Chapter 3

# Understanding disaster risk: hazard related risk issues

## SECTION II
## Hydrological risk


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# 3 Understanding disaster risk: hazard related risk issues

## Section II. Hydrological risk

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# Introduction

The following subchapters cover the principal hydrological risks and, in the case of landslides, hazards that are triggered through hydrological events. In the case of floods, the subchapters cover fluvial, flash and pluvial floods, as well as coastal flooding caused by wave actions and storm surges:

- Fluvial floods occur when river levels rise and burst or overflow their banks, inundating the surrounding land forming the river's floodplain. This can occur in response to storms with higher than normal rainfall totals and/or intensities, to seasonal strong weather systems such as monsoons or winter stormtracks, or to sudden melting of snow in spring.

- Flash floods can develop when heavy rainfall occurs suddenly, particularly in mountainous river catchments, although they can occur anywhere. Strong localised rainfall, rapid flood formation and high water velocities can be particularly threatening to the population at risk and are highly destructive.

- Heavy rainfall may cause surface water flooding, also known as pluvial flooding, particularly in cities where the urban drainage systems become overwhelmed.

- Floods can also be generated by infrastructure failure (e.g. dam breaks), glacial/lake outbursts and groundwater rising under prolonged very wet conditions, which cause waterlogging. In many cases, flooding occurs as a result of more than one of the generating mechanisms occurring concurrently, making the prediction of flood hazards and impacts even more challenging, and the probable resulting damage more severe.

- Coastal flooding is caused by a combination of high tide, storm surge and wave conditions. Development on flood plains increases the risk as does coastal erosion and sea level rise.

- Landslide occurrence is related to causal factors, which create a propensity for a slope to fail and trigger the specific external event that induces landslide occurrence at that particular time. In most cases, but not all, the timing of failure is associated with a trigger event.

- Heavy rainfall is a key factor in generating landslides, primarily through the generation of pore water pressures and a reduction in the effective normal stress. The second key factor for landslide generation is the impact of seismic events.

Floods and landslides affect a large number of people across the world every year, with severe socioeconomic impacts. Severe fluvial flooding repeatedly afflicts European populations, with trans-national events often being the most

damaging. It is estimated that GBP 150 billion (EUR 177 billion) of assets and 4 million people are currently at risk from coastal flooding in the United Kingdom alone, for example. Significant advances have been made in recent years to map these risks, to develop and set up EWSs for better preparedness and to improve the communication of risks to decision-makers and the public. However, variations in socioeconomic factors (land use, demography, migration) as well as changes in climate and weather patterns may lead to rapid changes in flood and landslide risk in the future and will require increased levels of adaptation.

This chapter describes the current knowledge regarding the drivers, impacts and key tools to manage risks for these hazards. It identifies a set of challenges and gaps for key stakeholders to further reduce and better manage their risks and to be prepared for future changes in risk.

# 3.4 Hydrological risk: floods

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## 3.4.1 Introduction: flood hazards and impacts

In principle, flooding is a natural phenomenon that affects all river basins around the world in more or less regular intervals and that fulfils essential functions in the natural ecosystem. However, owing to human settlements being established within floodplains and common development practices not leaving room for rivers under flood conditions, flooding is mostly considered for its negative rather than its positive effects (Watson and Adams, 2010). Alfieri et al. (2016) estimate flood impact at the European Union level to be ≈EUR 6 billion per year, affecting 250 000 people per year. Although flood impact assessment is an essential step by which to optimise flood mitigation measures, there are many sources of uncertainty that affect such complex estimates. For example, uncertainty may come from sparse and short datasets, poor knowledge of hydraulic structures such as dams and weirs along rivers, assumptions and extrapolations in statistical analyses of extreme floods, and depth-damage functions. The estimation of flood damages also depends on several assumptions (Merz et al., 2010). It involves challenges in defining damages for different elements at risk (e.g. houses, public spaces, industries), and transferring solutions in space (from one region to another) and in time (from one flood event to another).

Flooding causes long-term damage to health, with immediate impacts such as drowning, physical trauma, infections and chemical hazards, and also affects well-being, livelihoods and social cohesion. It is also not always easy to identify the local consequences of flooding, such as the effects caused by displacement, the destruction of homes, delayed recovery and the disruption of access to health services (WHO, 2013). Flooding can also cause damage to critical infrastructure and can interrupt health and social care service delivery and business supply chains (National Flood Resilience Review, 2016; Landeg and Lawson, 2014). Finally, flooding is also frequently associated with power outages, which themselves can have a detrimental impact on health and businesses (Klinger et al., 2014) and a knock-on effect on other critical infrastructure such as railways and wastewater services.

*Flood disasters affect a large number of people across the world every year, with severe social and economic impacts. Severe flooding repeatedly affects European populations, with trans-national events often being the most damaging.*

The vulnerability of riverside communities around the world is particularly worrying in the light of migration pressures, socioeconomic drivers and climatic change. Even those who live flood-adapted lifestyles are not resilient to severe floods that occur only rarely, particularly when the last big flood was beyond living memory (Garde-Hansen et al., 2016) and in light of the impacts of future climate change.

