; it enjoys (a certain degree of) credibility and trust, it is acceptable as a negotiator and external to the conflicts between local and regional authorities and different sections of administrations (see also Lofstedt, 2005).

In 2018 (November) and after deadly flood and forest fire disasters in Attica, certain schools requested the support of universities to organise seminars for pupils about seismic, forest fire and flood disasters. The Department of Geography of Harokopio University of Athens (a former partner in the INCA project), responded to the request and the author coordinated the organisation of seminars (in the university facilities) covering the whole management cycle of all three types of disasters. The organisation of seminars was based on the approach of the INCA project, while their interactive component was reinforced. Two questionnaires were completed by the pupils, one about the pre-disaster period and the other about the crisis period. Each questionnaire was filled both before and after the seminars. The questions aimed once more to check DRM knowledge before and after the seminars (with an emphasis on prevention) and identify changes in perceptions and awareness. Certain queries were aimed at judging pupils' relative trust in various sources of forest fire risk information.

Quantitative and qualitative analysis of the answers to the questionnaires confirmed and expanded the findings of the first experiment in Kalyvia municipality. The seminars improve pupils' knowledge easily but their perceptions are difficult to change because they depend on individual psychological factors, the family context and the school experiences of each pupil. The majority of pupils aged 12–14 years trust their family and school for risk information more than any other source. Also, while the majority feel certain about what to do in the event of an earthquake because of the relevant lessons and training they have had in school, this is not the case with floods and forest fires, for which an intensive educational and training effort should be undertaken, particularly towards prevention and preparedness. Finally, the majority of pupils trust collaboration between their school and a university as the basic source of knowledge and messages about disasters.

Changing cultures to promote risk prevention at the community, institutional and national levels is a long-term process that starts at school age and necessitates bridging of institutions' cultural divides.

5 Conclusion and recommendations

Multi-hazard events may include floods, fires, earthquakes or terrorist events and they all represent a challenge for societies and groups globally. Disasters usually have an impact on a population that is characterised by different levels of vulnerability due to people's education and culture. Disaster education and training therefore needs to work with a person-centred disaster approach that takes these educational and social variations into account. Given this, successful education and training needs to overcome top-down approaches, but emphasise collaboration and mutual learning, for instance through comprehensive policies reaching beyond individual nation states.

For several reasons, more often than not the risk culture and perceptions of broader societies, communities and risk-responsible organisations are biased towards an overemphasis on emergency response and disparagement of the criticality of prevention. In such cases not only more risk knowledge but also a change in the predominant culture is necessary. This can be achieved only through a long-term educating process that starts at school age (preferably) and presupposes bridging the divides between distinct and different organisational cultures. It can also be achieved by promoting cultural inclusion in all areas of the risk management system, which requires cyclical collective training programmes that engage all parties with the help of cultural intermediaries. Such promotions may also include hosting international events to integrate a variety of cultures and all social, ethnic and age groups, involving individuals and NGOs involved in DRM.

Research on disaster education and cultural inclusion is still an emerging field. There are to this date only a few large-scale collaborative projects that involve universities and public and private disaster organisations on issues around education and cultural inclusion. At the European level, there is no specific funding scheme that could support such research. This is particularly concerning because many public service providers, from fire services to schools, have collected considerable data that could be used to improve their service provision, but remain unexplored for lack or resources, skills and incentives to engage with that data.

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Chapter 5

Transferability of knowledge and innovation across the world

Online Version

5 Transferability of knowledge and innovation across the world

CONTENTS

5
Transferability of knowledge and innovation across the world

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1 Introduction to risk governance and its challenges

Early warning systems must begin with community ownership and engagement, which require a complete understanding of populations, including their vulnerability to potential impacts to hazards.

The key challenge for disaster risk management (DRM) policymakers and practitioners is how to effectively capitalise on the knowledge at local, national, regional (i.e. European) and global levels. This challenge may be overcome through documenting good practices (i.e. approaches and methods that solved a specific problem, produced expected results and provided benefits) and sharing and promoting them as appropriate. Good practices that enhance DRM effectiveness are a valuable source of knowledge for decision-makers and practitioners, and should be further studied and perused.

This chapter provides examples of good practices from the Member States of the European Union (EU) and the countries or regions outside the EU, showcasing approaches and methods utilised across the entire DRM cycle, from risk reduction to response and recovery. The good practices are presented in text boxes throughout the chapter, briefly presenting the challenge, the solution and benefits. Disseminating these good practices is beneficial for:

- improving an understanding of risk, contributing to Priority 1 of the Sendai framework for disaster risk reduction (2015–2030);
- recognising potential alternatives to manage cascading and compounding risk;
- avoiding limitations when planning and implementing measures to reduce risk in the context of interest.

Following the overview of the good practices and the prerequisites to promote knowledge transfer, DRM processes (viewed as a system of systems) are discussed and illustrated with two case studies of end-to-end impact-based early warning systems. An early warning system, viewed as a system of systems that enables effective DRM processes, is reliant on expert knowledge for risk assessment, interpretation and communication (Fakhruddin et al., 2019b).

It is essential that such systems begin with community ownership and engagements, which require a complete understanding of populations, including their vulnerability to the impact of hazards (Fakhruddin et al., 2019a). Two case studies, one in the EU and one in the Pacific, are presented, highlighting the importance of risk communication and knowledge transfer throughout the entire DRM process, followed by how these early warnings are received and acted upon. This then transitions to gaining an understanding of behavioural responses, especially to early warnings. Two case studies, one in New Zealand and one in Italy, examine behavioural response to natural hazards. The final section draws on conclusions from lessons learnt from these studies to improve knowledge of understanding behavioural response and risk communication.

2 Importance of knowledge transfer for system-based approaches

A great amount of knowledge of DRM remains fragmented, calling for good practices to be shared and tested more regularly to be applied elsewhere.

In a complex and multi-layered society, the capacity of social and political actors to govern depends on the exchange of resources, knowledge and expertise (Kooiman, 1993). DRM is no exception. It involves multiple actors with different interests, responsibilities and capacities, at various governance levels, from global to local. Many stakeholders are officially involved in the planning and implementation of measures to reduce risk, such as decision-makers, civil protection groups, non-governmental organisations (NGOs), experts and insurance groups. More recently, the importance of local and indigenous knowledge and practices has received increasing attention in the field of DRM (Hiwasaki et al., 2014). Although advances towards including knowledge and practices in DRM policies are becoming more widely recognised, implementation remains limited (Hiwasaki et al., 2014). A community-based participatory approach in the design and implementation of policies and projects is proven to be effective, through defining local people's vulnerabilities and capacities and being able to respond to and adapt to disasters (Samaddar et al., 2015) (Box 1).

Engagement of communities in policymaking is promoted through policy frameworks and institutional structures around the world, but it is still not at the desired level (Cheema et al., 2016). People may be motivated to contribute proactively to DRM by designing long-term processes, identifying benefits for participants and adapting legal frameworks for responsibilities to be shared and flexible (Scolobig et al., 2015). Lessons learned are not just repositories of knowledge; they may be used as a tool to raise awareness and open up discussions.

Hicks et al. (2019) reviewed literature on community engagement in DRM around the globe and concluded that research was not comprehensive: there are fewer experiences shared from Africa, and most of the literature analysed citizen behaviour in the aftermath of floods and earthquakes. It seems that citizens become highly active after an event and, as a way to cope with the event, they bond with the existing networks and look for new ones (Kim and Hastak, 2018). These community groups become less heterogeneous in the long run, grouping around ethnical, political or religious beliefs and not only based on the place of residence (Guarnacci, 2016; Baytiyeh, 2017). More information on citizen engagement in the EU is in Subchapter 4.2.

People learn, interact, transfer and combine knowledge from others (Nonaka and Takeuchi, 1995). Knowledge is enhanced by the characteristics of the space where the actions happen, so culture plays an important role in how collaboration and sharing happen among individuals and groups (Perry et al., 2019). Knowledge is transferred through dialogues, documents, learning by doing, and sharing lessons learned. Stories, as a repository of knowledge, support learning and innovation, and help solve the present challenges as well as those that may be faced in future (Brown and Duguid, 1991). Besides culture, knowledge transfer depends on the channel used and the willingness, trust and capacity of the one(s) sharing knowledge and the one(s) receiving it (De Long and Fahey, 2000; Davenport et al., 2001; Riege, 2005; Fakhruddin et al., 2019a). This section discusses ideas for promoting knowledge sharing and transfer, which in turn create new knowledge and synergies.

One way to share and transfer knowledge is through system-based thinking (Haimes, 2012; UNDRR, 2019). This

BOX 1.

Community-led DRM in response and recovery

From global to EU

Who?
Māori, indigenous people of New Zealand

Why?
There is an increasing recognition of the value of community-led initiatives that facilitate emergency response and recovery (Kenney and Phibbs, 2015). However, cultural approaches to DRM and recovery are rarely acknowledged. In New Zealand, Māori DRM initiatives are collaborative, effective and shaped by their cultural values (Kenney and Phibbs, 2015; 2014). This was witnessed during the 2010/11 Canterbury Earthquake Sequence (CES). There is a need to adapt cultural technologies and implement them into integrated DRM at local and national levels. The Māori community-led response to the 2010/11 Canterbury Earthquake Sequence exemplifies the ways traditional Māori knowledge values and practices are interrelated and actioned to facilitate DRR and community resilience for disaster response and recovery (Kenney and Phibbs, 2015; 2014).