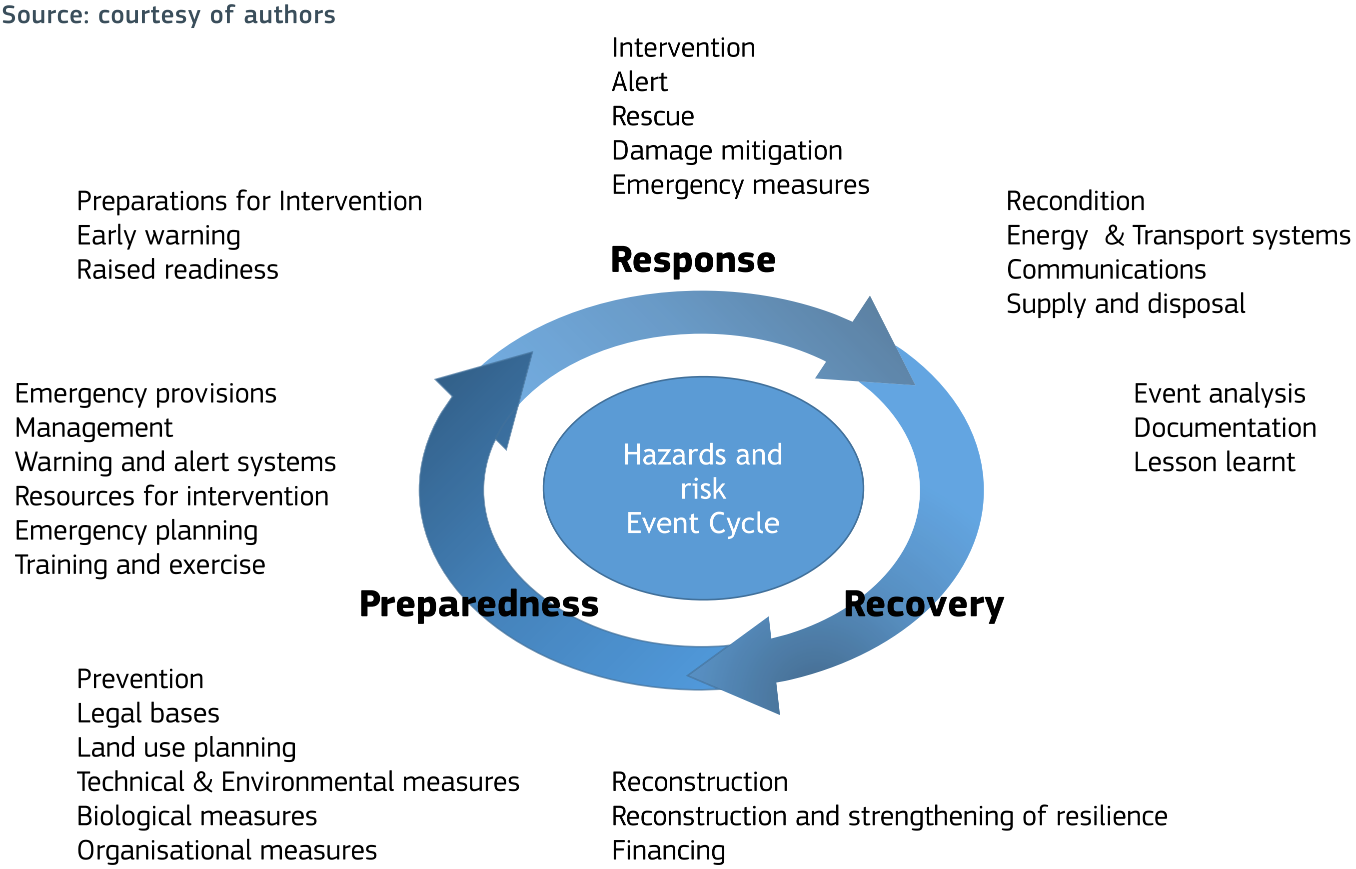
In this subchapter, the main drivers of flood hazard are introduced and flood hazard and risk mapping are discussed, particularly at the regional scale. Flood predictability is then considered, along with a review of the added value of flood monitoring, flood forecasting and EWSs.

## 3.4.2 Living with floods

Learning to live with flooding means that we recognise that flooding will continue to happen, as it is a natural phenomenon. There are many uncertainties in knowing when and where a flood will happen, both in the immediate term and in terms of probable climate change timescales, and when it does flood there is inevitably some disruption to our lives. However, there are many things that we can do to prepare better for floods and manage the risk, including strengthening components of flood prevention, flood preparedness, flood response and flood recovery, which are part of the disaster cycle (Figure 3.). Interventions can be taken during a flood to limit the impact of the disaster, including the evacuation of settlements or the creation of additional flood relief space through the opening of dykes or dams. This response is followed by a recovery phase after the disaster has passed, which includes relief meas-

**FIGURE 3.24**

**Hazards and risk event cycle**
**Source: courtesy of authors**



ures, reconstruction and event analysis. Often, this phase is aligned with the aim to achieve a similar economic standard to that before the event.