What?
The Māori community-led recovery network linked emergency management, government agencies and other responders to ensure that resources and support were available to communities during the response to and recovery from the 2010/11 Canterbury Earthquake Sequence. Māori knowledge, oral histories, value and practices shape behaviours and actions at community and individual levels to ensure community well-being (i.e. unity, family, building and maintaining relationships, community centres, support/hospitality and guardianship) (Kenney and Phibbs, 2015). Examples of this were providing food and shelter during the 2010/11 Canterbury Earthquake Sequence response and supporting communities during the recovery phase.

Community-based knowledge and programmes are an effective tool for building disaster resilience in communities. This example demonstrates how cultural knowledge, values and practices may be utilised during an emergency response and support community resilience in a way that is applicable to other countries with indigenous populations that have similar values and traditional knowledge.

means active involvement from all stakeholders and a feedback loop to continue building a better DRM system and enhance resilience. The global risk assessment framework, an open and collaborative global initiative of UNDRR to improve DRM, provides guidance on non-linear changes in hazard intensity and frequency, ensures that the guidance is well understood by citizens and policymakers, and requires accelerated systemic actions (Gordon, 2020).

Despite the wealth of scientific and indigenous knowledge, challenges remain in the systematic use of this knowledge and evidence from good practices, and in their integration into DRM process to inform policymaking and decision-making (Spiekermann et al., 2015). The main issue is largely related to the dispersion of information among various stakeholders without a coherent and coordinated approach (Spiekermann et al., 2015). Local disaster risk knowledge and information is not systematically used for decision-making in disaster risk reduction (DRR) policies. International agreements call for more inclusive approaches, including even the stakeholders that are not traditionally part of the DRM community (Brown et al., 2018). Uptake and use of knowledge from

BOX 2

Building the resilience of small businesses

From global to EU

Who?

National Incident Management Systems and Advanced Technology (NIMSAT) Institute, Louisiana (USA)

Why?

This was an effort to help small businesses, often lacking resources and knowledge, to be better prepared for all-hazards disasters. It aimed to improve disaster preparedness and response, providing situational awareness, locating local products and services, addressing critical recovery needs and restoring business as usual quickly. (Figure 1)**.**

What?

- Big business–small business platform

The 'big business–small business' platform was established by the NIMSAT institute in 2012. It engages big businesses to mentor small ones, helping them to strengthen their disaster preparedness and recovery. It is on a voluntary basis and promotes a proactive (whole-community) emergency management approach. Big businesses benefit from strengthening their supply chains and positive branding. Small businesses learn about resilience/business continuity, obtain missing resources and adopt best practices from experienced leaders who have been through disasters and know what it takes to survive.

Figure *1. Simulation exercise for ICS.*
Source*: Fakhruddin, 2015*

- Virtual Business Emergency Operations Center

The Virtual Business Emergency Operations Center is an online platform that facilitates collaboration between public, private and non-profit organisations (vBEOC, n.d.). It leverages best practices in information sharing, lessons learned from research in public–private partnerships, and experience in leading the Louisiana Business Emergency Operations Center. It has grown into a national network of organisations ready to implement the technology. Their technology is free, customisable, user friendly and capable of supporting existing processes and incident management systems.

This would benefit all countries, helping them to empower the community, raise awareness of DRM and engage private sectors. For more information: https://www.onvcp.org/iema/

good practices are encouraged (Box 2). Sharing knowledge and applying it to transferring best practice enables structures, process and systems to improve in the policy decision-making space (UNISDR, 2016). Culture has a strong effect on communities' survival and has proven to act both positively and negatively when people put into practice measures to reduce disaster risk (Kulatunga, 2010).

BOX 3

Scientific evidence at the service of local initiatives – Vertical Evacuation from Tsunamis: a guide for community officials

From global to EU

Who?
American Federal Emergency Management Agency (FEMA)

Why?
This project was undertaken to address the need for guidance on how to build structures to resist the force and impacts of large earthquakes and tsunamis. The aim of the project is to support coastal communities that are vulnerable to tsunami, which could inundate low-lying areas in a matter of minutes, and to enhance their capacity to evacuate to safety.

What?
The publication guide presents information on how vertical evacuation design guidance can be used and encouraged at the regional (state) and local levels. The purpose is to help government officials and the public by providing them with information to address tsunami hazard risk in their community and to determine the need for a vertical evacuation structure.

The guide includes characterisation of tsunami hazards, choosing between various options for structures, locating and sizing structures, estimation of tsunami load effects, structural design concepts and other considerations.

Many coastal communities are vulnerable to tsunami, especially nations that sit within or next to the Pacific Ring of Fire. This project is an example of good practice addressing the need for safety measures to prevent loss of life. It would be beneficial for many countries that need to address the gap in tsunami risk life-saving measures and determine the need for vertical evacuation structures.

New Zealand is an example of reviewing international frameworks such as FEMA's Guidelines for design of structures for vertical evacuation from tsunami (FEMA, 2012) as a guideline to inform a vertical evacuation assessment and planning guideline suitable to New Zealand's context and standards (MCDEM, 2018).

For more information: https://www.wbdg.org/FFC/DHS/femap646.pdf

BOX 4

Networks and partnerships in the Pacific North West Economic Region

From global to EU

Who?
Pacific North West Economic Region (PNWER) Center for Regional Disaster Resilience

Why?
State/jurisdiction governments understood that there are regional hazard impacts but the governments had influence only within their borders. The PNWER enables them to cross borders and have a collective approach to solve tough issues.

What?

- Regional Critical Infrastructure Protection Workgroup
  The PNWER conducts quarterly conference calls with the critical infrastructure protection (CIP) managers from the PNWER member states and provinces. This interstate, cross-border forum has generated an open forum to discuss key issues that affect the region.

- North-West Warning Alert and Response Network (NWWARN): www.nwwarn.org
  The NWWARN is a regional communication tool for cross-sector critical infrastructure communications. The online system provides information from trusted sources to protect critical infrastructure systems and ultimately the public. It is capable of providing early warning messaging and two-way situational awareness before and during a disaster. The PNWER has led this effort for over 8 years in cooperation with the Department of Homeland Security, the Federal Bureau of Investigation, FEMA, Washington State Fusion Center and private sector partners. For more information, visit: www.nwwarn.org

- Puget Sound Partnership for Regional Security Program
  The Puget Sound Partnership for Regional Security, together with the PNWER, conducted a seminar with regional critical infrastructure owners and operators. The seminar focused on transportation, supply chain and freight resiliency; developing a regional information-sharing and analysis capability; and pandemic and biological event resilience. In 2020, the focus will be on seminars for critical infrastructure owners and operators in the Puget Sound area. The outcomes from these events will be shared with the region's CIP managers.

Europe shares a landmass, so natural hazards often occur across multiple countries. This approach would allow a more collaborative approach between countries to ensure that their warning systems, procedures and policies are uniform.

For more information: http://www.pnwer.org/

BOX 5

Local and indigenous knowledge for community resilience

From global to EU

Who?
Small island communities in Indonesia, the Philippines and Timor Leste, supported by the United Nations Educational, Scientific, and Cultural Organization (UNESCO)

Why?
Local and indigenous knowledge has received increasing attention in the field of DRM and climate change adaptation. However, the knowledge of indigenous people is yet to be included in policy decision-making. Indigenous knowledge is crucial to understand long histories of interaction with the natural surroundings and potential impacts on the environment and loss of life (Figure 2). The wealth of such knowledge would enable communities to increase their resilience and be better prepared for future hazard events.

What?
The project documented indigenous knowledge and practices that help communities to predict, mitigate and adapt to hydrometeorological hazards. It developed tools for integrating indigenous knowledge with science on hydrometeorological hazard risk reduction and climate change impacts.

The aim of this project is to showcase the results to inform other national and local government entities to promote the use of local and indigenous knowledge to take actions and integrate such knowledge into planning and practice to increase coastal community resilience. This could be of particular interest for countries in the Pacific and Asia.

Figure 2. *Community consultation on disaster responses.*
Source: *T+TI, 2018.*

For more information: Hiwasaki et al (2014).

Mechanisms for enhancing knowledge transfer and uptake include:

- promoting more systematic dissemination of scientific information that would identify ways of translating it into practical methods that could be integrated into DRM policies (Box 3);
- identifying ways such as fostering stronger and more inclusive partnerships between scientific agencies, communities, governments and other networks to scale up the applications of science to policy and practice (UNISDR, 2016) (Box 4).

From empirical studies, some considerations have been found that could limit collaboration between different individuals and groups, particularly when they have different backgrounds and interests, such as (Mejri and Pesaro, 2015; Spiekermann et al., 2015; Sitas et al., 2016):

- values and interpretation of risk,
- personal attitudes and incentives,
- preconceived assumptions and stereotypes,
- discipline-embedded thinking,
- resistance to new practices,
- power structures,
- budget constraints,
- potential hindrances to accountability and transparency.

At the same time, individuals report not having enough time or incentives for learning and exchanging, especially in project-based organisations (Koskinen et al., 2003; Williams, 2008). Those represent a large number of stakeholders in DRM in some areas of the world, represented by groups or organisations of different types and sizes, such as civil society or non-profit organisations.

The purpose of sharing lessons learned is to apply them elsewhere. Some barriers are common in practice, such as (WHO, 2015; Singh et al., 2016; Sako et al., 2018):

- time and budget constraints,
- rebuilding of structures not in alignment with the context's values and institutions,
- political commitments,
- not addressing root problems, such as food shortage,
- low participation of users and of key actors (Box 5).

Identify how to strengthen and enhance existing technology initiatives that promote networking, information sharing and knowledge transfer to improve implementation of DRM strategies (Box 6). This should consider more systematic and reinforced science/policy and science/practitioners interfaces including scenario research to address future risk and challenges, and ways to track indicators by using community-driven impact assessments to better react proactively to early warnings.

BOX 6

Development of technology for emergency management systems

From EU to global

Who?
The European Data Interoperability Solution at Stakeholders Emergencies Reaction Consortium

Why?
To achieve a detailed common operational picture shared between organisations with different systems, between regions or even between countries.

What?
Emergel (EMERgency ELements) is a technology and supporting tool that provides interoperability between emergency management systems. The Emergel ontology contains the knowledge objects used by responders in different countries, along with their terminologies. It is used to allow the exchange of information between emergency management systems, and facilitates semantic interoperability by means of translation and mediation.

This is particularly relevant to countries that share borders, as they need to ensure that natural hazards and disasters can be managed across the country borders in a uniform and effective manner.

For more information: https://cordis.europa.eu/project/id/285069

3 Transferring practice: what works

A critical factor in addressing disaster risk reduction and climate change adaptation is the complexity and diversity of the stakeholders involved.

This section highlights the elements to consider to facilitate the transferability of best DRM practices between regions. Here, transferability means that techniques, knowledge or methods developed in one case study can be used in other places (Kelman et al., 2012).

3.1 Governance

The effects of climate change are being experienced now, and it is a major challenge for nations to address sustainable development and impacts on livelihoods, assets and critical infrastructure (Amin and Watkins, 2018). We first look at risk governance, and in particular the link between DRM and climate change adaptation (CCA). Risk governance plays an important role in facilitating knowledge transfer and informing practices.

DRM is dependent on researchers, governmental organisations and other sources integrating knowledge from best practices and lessons learned from previous disaster events. Knowledge and experiences from these experts can provide guidance for sound and informed decision-making and systematic approaches to effective DRM policy and practice.

Successful risk governance can be measured by how effectively the sectors are able to work together and incorporate knowledge into planning and practice (Box 7a and 7b). The EU features a wide range of approaches, some of which may fit risk governance systems outside the EU. A critical factor in addressing DRM and CCA is the complexity and diversity of the stakeholders involved.

There are no reasons for climate change to be separated from wider DRR and sustainable development processes (Kelman, 2017). The separation is related in part to the frequent administrative and political separation of the activities involved. For instance, Germany is organised in a decentralised way, which means that responsibilities are shared among different departments. Stakeholders dealing with DRM are associated with the Federal Ministry of the Interior,

Building and Community, while those involved in CCA activities are, for example, based at the German Environment Agency. However, it is not only the horizontal separations (i.e. different departments or ministries) that constitute a challenge, but also vertical ones (i.e. different levels of governance) (Marx et al., 2017). Switzerland exemplifies a strongly decentralised and yet hierarchical system where cantons (federal states) have a mandate to prioritise and implement measures, funded by and reporting back to the federal level (Abad et al., 2018).

France is one of the rare cases in Europe where DRM and CCA fall under the responsibility of the same ministry, the Ministry of Ecological and Solidarity Transition. However, the two policy areas are split into separate directorates, with DRM falling under the remit of the General Directorate for Risk Prevention and CCA falling under the remit of the General Directorate for Energy and Climate. This means that in France the main challenge is not how to prevent policies from diverging, but rather how to ensure they converge (Amaratunga et al., 2017).

BOX 7a

Climate change risk assessments from New Zealand and the United Kingdoms

From global to global

Who?
New Zealand Government

Why?
New Zealand is experiencing the impacts of a changing climate and needs to be better prepared to adapt to the effects. There is a need to mitigate greenhouse emissions for a more sustainable future, recognising the importance of minimising loss and damage associated with climate change adverse effects. In the absence of a worldwide effort to reduce emissions in accordance with the Paris Agreement, New Zealand is planning to develop policy and guidance to tackle climate change.

What?
The New Zealand Government's role is to provide a legislative policy framework and guidance to support local government and businesses to make decisions on adapting to climate change impacts (Ministry of the Environment, 2019). New Zealand has developed its first national climate change risk assessment framework, which consists of:

- a national climate change risk assessment, to improve the understanding of climate risks;
- a national adaptation plan, which outlines the approach to improving climate resilience;
- monitoring and reporting on implementation of the national adaptation plan.

Engagement events were held with central and local governments, climate change experts, Māori representatives and affected sectors. Significant engagement of all those involved meant a more comprehensive knowledge and skill base for understanding climate change risks to New Zealand.

This framework can inform a similar approach for mitigating adverse climate change effects in other countries. This is an example of good practice in addressing all aspects of climate change, as it takes into account both immediate and long-term effects in preparing for the future.

For more information: https://www.mfe.govt.nz/publications/climate-change/national-climate-change-risk-assessment-new-zealand-main-report

BOX 7b

Climate change risk assessments from New Zealand and the United Kingdoms

From global to global

Who?
United Kingdom Government

Why?
Under the Climate Change Act, the United Kingdom Government undertakes a country-wide climate change risk assessment every 5 years to understand present-day and future vulnerability, assess climate-related risks in up to 50 years' time and prioritise opportunities to manage these risks in the next 5 years (HM Government, 2017)

What?
The climate change risk assessment conducted in 2017 identified six immediate priority areas of climate change risk that need to be managed:

- flooding and coastal change risks to communities, businesses and infrastructure;
- risks to health and well-being;
- risks of water shortage;
- risks to natural capital;
- risks to domestic and international food supply and trade;
- new emerging pests and diseases.

This information is intended to assist local-level planning by government officials and policy and technical experts. However, it can also inform a similar approach to addressing the risk of climate change in other countries in the EU and prioritising similar actions if applicable.

For more information: https://www.theccc.org.uk/uk-climate-change-risk-assessment-2017/

At the EU level, the ESPREssO (Enhancing Synergies for Disaster Prevention in the European Union) project (ESPREssO, 2018), supported by the EU's Horizon 2020 framework, analysed Europe's approach to DRM and CCA. Three major challenges identified were: (1) creation of synergies between the DRM and CCA sectors at the national and EU levels; (2) enhancement of risk management capabilities by bridging the gap between science and policy at the local and national levels; and (3) facilitation of more efficient management of transboundary crises. ESPREssO established a Europe-wide forum of stakeholders from all governance levels, including policy, science and technical practitioners, to debate on and study these challenges. The outcomes will be of relevance beyond the EU.

Furthermore, Birkmann and von Teichman (2010) propose that the national level is the most suitable one to enable CCA and DRM communities to enhance the communication and match strategies between countries, irrespective of national differences. At the national level, agreed goals and targets are defined (such as what 'resilience' means) and policy and institutional frameworks are developed. Gaillard and Mercer (2013) point out that risk is materialised and vulnerability tackled on the ground, at the community level. Hence, the authors claim, there is a need to institutionalise good practices at the community level and use this, together with the scientific knowledge, to achieve large-scale results.

Community networks facilitate collaboration and participation for disaster resilience (Djalante et al., 2011). Many groups and committees have been created in the last two decades to pool knowledge on disaster and climate change, separately or collectively. National policies, strategies and plans for DRM and CCA need to ensure that gaps are detected systematically from national to community levels and addressed with appropriate measures (Standards New Zealand, 2009, Trogrlić et al., 2017, UNEP, 2008,). In that sense, global or national science and technology roadmaps (e.g. UNDRR, 2019a, UNISDR, 2016, UN-SPIDER, 2019), regional strategies (e.g. Amaratunga et al., 2015) or national disaster resilience strategies (e.g. NDRS, 2019) can serve to evaluate the networks.

The governance model should not only ensure that stakeholders and sectors interact and that governance levels are aligned and coordinated, but ensure a DRM system that promotes learning. From the evaluation of projects, programmes and policies, lessons learned should be collected and stored for future use. More information on linking levels and actors is provided in Subchapter 4.1, 'Linking actors, sectors and governance levels'.

3.2. Context

Second, we look at DRM solutions, as it is important to understand that good practice may not work as well in a new environment as in the original setting, or may be completely inappropriate (Szulanski, 2003; Delpeuch, 2008). From a 'contextual practice' point of view (Ambler, 2011) what is 'good' (or 'best') varies with the context. It is necessary to understand the challenges that one could come across when implementing good practices and what could be done to overcome them. Practices are rarely directly transferable. They often have to be adjusted and customised for the new application context and can evolve into a better version as improvements are discovered (Trucco, 2015). Cultural, social, institutional and political differences between countries always have to be considered when transferring practices to developing areas; lessons should be applied to solve the present and future needs of the particular place (Tiwari, 2015).

3.3. Tools and methods

If specific elements (i.e. determinants) of each good practice could be extracted, as well as lessons learned, it would be easier to connect them to DRM issues that could be addressed by applying them. Trucco (2015) identified four types of good practices (activities, procedures, tools and technologies), mapped their contribution to resilience depending on disaster response phases, and assessed them across three dimensions relevant to their wider exploitation. To be applied, knowledge should be captured, stored, retrieved and transferred into suitable methods and technologies. Monitoring and evaluation of the measures taken before and after a disaster is an interesting source of learning. For example, operational teams train and enhance their capacities to be ready for and respond to emergencies, as shown in Box 8. Exercises and drills are an opportunity to create capacities and to test protocols and plans, although they are not always carried out and few are followed up (Beerens and Tehlerb, 2016; Skryabina et al., 2017).

BOX 8

Com Romania – improving the resilience of emergency response buildings

From global to global

Who?
World Bank and Government of Romania

Why?
The project contributes to strengthening Romanian emergency response buildings against earthquake and extreme climate events so that these buildings remain fully operational in the aftermath of disasters. This will ensure that response efforts in the aftermath of disaster are not negatively affected, and in turn can help save lives (Figure 3) and reduce the socioeconomic impacts of future events due to natural hazards.