*Our best strategy for flood management is learning to live with flooding, that is, preparing ourselves today to be better adapted for flood risks tomorrow. The combination of a strong flood risk management policy, advanced early warning technology and increased international collaboration have the potential to reduce flood risk and improve disaster response from the local to the global scale. This requires different disciplines of knowledge, scientists, policymakers and practitioners to work closely together.*

If society has learned from the event, then any recovery is followed by a disaster risk-reduction phase, which includes preventive measures (e.g. creating natural retention in catchments, changing land use, rethinking urban design, planning and architectural norms, and implementing structural flood defences) and precautionary measures (e.g. supporting insurance mechanisms, refitting buildings, training and using EWSs). The aim is to minimise the vulnerability of society and to prepare it for an adequate response and recovery after the next event. The diversity in the way societies prepare for, respond to and recover from floods is largely governed by their experience with flood risk management and the magnitude of the floods that they have historically experienced (Thieken et al., 2007).

Improving flood preparedness requires contributions from many different disciplines of knowledge. Efforts are needed in terms of (1) improving risk governance, including institutional governance, legal provisions and financial instruments for planning, prevention and crises management, (2) understanding hazard modelling, incorporating meteorological forcing, hydrological, river and urban drainage processes, (3) forecasts and predictions, from short to long lead time ranges, and (4) emergency response recovery, including coordination of local operations, assistance to affected communities and recovery of disrupted services. Communication with and engagement of the public, water managers and decision-makers is key to effectively integrate these layers and to improve flood preparedness.

## 3.4.3 Drivers of flood hazard

Floods happen for a variety of reasons, but the main drivers are usually related to high rainfall, snowmelt and high river flow conditions (see Chapter 3.6). Fluvial floods occur when river levels rise and burst or overflow their banks, inundating the surrounding land that forms the river's floodplain. This can occur in response to storms with higher than normal rainfall totals and/or intensities, seasonal strong weather systems such as monsoons or winter stormtracks, or the sudden melting of snow in spring. The spring 2006 flood in the upper part of Elbe river basin is an example of a flood event driven by snowmelt combined with precipitation (Younis et al., 2008). With the rapid increase in temperature in April, snow that was present in the catchment was completely melted in 7-14 days. While temperature is generally easier to forecast than precipitation, the assessment of the quantities of snow accumulated in the catchment during the winter season can be a challenge for many EWSs.

*Floods can be triggered by rivers bursting or overflowing their banks, storm surges in the ocean, tsunamis, groundwater rising, glacial outbursts or dam failures and from surface water runoff in our cities after heavy rain.*

The severity of fluvial floods can be enhanced when the landscape is already saturated with water. Runoff due to rainfall cannot infiltrate the ground and, instead, flows directly to the river channel, rapidly contributing to increased river levels. This occurred in the winter 2013/14 floods

in the south of the United Kingdom, where an unusual series of storms led to widespread flooding (Huntingford et al., 2014; Muchan et al., 2015), and in the 2013 floods in Germany (Schröter et al., 2015).

Flash floods can develop when heavy rainfall occurs suddenly, particularly in mountainous river catchments, although they can occur anywhere (Gaume et al., 2009; Brauer et al., 2011). In flash floods, the rate at which river water levels rise is very rapid and the flood forms quickly. High levels of localised rainfall, rapid flood formation and high water velocities can be particularly threatening to the population at risk and highly destructive. Challenges in the management of flash floods include the short preparation time to activate flood alerts and emergency response, the sudden nature of the phenomenon, which often catches the population at risk by surprise, the difficulties of numerical weather prediction models in forecasting localised convective storms, and the lack of quantitative data at small catchment level to improve the understanding and modelling of flash floods (Collier, 2007; Leichti et al., 2013; Alfieri et al., 2011).

Heavy rainfall may cause surface water flooding, also known as pluvial flooding, particularly in cities where the urban drainage systems become overwhelmed. In these cases, event monitoring from telemetric rain gauges or meteorological radar needs to be coupled with hydrological, hydraulic and drainage system models for flood mapping (Liguori et al., 2012). Challenges remain with regard to estimating accurately rainfall displacement over an urban area, as well as with regard to precise knowledge of the capacity of the sewer system as a result of, for instance, debris blockages, infrastructure failure (broken or cracked pipes) or a reduction of pluvial capacity (Chen et al., 2016).