Figure 3. *SMURD (the Mobile Emergency Service for Resuscitation and Extrication) in action near Cluj-Napoca.*
Source*: Wikimedia Commons.*

What?
The project aims to enhance the resilience of critical response facilities and strengthen institutional capacities for emergency preparedness and response in Romania. It specifically supports priority retrofitting and reconstruction of vulnerable General Inspectorate for Emergency Situations buildings, fire stations and police buildings. These buildings will also be modernised to meet operational requirements, energy efficiency, universal access and gender considerations given the changing demographic in emergency response. The project also guides infrastructure planning of emergency response buildings. It strengthens institutional capacity for operational readiness through training, acquisition of essential emergency equipment, development of data and information on disaster and climate risks, and public awareness activities. These integrated efforts in the emergency response and civil protection sectors could be linked to DRM and CCA.

Knowledge is also produced after transfer and application. In DRM, knowledge comes from different stakeholders and levels, within their own realities and cultures; much of the knowledge that could be relevant to share is contained in individuals' minds or within groups of people (Boxes 9 and 10; see also Subchapter 4.1). Organisations should exploit the knowledge that remains uncodified, based on the experiences of individuals or groups, particularly for the personnel engaged in operations to deal with uncertain events, such as emerging public health incidents (Sanford et al., 2020), to avoid reinventing the wheel in the aftermath of an event (Koria, 2009).

BOX 9

Cross-border approaches to increasing resiliences

From global to EU

Who?
Pacific North West Economic Region (PNWER) Centre for Regional Disaster Resilience

Why?
The aim is to create and foster cross–sector partnerships focused on infrastructure security and disaster resilience.

What?
The PNWER has organised six critical infrastructure interdependency exercises since 2012. Each exercise was designed by the stakeholders and reflected regional concerns on terrorism, cybersecurity, natural hazards, pandemic flu, supply chain resilience, public health and flooding. An integrated action plan was created based on the findings and recommendations of the exercises. Numerous projects from the action plan are under way.

BOX 10

Upgrade of information management

From EU to global

Who?
Instituut Fysieke Veiligheid (Institute for Physical Safety), Netherlands

Why?
The aim is to enable all responders within Dutch safety regions (local and regional public authorities) to collaborate closely to manage critical events and disasters.

What?
The *Landelijk Crisismanagement Systeem* (National Crisis Management System) is a distributed information system focused on geographical information and linked data. It contains modules for communication, coordination and logistics; efficient exchange and disclosure of information; and drafting a geographical information system (GIS) view.
Similar GIS platforms may be used in other countries, leveraged for multiple uses, such as community outreach, emergency response and action by government agencies.

For more information: https://www.lcms.nl/about-lcms

Regardless of the methods and technology, the lesson learned should contain a set of information to be analysed and incorporated elsewhere by potential users (Davenport and Prusak, 1998):
- from the context;
- on the culture;
- about the expertise, procedures and protocols of the groups engaged

Developing local to global user-friendly systems for information to be exchanged on good practice, easy-to-use and affordable technologies and lessons on policies, plans and measures would contribute to the Sendai framework ambitions (Izumi et al., 2019; Rahman and Fang, 2019). Along the same lines, Hick et al. (2019) stated the need to better exploit lessons learned on citizen engagement in DRM at the international level (Box 11).

A set of capacities is needed for the collection, storage and transfer of knowledge, but particularly for the reuse of it in the form of lessons learned. School education (Box 12), together with family and community learning, has proven to be useful to raise awareness of earthquakes among pupils in Japan and to teach them how to prepare themselves to deal with such events (Shaw et al., 2004). In developing countries, formal courses, together with

BOX 11a

COVID-19 tracing and tracking technology in Australia, Austria, Bulgaria, Cyprus Czechia, France, Greece, New Zealand, Norway, Poland, Portugal, Singapore, Slovakia, South Korea and Spain.

From global to global

Who?
Nations around the world including the EU Member States

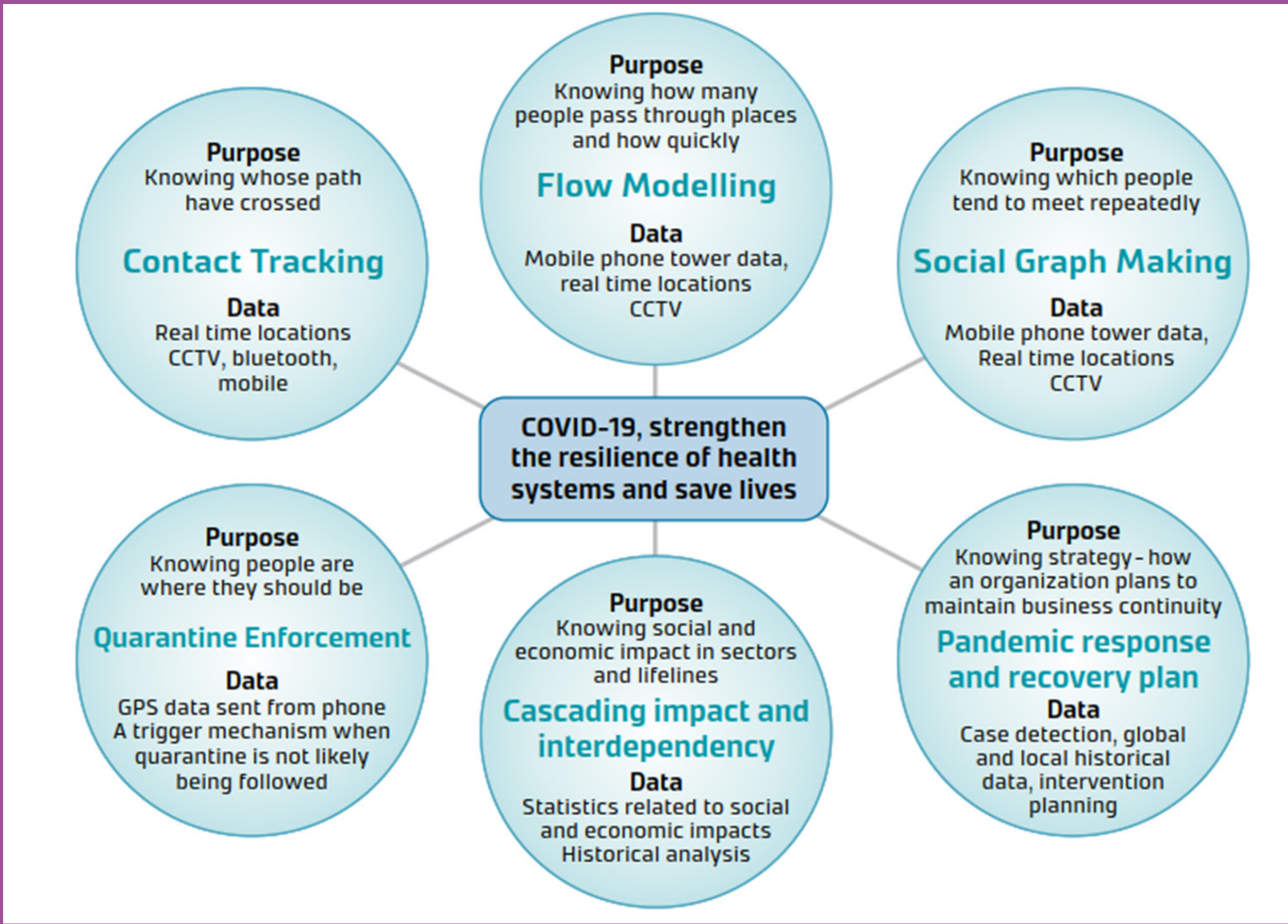
Why?
Emerging technologies are important in the response to the COVID-19 pandemic and attempts to mitigate it. It is necessary to minimise and mitigate transmission in the hope of preventing the spread within communities. Technologies and tools are utilised to act decisively and prevent further spread, or quickly suppress or minimise the transmission of COVID-19. Technologies are able to trace people's location and identify potential clusters and thus enable responders to alert people to transmission.

What?
Enhanced surveillance and contact tracing technologies are being employed around the world to understand transmission, outbreak assessment, risk and cascading impact assessments (Figure 4). Technologies such as geolocation trackers, cell site location information, Global Positioning System satellite and Bluetooth data, and location apps enable quicker detection and prevention of this pandemic. In Singapore, for example, an app has been developed to accurately trace and track active COVID-19 cases. Many countries around the world are adopting a similar approach and believe this is best practice to track and trace COVID-19.

BOX 11b

Systematic thinking, especially for those responding to COVID-19 pandemic, provides important lessons and ways to significantly improve the fight against potential pandemics in the future. All countries can learn from best practice during this global pandemic.

***Figure 4**. Tools and approaches to face COVID-19 emergency. **Source:** Fakhruddin, 2020.*



other activities for children, such as games and puppet shows, have been proposed as promising methods to transfer DRM knowledge among families and communities (Izadkhah and Hosseini, 2005; Fernandez and Shaw, 2016). For more examples and insights into education, see Super case study 5, ‘Education, cultural inclusion and disasters’.

BOX 12

Community resilience through education

From global to global

Who?
Scottish Environment Protection Agency, Scotland

Why?
Schools are at the heart of communities, and young people are particularly vulnerable to emergencies, but they also have ideas, energy and commitment that many adults would envy.

What?
Scotland's approach is to fund an education post, supported by resilience and flooding teams as well as by the Scottish Environment Protection Agency. This engagement supports resilience professionals in their awareness-raising duties under the Flood Risk Management Act. Schools get access to detailed information about flood plains, flood protection schemes and other areas of interest in the local area, which helps bring the learning to life in the classroom. Gathering case studies and sharing them at the national level has been useful in showing resilience professionals and education colleagues what awareness raising looks like in practice. Both resilience and education professionals have seen the relevance of integrating resilience into the Curriculum for Excellence.

Getting young people involved in the global context means there will be more community buy-in to DRM systems, and also an understanding of DRM principles from an early age that will make future education and DRM procedures easier to communicate. This will be particularly beneficial in developing countries.

For more information: https://floodlinescotland.org.uk/creative-engagement

4 What a system-based approach looks like

DRM should be seen not in isolation but in dynamic relationships with the larger context (i.e. social, political, financial and ecological systems). The main value of a system-based approach is the underlying philosophy of seeing the bigger picture.

Successful risk reduction requires an all-hazards, system-based approach, engagement with local communities, and cross-sectoral and multidisciplinary collaboration. A system-based approach is composed of interconnected and intra- and interdependent subsystems of communities and infrastructures, with multiple functions, operations and stakeholders. This method is also referred to as a system-of-systems approach.

Chapters 2 and 4 discuss theories of system-based thinking and system-based approaches. This section discusses case studies of good practice in impact-based early warning systems as successful DRM processes.

Early warning systems (EWSs) are a critical component of DRM, with a role beyond detecting and monitoring hazards (WMO, 2013). Along with a thorough risk assessment, it is critical that warnings be disseminated quickly through coordinated systems. Issuing warnings will not have a real impact if communities, companies and authorities at the local, national or international level do not develop emergency plans and respond accordingly to the upcoming risk. In other words, an EWS should be seen as a system within the system of society and the economy.

This comprehensive approach to DRM requires coordination and synergies between different agencies, taking into consideration DRM phases. A lack of coordination between the agencies, or the failure of one of these components, may cause the failure of the entire system (Luther et al., 2017). This means that an early warning may not be generated correctly or it may not be delivered effectively. In any case, the population to be warned would not react appropriately.

The critical role of each component of EWS is made clear by the experience of the great east Japan earthquake and tsunami, which hit Japan's east coast in 2011. Japan has a long history of dealing with earthquakes and tsunamis. The country had developed advanced EWS and DRM measures. It is believed that Japan was using one of the most advanced EWS in the world. Many of its forecasting technologies and numerical models were provided to other countries needing EWS support, such as Indonesia and Peru. However, underestimations of the 2011 earthquake and tsunami led to devastating effects, as presented in Super case study 2. Underestimation of the earthquake disaster risk and its cascading and interlinking consequences caused catastrophic damage and the evacuation of 160 000 people (Norio et al., 2011; Pushpalal et al., 2013). This reminded the DRM community that a system-based approach is essential to understand dynamic relationships with the larger context (i.e. social, political, financial and ecological systems) and their interdependency and consequences, in order to assess and manage risk properly.

Warning systems need to be established and supported throughout normal times. Early warnings are associated with emergency conditions, but their usefulness is determined by the extent to which they are installed and active beforehand. Organisations associated with early warnings need to encourage collaborators to focus on the fundamental objective of their efforts: to enable timely, coherent and effective response to a warning by officials and the public. There is often the need for political will to respond to the evidence of early warning, especially the very early signs, when the government is possibly facing more immediate priorities. For this reason, early warning functions need to be linked to risk assessment and preparedness programmes within a coherent DRM strategy. To further this relationship, there is a need for continued research and development of the technical aspects of EWS for explicit user-determined needs and applications.

The lack of multidisciplinary and transboundary cooperation can represent a challenge for successful EWSs. EWSs are often developed to address single hazards, but a unilateral approach may lead to the generation of an unforeseen cascade of events (Basher, 2006). It is within this context that the concept of multi-hazard EWS (MHEWS) was introduced and defined by UNDRR in 2017. MHEWSs address several hazards and/or impacts of similar or different type in contexts where hazardous events may occur alone, simultaneously, cascading or cumulatively over time, and take into account potential interrelated effects. It is now clear that an MHEWS increases the efficiency and consistency of warnings through coordinated and compatible mechanisms and capacities, involving multiple disciplines for accurate hazard identification and monitoring of multiple hazards.

To address this gap actively, the United Nations Office for Disaster Risk Reduction (UNDRR), the World Meteorological Organization (WMO) and UNESCO, along with other major international and national organisations, have collaborated to establish the International Network for Multi-Hazard Early Warning Systems.

Germany has an MHEWS operated by the Deutscher Wetterdienst (DWD), the German Meteorological Office. The DWD issues 27 types of warnings for about 450 districts or parts of districts in Germany and for different height levels (DWD, 2012). It regularly holds feedback meetings and training sessions with DRM authorities to ensure a coordinated approach. It states that 'a good early warning system should follow the four rules of service delivery (availability, dependability, usability, credibility)' (DWD, 2012, pp.30). The DWD has learned in developing the system that cooperation, partnership and communication at all levels between national meteorological and hydrological services and disaster management organisations is the key to successful development of EWSs (DWD, 2012).

The WMO initiated the South-East European Multi-Hazard Early Warning Advisory System project in 2016 to assist its members in the region to upgrade or install EWSs and improve community resilience (WMO, 2018). The project addresses gaps in forecasting and warning provision at national and regional levels by developing a regional MHEWS and harmonise national EWSs.

The 10 essential elements that combine to build an effective EWS are shown in Figure 5.

Building Resilience to High-Impact Hydro-Meteorological Events through Strengthening Multi-Hazard Early Warning Systems in Small Island Developing States (SIDS) and South East Asia is a multinational project (WMO, 2020a). Its aim is to strengthen weather-, climate- and water-related impact-based decision support services to MHEWS stakeholders, by:

- increasing the engagement of national meteorological and hydrological services in national and regional MHEWSs and DRR mechanisms;
- increasing access to and utilisation of regional and global hydrometeorological data and products to support development of impact-based forecasts and warnings;
- strengthening capacity for development of impact-based hydrometeorological products to support MHEWS stakeholders in decision-making.

This project aims to achieve improved governance by strengthening national and regional DRM and early warning mechanisms with increased engagements between MHEWS stakeholders, social and economic sectors and communities, in addition to enhanced product development and service delivery.

Figure 5. *End-to-end impact-based early warning system. **Source:** Fakhruddin and Schick, 2019.*

Enhancing the development of and access to services will enable countries to support the development of impact-based forecasts and risk-informed warnings. An example of this is the newly developed cyclone EWS in Fiji (WMO, 2019), which is the first cyclone EWS for the Pacific. The Fiji Meteorological Service serves as a WMO-designated Regional Specialised Meteorological Centre for tropical cyclone warnings and advisories for the south-west Pacific. Fiji continues to enhance its tsunami EWSs by adding additional tsunami sirens for the most vulnerable communities and using advanced science such as probabilistic tsunami hazard assessment to understand its exposure and vulnerabilities (Tonkin +Taylor Ltd., 2020). In addition to this, the project has enhanced Fiji's MHEWS by completing a national strategic plan and implementing a flash flood guidance system (WMO, 2020) and data training.

5 Risk communication: where it gets local

Creating an enabling environment for community participation will ultimately empower the community and get its members involved in the issue rather than simply being informed of the issue.

A significant level of knowledge needs to be developed on human response to warnings at the emergency warning organisational and individual/family levels. General principles for coordination and effective organisational responses are well defined. Coordination seems to be maximised when organisations know what they are supposed to do in an emergency and who is to do it, have designated and understood communication ties to others in the network, and maintain flexibility (Anderson, 1969; Mileti and Sorensen, 1987; Lindell and Perry, 1992; Anderson-Berry, et al., 2018).

Communication problems, due to equipment and human failure, are the most significant causes of poor warning dissemination. An example of coordination in DRM can be seen in France. Following the devastating December 1999 winter storm Lothar, which resulted in 100 deaths, a public warning system called Vigilance was developed as part of revised emergency planning and response mechanisms. The system delivers regular and descriptive information about the meteorological phenomena and informs the population directly so they can take responsibility for their safety (Meteo France, 2010). The system proved useful when a storm similar to Lothar occurred in 2009, and resulted in only eight deaths. The Vigilance system was upgraded to include heat and health warnings in 2004 and river flood risk warnings in 2007 (World Meteorological Organization, 2012).

A system similar to the Vigilance warning system can be implemented in developing countries, as hydrometeorological hazards pose risk to lives and livelihoods globally. Events such as storms, floods, droughts, heatwaves and cold waves are responsible for the greatest proportion of losses from adverse natural events globally. Well-prepared and well-resourced hydrometeorological services can help in minimising the disruptions caused by natural hazards by providing warning to governments and communities (Palwarty and Sivakumar, 2014). An example is the Kerala flood of 2018, when an unprecedented amount of rainfall caused reservoirs to fill, forcing dam gates to open, which led to the widespread flooding of downstream areas. Depths of water reached 4.5 m and more than 400 people were killed in what officials said was the worst flooding in 100 years. Investigations revealed that inaccurate weather forecast and opening of dam gates in a hurry were two major factors that contributed to this disaster. The Chief Minister of the state pointed to the accountability of the India Meteorological Department for underestimating the rainfall, forecasting one third of the actual rain received. Weather monitoring and forecasting have come a long way, but extreme weather events such as the Kerala flood point to the fact that we still have miles to go.

The importance of the social and cultural aspects of risk has been widely recognised; however, new insights continue to emerge as communication technologies and behaviours evolve (e.g. Taylor et al., 2018). Understanding natural hazard risk at the community level is essential for successful hazard risk reduction.

A recent research project (Fakhruddin et al., 2019b) carried out in a small coastal community in New Zealand has highlighted certain deficiencies in this area. The data collected suggest the following factors should be considered in DRM.

- Multi-hazard risk communication systems may be beneficial to cover all hazards that the community feels are evident, not only those the authorities and or agencies see as relevant.