Floods can also be generated by infrastructure failure (e.g. dam breaks), glacial/lake outbursts, storm surges and wave overtopping at the coast (see Chapter 3.6), and groundwater rising under very wet prolonged conditions, thereby causing waterlogging (Macdonald et al., 2012). In many cases, flooding occurs when more than one of the generating mechanisms happen concurrently, making the prediction of flood hazards and impacts even more challenging, and the probable resulting damage more severe. In addition, longer-term drivers of flood impacts are also of concern in many vulnerable areas. They include changes in land use, population and geomorphology and the impacts of a changing climate (Alfieri et al., 2015; Slater et al., 2015). These issues are not straightforward to determine because of the many uncertainties involved in using climate and socioeconomic models to drive flood hazard predictions and the difficulties in their evaluation (Cloke et al., 2013; Hall et al., 2014; Hirabayashi et al., 2013; Kendon et al., 2016; Vormoor et al., 2015).

## 3.4.4 Flood hazard and risk mapping

Flood risk can be calculated from the hydrological flood hazard by including information on the exposure and vulnerability of populations and assets. They are needed at different spatial scales, from local and national to global scales, and at different temporal scales, from upcoming days to decades. Flood risk management measures are key to flood hazard and risk mapping. Flood risk management is considered at the European level by the Floods Directive 2007/60/EC (European Commission, 2007) which directs EU Member states to adequately assess and manage their flood risk. This involves mapping the flood hazard extent, assessing the flood risk and producing flood risk management plans, which also consider the longer-term drivers of land use and climate change.

Flood hazard can be calculated by assessing the probability of any particular area being flooded. Usually, it is undertaken with respect to a particular level of flood, for example, the 0.01 Annual Exceedance Probability threshold (also commonly known as the '100-year flood' with a return period of 100 years, which is better understood as a flood that has a 1 % probability of occurring at any given location in any given year). Flood risk takes the flood hazard and combines this with information on the potential damage to society, such as vulnerability and the exposure of assets and populations in the floodplain. Approaches can be different depending on the temporal and spatial scales at which the flood hazard and risk assessment are applied, on the modelling tools and data available and on the type of flood hazard (e.g. if it is a fluvial, surface water or coastal flood).

A fully comprehensive flood risk map requires a great number of data, a series of floods events over a long peri-

od and a chain of models and assessments (Sampson et al., 2014, Dottori et al., 2016), although simpler mapping based solely on flood events or other historical information can also be useful (Boudou et al., 2015).

*Flood hazard and flood risk maps are required for land use planning, floodplain management, disaster response planning and financial risk planning. They can be produced at increasingly higher resolutions using flood modelling tools. Uncertainties can be taken into account by using probabilistic methods. A focus on flood hazard impacts can enhance communication to the public.*

For fluvial floods, a full risk mapping requires long-term series of hydrometeorological data, satellite data on the flood extent for the assimilation of spatial information, large datasets on population/asset exposure and flood protection standards (Scussolini et al., 2016), and commercially sensitive damage data from insurance companies, which are often not openly accessible. Longer timescale changes in flood risk are usually assessed through scenarios of climate change and socioeconomic development (Apel et al., 2008; Winsemius et al., 2013). These can take into account flood policies, such as the implementation of flood protection measures, as well as the interaction of human and physical systems, such as the adaptation effect and the failed levee effect (Di Baldassare et al., 2015; Collenteur et al., 2015).

Flood hazard maps can be produced by using hydraulic models to simulate water flow along rivers, over floodplains and in urban surface water accumulation zones. Simulations are often combined with Geographic Information System (GIS) techniques to build flood maps. This ideally requires substantial observed data for model calibration and validation. For fluvial floods, hydraulic models can use time series of historical river flows, historical rainfalls or time series of synthetic design rainfall events, in conjunction with catchment hydrology rainfall-runoff models. However, even the most sophisticated approaches have difficulty producing robust estimates of extreme events (Sampson et al., 2014), which can be problematic if these maps are the only resources used to support decision-making processes, such as urban planning. Describing flood inundation hazard and risk using probabilistic methods is therefore encouraged (Romanowicz and Beven, 2003; Pappenberger et al., 2006). For example, flood inundation hazard can be mapped from the development and set-up of flood inundation models, a sensitivity analysis using observations, the use of the multiple acceptable ('behavioural') model parameter sets to perform 'ensemble' (multiple) simulations using an uncertain synthetic design event, or an ensemble of scenarios, as input to the flood inundation models (Di Baldassarre et al., 2010). Probabilistic methods can be used, as they assume that, whichever model is chosen, it will not perfectly represent all flood propagation and inundation processes involved. This can be very important when modelling flood inundation in changing environments, when they are subject either to strong land use changes or to climate changes.

Regional-scale fluvial flood hazard mapping has been improved by the use of satellite data assimilation and flood models to map flood inundation pathways. Global flood hazard maps can also be useful in the assessment of flood risk in a number of different applications, including (re) insurance and large-scale flood preparedness. These maps can be created using large-scale computer models of rainfall-runoff processes in river catchments and river routing. They may, however, require the use of a variety of post-processing methods to better adjust simulations to local measurements (Pappenberger et al., 2012; Ward et al., 2013; Winsemius et al., 2013; Dottori et al., 2016). At the local scale, surface water flood hazard mapping (pluvial flooding) has benefited from recent improvements to fine-scale surface water modelling, particularly in cities, on 1-metre or 2-metre grids, integrating topography, land use, urban structures and potentially also subterranean drainage and flooding impacts (Tyrna et al., 2016; Palla et al., 2016).