- Consideration should be given to the demographics of the community, such as the varied cultures and languages, age distribution, mobility, disability (e.g. to consider appropriate warning dissemination methods and subsequent evacuation procedures for the elderly).
- Instead of general public engagement sessions, age-, gender-, culture- and/or location-specific engagement is suggested to enhance risk perception and reduce risk.
- Seek input from residents regarding the level and nature of risk they attribute to each hazard and why, and continue to review the hazards facing the community as the environment, population and social structure of the community change.
- Strengthen collaboration between policymakers and the community, and consult with the community on what methods it would suggest, or prefer, to communicate hazard risk or mitigate hazard risk. Do this early on in the process. Creating an enabling environment for community participation will ultimately empower the community and get its members involved in the issue rather than simply informing them of the issue (Fakhruddin et al., 2019b).

Fraser et al. (2016) analysed evacuation behaviour in response to two local-source earthquakes in 2013 in Wellington, New Zealand. Although they were widely felt and injured over 100 people, the magnitude of the earthquakes did not meet the threshold to issue an official evacuation warning to the public. The survey found that the majority of respondents did not evacuate. Despite this, 55–60 % of respondents believed that a tsunami could have occurred following each earthquake, but chose not to evacuate. Respondents' previous attendance at local tsunami information meetings significantly influenced their perception of the likelihood of tsunami damage, but did not influence respondents' perceptions of the likelihood of injuries or casualties. This research concludes that it is important to engage with at-risk communities, through education, training and drills on the appropriate protective actions to take following natural cues (earthquakes) or an official tsunami warning, in addition to active participation in defining, designing and implementing disaster risk management initiatives at community level.

This contrasts with research carried out by Alexander (1990), which summarised responses after an earthquake on 23 November 1980 struck southern Italy. The results concluded that the majority of the students had no earthquake experience; they relied significantly on older relatives or companions to interpret the risk for them and followed the actions of those around them. Engagement and education are increasingly recognised as the most effective forms of communication (NASEM, 2017). A more recent example of how communities consider flood risk reduction comes from central and eastern European states. Owing to the devastating impacts of floods in Czechia, Poland and Romania, the EU has been taking a bottom-up approach whereby communities are involved in strategies for flood risk reduction. In 19 studies on flood risk perception, it was found that risk reduction was considered a 'temporary event rather than a process' and there was a 'strong reliance upon regional and national authorities' for prevention measures and risk communication (Raška, 2015, p. 2 163). The results of Fraser et al. (2016) have shown that measures to help at-risk communities understand the hazard have been effective and could be utilised to improve risk perception in other regions, such as central and eastern Europe. Participatory approaches to DRR, such as community-based DRR and co-production of knowledge, are recognised as challenging, albeit a prerequisite for effective risk action (e.g. Cadag et al., 2017).

6 Conclusions and key messages

The chapter discusses synergies between international and EU examples by way of good practice examples of DRM activities. It argues that DRM strategies should act on a system of systems, in which all elements should be viewed as equally important.

The EU system and framework for DRM is extensive and research based. This makes the system easily transferable, so the EU system can be adopted and customised for multiple global contexts and locations. In comparison, the global system of DRM often arises as a reaction to an event and is thus largely location specific or contextually based. The EU approach is perhaps a good starting point for countries; however, learning from around the world should be incorporated into all DRM plans so they can be location and context specific to be more efficient and effective. Communities, organisations and agencies around the globe, and in particular in less developed countries, may have capacities in place (at individual, social and system levels) that are overlooked, which should be identified, protected and shared. The projects and initiatives described show some of the varied groups, DRM phases and methods that should considered to enhance the capacity of the systems as a whole.

Good practices highlight the importance of appropriate risk communication and the necessity of understanding how communities could respond to new risk information. While cultural, legal and economic contexts may differ, synergies and transferability require partnership and capacity building. Effective education and outreach must be based in a thorough understanding of the process that individuals go through when they make decisions about modifying their behaviour and willingness to accept new ideas and technologies.

Policymakers

- Policymakers should work on goals and objectives to be reached at the level of governance they are working in, indicating the vision to follow. This would facilitate the selection and use of good practices. In particular, they should collaborate with the relevant stakeholders to define some ambiguous terms, such as resilience.

- At the same time, policymakers should exploit synergies with other levels, ensuring that the goals and objectives are coherent across all levels.

- Policymakers should design and reinforce instruments that would facilitate bottom-up and on-demand projects and actions, particularly in developing countries. This requires investments in the long term and linking DRM and CCA with poverty and inequality. They should find incentives for others to collaborate, and should ensure that funding mechanisms allow local ownership and promote actions that are aligned to local needs.

- There is a need to open the decision-making arenas to new forms of leadership and new arenas for collaboration with the different actors in DRM. There is an important space for action in international forums and arenas, where policymakers from subnational levels should also take part.

- Policymakers should exploit the results of research and lessons learned, promoting the implementation and further testing of initiatives and projects.

- Likewise, formal institutions should be part of the change, not only facilitating channels for knowledge flows and coordination, but also developing their capacities.

Practitioners [1]

- Above all, practitioners should define well what a good practice is, considering political decisions and agreements.
- Documentation of good practices requires not only presenting the final positive results but also describing the challenges and limitations. Identifying good (or bad) practices should result from rigorous monitoring and evaluation, to ensure impacts are known.
- The lessons should be shared at events or meetings, used in capacity building, and actively distributed to targeting groups that are especially vulnerable, or have special needs, and groups that have well-known capacities but are not traditionally engaged in DRM. Studies show that citizens are sometimes engaged after events, as part of recovery and reconstruction. Practitioners should define strategies to elicit citizens' participation in other projects or in the monitoring or evaluation of the measures implemented.
- Capabilities may exist at organisational level but each organisation should ensure capacities are downscaled to operations and tasks so that lessons learned can be used. Sharing knowledge with peers and creating communities of practice should be facilitated and rewarded by the organisations, while observations and new insights from exercises should be used in further developments.

Scientists

- Scientists are valuable partners for knowledge co-creation at any governance level. It is recommended that they engage in networks and projects with other actors, as interface and knowledge brokers. They should be open-minded to new approaches when defining needs and alternatives.
- Many empirical studies on knowledge creation and sharing come from the private sector. This leaves a gap for research on knowledge creation and sharing in DRM.
  It is recommended to focus on the impact of new types of leadership and the barriers to them, and on the relations between public sector and other stakeholders as part of new governance models in DRM.
- There is a shortage of studies on how to engage the private sector and communities in new initiatives and technologies.
- Citizen engagement should be better explored in some regions, such as Africa, and in dealing with technological hazards.

[1] Practitioners here are governmental officials who work to implement policies and programmes; groups that directly work in disaster risk management, such as civil protection; and non-profit organisations.).

Citizens

Research reiterates the value that communities can add in DRM planning and implementation. Citizens should actively engage in the opportunities given to raise their voice and to engage with others in the design of measures; there are opportunities within their communities, such as through religious or political groups. The post-event period seems to be a good window of opportunity for that, as policymakers and practitioners are more willing to collaborate for a sustainable recovery.

Scientist and practitioners

They should work together to push for testing and reuse for innovations and technologies that are affordable and relevant to the context, to make them ready for use in capacity-building activities.

Practitioners, scientists and citizens

There is not much evidence of the real impact of many capacity-building, training and educational activities. It is necessary to evaluate some promising approaches (Ronan et al., 2015) and to ensure that they lead to risk reduction. Practitioners and citizens, together with scientists, should endeavour in the long-term evaluation initiatives to (1) ensure that the elements that would facilitate the application and reuse of knowledge at local and community levels are in place in advance and (2) define which approaches are most effective at finally reducing impacts. While international and regional bodies may invest in evaluation, there is the risk that lower levels lack the capacities in the long run to learn from the past or are not properly engaged in the process (Hagelsteen and Becker, 2013).

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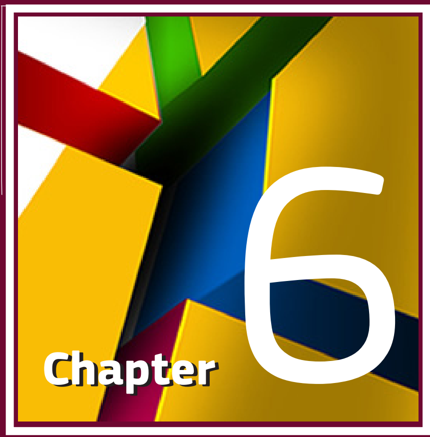

Conclusions and final recommendations

Online Version

6 Conclusions and final recommendations

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CONTENTS

1 Conclusions

The report *Science for Disaster Risk Management 2020: acting today, protecting tomorrow* studies the impacts of disasters on a wide range of economic and social sectors as well as the consequences for the affected communities and ecosystems. A comprehensive assessment of the disaster impacts after an event enlarges our understanding of disaster risk and contributes to making disaster risk management (DRM) more effective. This requires having in place mechanisms of co-development and evidence-based governance that capture the knowledge and needs of diverse stakeholders, which (1) supports an early identification of risk drivers and (2) ensures the use of data and information on past events to formulate effective prevention, mitigation and adaptation measures.

'Impacts' consist of the direct damages and losses from an event (such as deaths, injuries, physical damage to buildings or interruption of services), the cascading effects that propagate, both in time and space, just afterwards, the recovery costs and the opportunities that may arise after the event. The report presents the usual consequences of disastrous events on five groups of assets: population, economic sectors, critical infrastructures, ecosystem services and cultural heritage. The consequences depend on:

- the hazard that materialises, its duration and its magnitude;
- the vulnerabilities and capacities of the asset and the whole system where they are located;
- the actions taken to respond and recover from the event.

The authors of the report, and in particular those of Chapter 3, relate the impacts to the indicators that measure progress towards targets A, B, C and D of the Sendai Framework for Disaster Risk Reduction, while introducing others that can easily emerge in time and space. The report reviews methodologies to analyse the impacts addressed, highlighting the challenges and potential opportunities for strengthening risk and crisis management practices.

The report includes several past disasters, moving towards the identification of practical approaches and potential solutions to these events. The study of impacts represents an important opportunity for the DRM community to learn about disaster risk, to understand how to better plan for future events and thereby facilitate response and recovery. Information gathered about past events helps to identify the failures in communication and in response protocols, the barriers in governance, the lack of awareness and the gaps in knowledge and data. The past events analysed by the authors show how the events triggered changes in the policy framework, raised awareness and pointed out areas that should be further developed by research.

Although progress has been made in recent years to improve the understanding of disaster risk, societies, institutions and organisations engaged in DRM still focus on emergency response and on the most immediate consequences of an event. Prevention and mitigation actions seem to be undervalued in practice. For instance, more efforts need to be made to integrate knowledge of ecosystems, restoration and nature-based solutions into disaster risk planning policies. DRM should evolve to reinforce anticipation as well as increasing the interconnection of the various phases of the DRM cycle.

The complex nature of risk represents a challenge to identify which impacts are relevant and require monitoring and response, especially for those that emerge some time after the event or those that are geographically far from the place where the hazard first occurred. Some impacts appear with time lag, such as post-traumatic stress, disruptions of supply chains, biodiversity loss or economic recession, and many others are triggered by primary impacts. The DRM community has generally focused on the direct effects of hazards on the asset exposed, although the lack of proper management of indirect consequences can speed the propagation of these impacts to other sectors, services and assets.

Disruptions or limitations in services and economic sectors strongly shape the socioeconomic and cultural dynamics of a place. These potential impacts should be examined and prioritised based on the societal values of the place, to finally choose which impacts are to be avoided. This will, in turn, determine what should be protected and secured, and help define both recovery and preventive actions.

Intangible impacts are commonly overlooked. As they cannot be fully valued in economic terms, intangible impacts are difficult to incorporate as part of disaster risk management. In the medium and long-term, these impacts are frequently difficult to identify while their rate of loss can be unknown. Furthermore, not being able to recognise all the functions, benefits and value of the asset, as happens with ecosystem services and cultural heritage, hinders the possibility of managing their potential vulnerabilities. International strategies and frameworks started to consider those assets, facilitating that these type of assets are included in the political agenda of countries and regions. Nonetheless, guidance is needed to cover them properly, both before and after a disaster. Given that damages and losses to ecosystem services, cultural heritage and other social values and activities can be hard to compensate for and restore, a precautionary approach is advised when planning and implementing DRM measures.

As a result, methodologies to analyse impact have been mainly developed for direct and tangible damages and losses. These have reached different levels of sophistication depending on the asset and the hazard under consideration. The authors conclude that any methodology to analyse impact would rarely improve or be fully used in practice without the data and the information gathered after the event.

Data and lessons learned are not collected uniformly; they are kept by different levels of governance, institutions and groups; and they are often not available for other purposes beyond particular response or recovery actions. Lessons are not always applied to enhance the whole system. Moreover, resources are rarely assigned to maintain data collection and dissemination over time. Inconsistent data collection and recording hinders its comparison and introduces uncertainties when used in modelling.

The authors urge a shift from a merely short-term perspective, generally focused on reacting to mitigate immediate consequences, towards a long-term view by tackling the underlying drivers of risk (exposure, vulnerability and capacity). The financial flow during the recovery phase should support and generate new knowledge on how to influence risk drivers. Likewise, risk assessment should apply longer time spans, which would help DRR and climate change adaptation groups to integrate and exploit synergies when studying and tackling vulnerabilities.

The report shows diverse and innovative approaches in the collection and sharing of loss and damage data, which should be further developed using new technologies, such as remote sensing techniques, artificial intelligence, sensors, drones and apps. Some of the options proposed facilitate the participation of a variety of stakeholders, promoting a shared culture of risk.

The scientific community is particularly interested in making the most of the data and information after a disaster, aiming to improve the capacity to predict future events. The interdependencies between hazard intensities and damages and losses when various assets are affected, either simultaneously or in cascade, could be better understood with more organised and comprehensive collection and use of impact data. This would enhance our resilience to future events.

At the same time, actions taken to prevent, mitigate, prepare for and/or adapt to risk cannot be evaluated, and therefore improved, if baseline data is not available. Specific data should be collected before the event to assess the value and vulnerability of exposed assets. All of these call for the definition of metrics and terminology, fully consistent when describing pre- and post-event data, which would allow comparison between groups, sectors, hazards and geographical areas.

Metrics, and their corresponding indicators, should be comprehensive to cover different hazards and sectors. They should be applicable at the local level, and coordination mechanisms should exist to ensure they are used for different purposes and at various levels. There are already initiatives and databases in place, such as the Risk Data Hub and the Disaster Loss and Damage Working Group, which could be connected with the purpose of increasing the knowledge in disaster modelling and mitigation, saving time and resources. At the global level, there have been efforts to coordinate the indicators of the Sendai Framework for DRR with the Sustainable Development Goals and the Paris Climate Agreement.

The study of the impacts shows the effect of globalisation and the many links between sectors and assets, at all levels of governance. DRM requires different sectors and groups to be mobilised and work together. The co-design, co-implementation and co-evaluation of DRM actions with a multidisciplinary and cross-sectorial approach is crucial to increase resilience by designing and implementing evidence-based policies. The costs of response, recovery and reconstruction should be reported, for accountability, and compared with those of prevention and mitigation, to support decision-making.

Differences in responsibilities, interests, language and experience often hinder collaboration among stakeholders. Trust emerges as a prerequisite to overcome these differences, supporting the diverse groups to learn and to create together more comprehensive and widely accepted actions. Long-term partnerships and clarification of roles would facilitate collaborations. Efforts have been made to facilitate the science–policy interface, helping scientists and decision-makers to jointly create disaster risk actions based on shared data and information. Still, two major groups should be better engaged with the rest: citizens and the private sector.

Citizens are acknowledged as fundamental for real action to be implemented, although it is recognised that generally the current governance systems do not fully facilitate the integration of bottom-up initiatives. These initiatives should serve to consult and empower citizens, tailoring the system to their needs, abilities and limitations. Experience shows that communities are more easily engaged during the recovery processes, owing to their urgency, but the situation rarely extends over the medium or long term. In the face of growing globalisation and climate change, communities need to be engaged to enhance resilience, as decisions need to be taken in uncertain environments or when adaptation is acutely required.

Together with citizens, the private sector needs to be engaged as an active stakeholder, addressing its needs for data, information and knowledge before and after an event and reinforcing its obligations in relation to disaster events. Incentives could be developed for different groups, to make them feel part of the activities to manage disaster risk ensuring private and public efforts support an adaptive, inclusive and agile DRM system. Specific mechanisms should be explored and created to guarantee that, in specific circumstances, data from the private sector are shared with practitioners and scientists.

The report has also shown that more cooperation is still required within the scientific community as well as with other stakeholders. The role of social sciences and humanities has to become more prominent in relation to impact assessment. At the same time, those disciplines have to make an effort to deal with risk in an operational (and even quantitative) way, proposing approaches for measuring social impacts.

The past events described, and in particular the super case studies, show the lack of preparedness of our societies to face some events that, although they could be considered as being of low probability, have enormous impacts at local and national levels. The report calls for cross-border partnerships and collaboration at different levels of policymaking processes.

These different types of collaborations need to be carefully planned, putting mechanisms in place to detect needs and proposals for action. These would serve to jointly develop capabilities and share capacities. Coordination among agencies and other stakeholders is therefore key. As said, all types of impacts should be closely monitored during recovery, to avoid the emergence of new impacts or the increase in vulnerability of some societal groups, sectors and/or ecosystems. The first steps to reinforce capacities should start in the recovery phase.

2 Recommendations for the audiences

The chapters and subchapters contain specific recommendations on the topics they consider.

All stakeholders have roles to play, but some tasks require a particular group or community to take the lead on them.

2.1 Tasks led by policymakers

Facilitate and promote collaborative processes to collect input from practitioners, scientists, the private sector and citizens.

- Design mechanisms to facilitate bottom-up approaches: open to new types of leaderships the arena of decision-making and collaboration for the implementation and evaluation of DRR measures.

- Collaborate with scientists and practitioners in the monitoring and evaluation of non-structural and new approaches to preventing, mitigating and adapting to risk. Take advantage of the post-disaster phase to fund new endeavours that are in line with the vision and medium-term strategies of the territory.

- Engage in discussions with other governance levels, within the country and internationally, to promote more complete assessment of progress in reducing risk, which requires indirect and intangible impacts to be properly addressed. It is important to consider impacts on health, ecosystem services and cultural heritage. DRM communities should work on important challenges that hinder sustainability: the mitigation of and adaptation to climate change, ecosystem degradation and the loss of biodiversity.

- Work to ensure that a precautionary approach guides policy debates: the benefits of prevention and mitigation action may be difficult to define in the short term. Devote efforts to tackle the full spectrum of damages and losses.

Develop a policy frame to collect, store and reuse data and information, including good practices and lessons learned, during response and recovery processes.

- Design mechanisms to help knowledge flow across different governance levels, particularly from the local level to the national, while scientific support is enabled to more easily reach local and regional levels.

- Establish frameworks for the collection at the most local level possible, as well as retrieval and sharing of data after an event among governance levels. The framework should take into account the databases that already exist on DRM, mainly sector-specific, alongside others that are related to the specific context, as necessary to understand the baseline situation (before the event). The databases can be national or international, but the framework should be wide enough to consider different types of damages and losses so that it can collect and use data constantly. The frameworks should carefully regulate who and how non-public organisations can take part of these activities, ensuring that data is accessible and of quality for different purposes.