All numerically produced flood hazard maps, regardless of their spatial scale, require validation in order to be useful. This can be very challenging because of a lack of robust observed data. On local, regional or national scales, validation can be undertaken,

at least to some extent, on the basis of past observations of inundation extents, from satellite, ground-based observations or community-based data sources, as well as from river stage and discharge measurements from river gauges. In contrast, the accuracy of global maps is far more challenging, as globally consistent observations can rarely be obtained. Trigg et al. (2016), for instance, describe several different global flood hazard maps, which have been individually validated within a limited context. The estimates of global flood hazard obtained are compared to analyse their consistency and to provide an estimate of model uncertainty. In Africa, the agreement between the different models is relatively low (30-40 %), with major differences in magnitude and spatial extent particularly observed for deltas, arid/semi-arid zones and wetlands, which are all areas that suffer from a lack of data for validation. Such discrepancies can have significant impact: for example, the models showed a large discrepancy in the Nile delta, where approximately 95 % of the population of Egypt lives. This highlights the fact that any global flood hazard map should be used with caution and that multimodel products may be useful (Trigg et al., 2016). The role of databases and post-event analyses is key to improve our understanding of global flood hazard and risk (de Moel et al., 2015).

## 3.4.5 Flood monitoring, forecasting and early warning systems

The predictability of hydrological systems varies because of the large number of non-linearities in these systems, the challenges in the observability of the state of the hydrological variables, the presence of outliers (rare occurrences), the variability of external forcing and the numerous interactions among processes across scales (Bloschl and Zehe, 2005; Kumar et al., 2011; Peña et al., 2015; Lavers et al., 2011). Different types of floods are predictable with different time ranges. Flash floods driven by convective rainfall are notoriously challenging to predict ahead in time to produce effective early warnings (Collier, 2007; Berenguer et al., 2005), whereas slower developing floods in large catchments can be predicted several days ahead of time with the use of probabilistic flood forecasting systems (Emerton et al., 2016). The use of satellites and EWSs based on computer-intensive forecasts has recently enabled distinct improvements in our ability to provide effective information on the likelihood and severity of upcoming flooding and the extent of the affected area (Alfieri et al., 2013; Revilla-Romero et al., 2015). This information can be provided to agencies, responders, stakeholders and the public in various forms, including interactive watch or warning maps and flood guidance statements (e.g. FFC, n.d.; Vigicrues, 2017).

However, there is substantial uncertainty in predicting floods, which stems from the uncertainty in the atmosphere, the complexity of the land-surface processes and the imperfection in the computer models used to represent them (Cloke and Pappenberger, 2009; Rodríguez-Rincón et al., 2015). Ensemble techniques can be used to represent the main sources of predictive uncertainty. These use multiple simulations based on different model set-ups, model parameters, initial conditions, data, etc. Rather than just providing one 'best guess' prediction, ensembles provide a whole range of model realisations and equally possible predictions for the future. Information can be obtained on which scenarios are most likely to happen and on the worst possible scenario (given our current knowledge of initial conditions and process representation). This can be useful to communicate forecast uncertainty and to help stakeholders to take more informed decisions (Cloke and Pappenberger, 2009; Stephens and Cloke, 2014; Zsótér et al., 2016). The HEPEX initiative (Hydrologic Ensemble Prediction Experiment, n.d.) seeks to advance the science and practice of hydrologic ensemble prediction and its use in risk-based decision-making by engaging researchers, forecasts and users in several community activities.

Real-time monitoring and rapid mapping of floods based on satellite data have been implemented at a variety of scales and by a number of different actors to detect flooding severity and extent in affected areas. For instance, the Copernicus Emergency Management Service—Mapping (2017) integrates satellite remote sensing and available in situ data to provide stakeholders with timely and accurate geospatial information in emergency situations and humanitarian crises (not just for floods, but also other hazards). It operates for the full emergency management cycle and can be broadly divided into (1) a Rapid Mapping component, which provides on-demand information within

hours or days, usually immediately in response to a disaster event, and (2) a risk and recovery mapping to support activities in the area of prevention, preparedness and disaster risk reduction. Another activity in the area of monitoring flooding from space and their impacts is the Dartmouth Flood Observatory (n.d.). Maps are published to provide an overview of flooding impact and extent, and a day-to-day record of flooding occurrences is built for analyses at a later stage. The use of space-based information facilitates international flood detection, response, future risk assessment, and community-wide hydrological research. Improvements in rainfall data assimilation to meteorological models (e.g. Ballard et al., 2016) and soil moisture, discharge and water level data or flood inundation characteristics to flood models (e.g. Garcia-Pintado et al., 2015; Alvarez-Garreton et al., 2015) have also provided improvements in flood forecasting and hazard mapping. Many other vital data have emerged, derived from ground-based imagery flood monitoring, crowdsourcing, unmanned aerial vehicles, rapid flood mapping and post-event data collection by authorities, researchers and local communities (e.g. Walker et al., 2016; Le Coz et al., 2016; Perks et al., 2016).