- Develop mechanisms for damage and loss data to be shared by the private sector, without compromising or violating privacy.

- Engage with practitioners and scientists to understand the uncertainty around the results obtained from analysis and forecasts. These dialogues would facilitate sharing of tacit knowledge.

Ensure proper monitoring and evaluation of the corrective measures planned and implemented.

- Monitoring and evaluation of policies and programmes implemented should be specially reinforced, particularly after an event, engaging diverse stakeholders. These evaluations are an opportunity to make changes at the levels of projects, organisations and risk management culture. This type of actions would enhance accountability and transparency, reinforcing trust.

- Develop frameworks to identify and properly assess capabilities and capacity needs, and their development to mitigate and prevent risk. To do so, consider the institutions already engaged in DRM by law and explore how these can cooperate with other groups and organisations, such as the private sector and citizens (individually and through civil society organisations). The roles and responsibilities of the diverse stakeholders and groups must be clarified while power imbalances are addressed.

- Introduce innovative funding mechanisms to encourage and enable alignment and joint investment between various public sector agencies and public–private partnerships. Those partnerships serve to cover the different dimensions of assets and the relation between them. Moreover, sectors are usually divided into various subsectors, which should work together to ensure resilience.

2.2 Tasks led by practitioners

Provide feedback to ensure that tacit knowledge is endorsed by policymakers.

- Practitioners should take a more active role in the policy arena and in particular in the prevention and mitigation of disaster risk. Practitioners should channel impact data and lessons learned from response and recovery to groups in charge of risk assessments and planning and monitoring of measures to reduce disaster risk.

- Support decision-makers in the preparation of a comprehensive framework for impact assessment. Propose procedures to collect disaster impact data across sectors and governance levels for different purposes. Work closely with scientists in the collection and analysis of data after an event.

Be creative and perseverant in your tasks embracing innovation.

- Practitioners should think outside the box when drafting preparedness actions, including training and exercises, to be ready for the next event, not for those that have already occurred. Pay particular attention to thinking of more complex scenarios, including cascading effects and compound events. Simulation exercises should be carried out together with key actors, such as operators and representatives of critical infrastructures, important industrial sites, economic activities, and natural spaces or natural resources.

- Update the contingency plans and other initiatives, based on the lessons learned from simulation exercises. Address impacts beyond those that are direct and tangible. Work with operators of industries and infrastructures, business representatives and nature conservation groups to learn together and reinforce prevention, mitigation and adaptation measures.

Help the scientific community with data and feedback.

- Support the knowledge flow among different administrative levels and share your tacit knowledge with other groups, in particular with scientists. Properly document lessons and experiences learned, enabling others to compare, share and test them.
- Work to collect detailed data on response and first recovery stages and ensure that they are available later for other purposes.
- Work with scientists to help the private sector and citizens to participate in the implementation of innovative approaches to reducing risk, and in particular to the collection and analysis of impacts.

2.3 Tasks lead by scientists

Continue research efforts on disaster risk dimensions and management.

- Efforts should be devoted to improving the methods to capture indirect and intangible impacts. For that, the scope of impact analysis should be widened to accommodate cascading effects or to study compound events, considering the links of the asset studied with others, in time and space.
- Engage in activities beyond risk analysis, such as risk identification, risk

transfer, scenario building and strategic foresight. It is necessary that the groups engaged in risk analysis are engaged in these exercises.

- Risk treatment requires special dedication. The cost and effect of mitigation measures should be studied after an event, paying attention to the causes and drivers that increase disaster risk. At the same time, propose measures to prevent and mitigate losses and damages that could be put in practice by citizens and the private sector. Here DRM and climate change adaptation groups can easily collaborate.

- Methodologies for measuring the value of assets should be further developed and adapted to address measuring loss in value.

- Research should be devoted to studying the socioeconomic processes and factors that lead to impacts on the various assets presented in the report, particularly at individual and community levels. There are few studies on this topic in Europe.

- Further develop new techniques and methods to collect and analyse the vast amount of impact data. Show their added value to policymakers through examples and good practices.

Acquire additional knowledge by interacting with other communities.

- Efforts are still necessary for different scientific groups and disciplines to ensure relevant results are obtained. A good starting point would be for different disciplines to work together to propose impact metrics to be monitored (in time and space) after an event, which would be the same as those to be used in forecasting risk. Propose these for drawing up and updating a framework for impacts to be assessed. Support policymakers in that endeavour, pointing out the opportunities and the challenges to be overcome.

- Facilitate a culture of learning with the other stakeholders, and in particular with the practitioners and the groups working in the field, by testing new tools and approaches in various contexts. Go beyond the traditional role of giving advice and transferring information.

Make sure the knowledge is useful and used.

- Work to synthesise research results and define problems for non-expert audiences.
- Together with practitioners, present the gaps in knowledge regarding propagation of effects within sectors and assets in particular areas of interest. During relief and response phases, support practitioners to assess scenarios.
- Work with practitioners to make sure that models and tools to analyse impacts are available and endorsed by them.
- Collaborate with practitioners in reaching citizens, before and after an event, through educational programmes and communication campaigns. Carry out research on how to mobilise different groups that are traditionally not engaged in DRM.

2.4 Tasks led by citizens

Raise your voice for a more resilient future.

- Discuss DRR with family, friends and neighbours, and invite them to participate more actively by volunteering, attending events at which policies and programmes are presented to communities, speaking up when plans and projects are open for public comments, and reward political groups that have worked to reduce disaster risk, among other ways.

Be active to reduce disaster risk at a local level.

- Become aware of the responsibilities and benefits of managing disaster risk. Be well informed and be engaged in workshops, training or discussions at the local level. Engage in disaster risk management activities, through different organisations that are on the ground (such as religious, communal groups or local environmental protection groups) or specific projects that may arise from various institutions.

- Invest in individual and communal protection measures and evaluate the measures taken.

- Facilitate the work of responders during an emergency, and avoid passing on information that could be misleading or confusing.

Engage with other stakeholders in DRM activities.

- Contribute to damage data collection efforts, through platforms, social media and apps. Be open to sharing both tangible and intangible impacts to make the identification and analysis of impacts more comprehensive.

- Engage in disaster risk management activities, through different organisations that are on the ground (such as religious, communal groups or local environmental protection groups) or specific projects that may arise from various institutions.

- Cooperate with policymakers in defining a vision for the territory, especially in the post-event period. Keep in mind that some changes may be required in the landscape and the functioning of the area to build back better and exploit new opportunities.

- Participate in a DRM learning culture, in particular engaging in discussions with scientists and practitioners to define and value intangible assets, before the event.

- Various activities represent a business opportunity, which could be exploited by small and new businesses, for example related to the framework(s) for collecting, retrieving and sharing loss and damage data and to the implementation and evaluation of new prevention and mitigation projects at the local level.

It is worth mentioning that all four communities need to join in a discussion of important but ambiguous terms, such as ‘resilience’, ‘impact’ and ‘affected people’.

3 Future challenges

In the moment of writing, EU and the world is struggling to manage the many and varied consequences related to the COVID-19 emergency. The pandemic represents our present but other impacts could arise and materialise in the next months and years while some underlying drivers of disaster risk could intensify. Institutions and groups engaged in disaster risk management should update their plans and protocols to the new risk landscape.

The availability of accurate and complete data which can be used for different purposes remains key to draft and implement the strategies and policies required to urgently address disaster risk and climate change. The COVID-19 pandemic can be an opportunity for identifying relevant loss and damage indicators and to learn criteria on how to consistently monitor them in time and space. As it is necessary to have a comprehensive understanding of the impacts to really reduce risk in practice, efforts should also focus on recognising and analysing intangible impacts.

Uncovering this type of impacts would support building broader scenarios and more robust risk assessments, which would lead to a better prioritisation of prevention and mitigation action. All aspects of our livelihood are at risk but knowing how the impacts might evolve after a hazardous event helps us to timely prevent, prepare and respond to in early stages and stop their propagation. In a more connected world, where compound and cascading events would be the norm, the borders within the EU seem to face although the existence of two opposite movements: one that boosts for EU shared goals and another that is mainly concerned about national politics.

Big data is a valuable resource for the future of disaster risk management that should be promptly exploited, for which capacities and strategies should be developed to protect data and timely process it. At the same time, urban population is expected to continue increasing so particular efforts should be devoted to count with data at the lowest level possible to plan appropriate measures at city level. The technology for storing, manipulating and communicating big data can have negative effects on the environment that should be also addressed.

Citizens can take a wider role in the use of data and information. By engaging them in the interpretation and sharing of results, local knowledge would be easily integrated in the analysis of data while awareness would probably raise more easily among communities. New tools and products would need to be developed for the collection, storage and sharing of data and information on loss and damage but it is equally important to create and test innovative approaches to maximise the use of these in practice. The increasing diversity among communities and regions (in terms of age, educational studies, religion, language, place of origin, etc.) should be considered.

Several groups would be interacting in the DRM policy arena, with their own interests, possibilities and limitations, so resources should be allocated over time for networks and coordination mechanisms to allow innovation and ensure inclusiveness. As COVID-19 may intensity inequalities in our communities, it is urgent to tackle the power inequalities that may exist among the members of these partnerships and networks. All voices should be raised and considered for recognising the great range of effects related to disasters and for disclosing the benefits of the measures funded to manage risk.

ACKNOWLEDGEMENTS

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Chapter 2. Integrating the risk management cycle

Subchapter 2.1 Risk Assessment

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KJ-NA-30183-EN-N

Disaster
Risk
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Publications Office
of the European Union

ISBN 978-92-76-18181-1
doi:10.2760/438998