Numerical weather prediction models have now improved to the point that operational centres can set up hydrometeorological systems that are able to forecast river flow and flooding on larger catchments several days, and even weeks, ahead of an upcoming flood event at global scales (Emerton et al., 2016). Transnational forecasting and warning systems can be of particular benefit, as they provide consistent and comparable information for rivers that cross national boundaries. They can also be useful as support information for all nations that do not have adequate flood forecasting and warning capabilities (Alfieri et al., 2012; Thiemig et al., 2015). As Emerton et al. (2016) argue:

*Flood forecasting and EWSs are identified as key preparedness actions for flood risk management and can be implemented at local scales through to continental and global scales. Radar and numerical weather forecasting systems can be used as inputs to flood forecasts, but uncertainties should be taken into account using ensemble (probabilistic) forecasting techniques.*

Operational systems currently have the capability to produce coarse-scale discharge forecasts in the medium-range and disseminate forecasts and, in some cases, early warning products in real time across the globe, in support of national forecasting capabilities. With improvements in seasonal weather forecasting, future advances may include more seamless hydrological forecasting at the global scale alongside a move towards multi-model forecasts and grand ensemble techniques, responding to the requirement of developing multi-hazard EWSs for disaster risk reduction. Flood magnitude and return period (or average frequency of occurrence) can be assessed for single points on a river. However, for those applications that require a measure of flood severity across an entire region, or 'floodiness', as, for example, in the case of initiating and forecasting the need for humanitarian actions, floodiness indices can be used to provide a spatial view of the risk of flooding (Stephens et al., 2015). Although several applications still rely on rainfall forecasts as a proxy for imminent flood hazard, Stephens et al. (op. cit.) have shown that monthly floodiness is not well correlated with precipitation, which demonstrates the need for hydrometeorological EWSs at such scales.

## 3.4.6 Copernicus Emergency Management Service: floods (EFAS and GloFAS)

The European Flood Awareness System (EFAS, 2016; operational since 2012) and GloFAS (GloFAS, 2017; due to become operational in early 2017) aim to provide early flood information to national authorities to support national capabilities, particularly with earlier and probabilistic information. EFAS additionally provides information to the European Commission's ERCC to support flood disaster response.

The EFAS project was initiated following the severe 2002 flooding that took place across Europe and has

since been enhanced with research developments and user feedback. Large-scale systems not only save lives by increasing flood preparedness, but also have a significant economic benefit. Pappenberger et al. (2015) provide evidence of the monetary benefit in cross-border continental-scale flood EWSs. The potential monetary benefit of EFAS was estimated by combining warning information with existing flood damage cost information and calculations of potential avoided flood damages. The benefits were estimated to be of the order of EUR 400 for every euro invested (Pappenberger et al., 2015).

The benefits of an EWS can also be demonstrated in individual cases of flood warning. For example, EFAS proved to be useful in the widespread flooding that occurred in the Balkans region in south-eastern Europe in 2014. Weeks of continuous rain, combined with an exceptional storm on 13 May, led to heavy flooding in Bosnia-Herzegovina and Serbia, but also in Slovakia, southern Poland and the Czech Republic. The impact

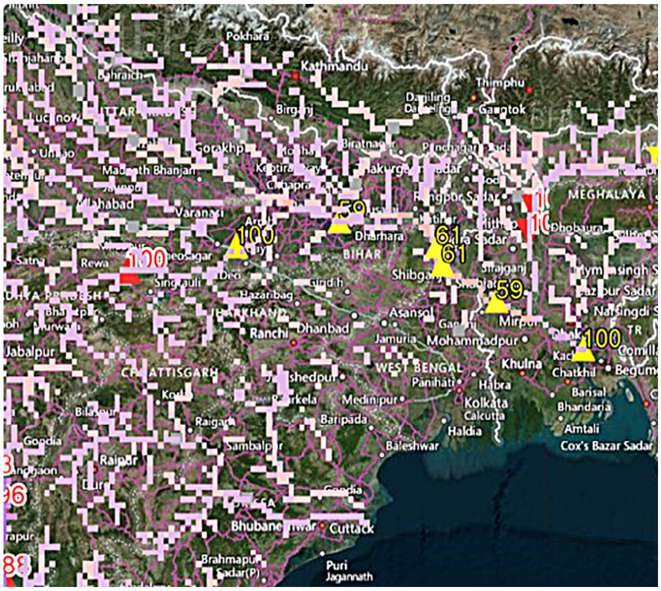
**FIGURE 3.25**

**GloFAS forecasts of the River Ganges floods in July/August 2016.**

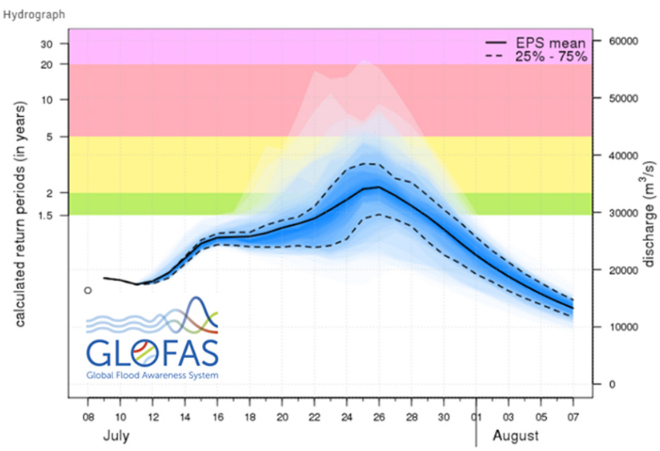
a) forecast map showing river pixels with upcoming floods;
b) forecast ensemble hydrograph for the Ganges at Begusarai (Bihar) on 8 July 2016; 1 week before the flooding started and 18 days before the peak;
c) forecast ensemble hydrography on 21 July 2016, showing the flood peak on 27 July with 98% probability of exceeding the severe alert threshold (20 year return period) and 50% probability of exceeding the 50-year return period.
The colours of the triangles and pixels in (a) and shading in (b,c) are: purple represents severe alert of ≥ 20 year return period; red, high alert of ≥ 5 year return period; yellow, medium alert of ≥ 2 year return period.

**Source: GloFAS (2017)**

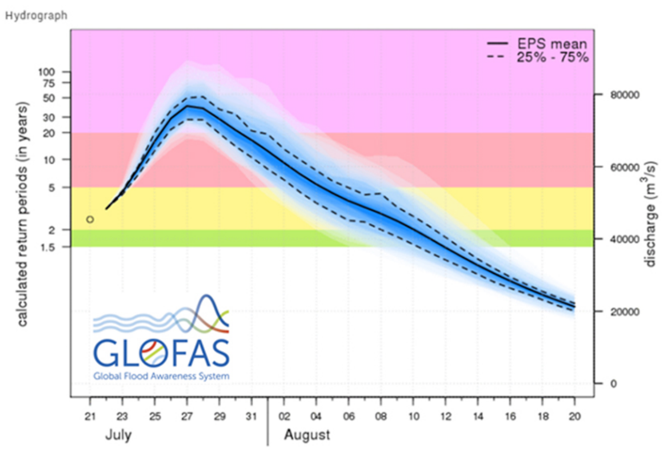
**a)**




**b)**




**c)**



of flooding was so severe that Bosnia-Herzegovina and Serbia requested assistance from the European Union through the EU Community Civil Protection Mechanism. EFAS provided early warnings from 11 May onwards and notified national authorities and the ERCC operating within the Commission's Directorate-General for Humanitarian Aid and Civil Protection (DG ECHO). This facilitated a coherent European disaster response during the numerous emergencies.

*There is likely to be a substantial monetary benefit in cross-border continental-scale flood EWSs. In Europe, transnational flood early warning is undertaken by the Copernicus Emergency Management Service: Floods, which consists of the European Flood Awareness System (EFAS) and its global twin system, the Global Flood Awareness System (GloFAS).*

Similar examples can be provided for GloFAS. In August 2016, flooding occurred along the Ganges River in India. According to India's Central Water Commission, the Ganges in the Patna district was just 8 cm below the highest recorded water level, which forced thousands to flee their homes into relief camps. GloFAS was able to provide flood forecast information several weeks in advance (Figure 3.25). However, it is also clear that significant training is still required in order for such forecasts to be useful and to enable decisions from probabilistic information (Pagano et al., 2014). Training needs to be provided within the relevant context of international, regional and local organisations. For example, GloFAS has provided training through the RIMES (Regional Integrated Multi-Hazard Early Warning System) and UN-ESCAP (United Nations — Economic and Social Commission for Asia and Pacific), with participants from national hydrometeorological services in Bangladesh, Bhutan, Nepal, India, China and Pakistan (via the internet) and representatives from several international organisations.

In a recent case study in Uganda, Coughlan de Perez et al. (2016) have shown that global systems combined with local expertise and knowledge have the potential to assist in reducing flood disaster impacts by triggering preventative action before flooding. The system for forecast-based financing automatically triggers action when a flood forecast arrives and before a potential disaster. While not a perfect indicator of flooding, GloFAS forecasts proved to be reliable in forecasting a specific chance of flooding (exceedance of a pre-defined danger level) and was useful as an EWS.

## 3.4.7 Communicating uncertainty and decision making

Decisions are taken at different stages in the production of a forecast, as well as after its public release (e.g. as a flood warning, often based on expert judgement). Human expertise is in constant interaction with automated tasks in flood forecasting (Pagano et al., 2016) and controls much of the output information of a flood forecasting system. Training and reforecasting of critical events increases the capacity to deal with uncertainty information and enables optimal decisions to be made (Ramos et al., 2013; Crochemore et al., 2016; Arnal et al., 2016). Risk-based decision-support frameworks have to be tailored to the problem in question but also flexible to allow different flooding situations and, often, unprecedented flood events, to be handled (Dale et al., 2014). Challenges at present include providing tailored warnings that are acted upon by responders and the public (Demeritt et al., 2013; Dittrich et al., 2016), and developing decision-support systems that can integrate the different stages of flood risk management, without losing information on uncertainty, warning time, forecast accuracy and reliability. This should help decision-makers to understand the strengths and weaknesses of a forecasting system for different scales and events.

Similarly, flood hazard and risk mapping also involves many layers of data collection and modelling output display. It is crucial that communication

is ensured at all stages and that essential information for decision-making is not lost (see Chapter 4). Communication not only targets decision-makers at public or private companies, but also involves communication to the public and to experts (Environment Agency, 2015) who may prefer information to be described in terms of possible impacts. The visualisation of model outputs and maps is part of the communication process (Pappenberger et al., 2013). Usually, communication will cover information on alerts, watches and warnings, risk maps and vulnerable areas that can be potentially affected by floods of different magnitudes and return periods (100-year flood, 10-year flood, etc.), but also guidance on using and interpreting maps. It is important that communication follows Open Geospatial Consortium (OGC) standards, such as providing information as Web Mapping Services (WMS) or WaterML, so that it can be easily integrated into other systems and be more effective. The communication of flood hazard and risk and the associated uncertainties should be a strong focus at all stages in the prevention, preparedness, response and recovery cycle. It should also be active during recovery in order to facilitate post-event surveys, to speed up recovery with the help of local communities or to convey lessons learned (Marchi et al., 2009; Stephens and Cloke, 2014; Javelle et al., 2014).

Efficient communication is also dependent on how users perceive risk and understand uncertainty, and tend to act in the face of uncertain information (Ramos et al., 2010; Bubeck et al., 2012). A two-way approach can enhance, and even modify, established links between modelling outputs (hazard and risk maps) and social actions. Through an increased understanding of user needs and institutional and social vulnerability drivers (Rufat et al., 2015, Daupras et al., 2015), existing bottlenecks in flood response, such as areas of difficult access or with high rates of injuries and fatalities, can be detected and targeted in the maps. With time, behaviour changes can even bring modifications to the vulnerability zones and can modify flood risk maps that cross flood vulnerability with hazard. In this process, building trust and confidence is essential. Uncertainties are not necessarily unwelcome by the public and stakeholders (McCarthy et al., 2007), and explicitly acknowledging uncertainty in flood risk mapping is also valuable for decision-makers (Michaels, 2015). The communication of uncertainty can help modellers and forecasters by strengthening a relationship of confidence between them and the users of their products.

*Flood forecasts and flood risk maps have associated uncertainties and are useful if decision-makers can understand and act upon the information provided, so forecasting and mapping must be in harmony with user needs and requirements to bring added value to the whole process of flood hazard and risk management.*

One uncertainty that it is essential to consider in all aspects of flood risk management is the projected future changes in flooding risks to communities, businesses and infrastructure. This means considering adaptive management approaches in the design of flood risk management policy and infrastructure (Gersonius et al., 2013). The degree of uncertainty in the impacts of climate change projections requires the consideration of flexible adaptation pathways. Regardless of the sources of uncertainties, more needs to be done in flood risk management policy and practice to make our societies resilient to future flood risk (CCC, 2017; EEA, 2017).

## 3.4.8 Conclusions and key messages

Flood disasters affect a large number of people across the world every year, with severe social and economic impacts. Severe flooding repeatedly affects European populations, with trans-national events often being the most damaging.

### Partnership

Our best strategy for flood management is to learn to live with flooding, that is, to prepare ourselves today to be better adapted for flood risks tomorrow. The combination of strong flood management policy, advanced early warning technology and increased international collaboration has the potential to reduce flood risk and improve disaster response from the local to the global scale. This requires stakeholders from different disciplines, scientists, policymakers

and practitioners to work closely togetherin partnership.

## Knowledge

Flood hazard and flood risk maps are required for land use planning, floodplain management, disaster response planning and financial risk planning. They can be produced at increasingly high resolution for fluvial and surface water flooding (and coastal flooding) using flood modelling tools. Uncertainties can be taken into account by using probabilistic methods. A focus on flood hazard impacts can enhance communication to the public.

## Innovation

Flood forecasting and EWSs are innovations that are key preparedness actions for flood risk management and can be implemented at local scales through to continental and global scales. Radar and numerical weather forecasting systems can be used as inputs to flood forecasts, but uncertainties should be taken into account using ensemble (probabilistic) forecasting techniques.

There is probably a substantial monetary benefit in cross-border continental-scale flood EWSs. In Europe, transnational flood early warning is undertaken by the Copernicus Emergency Management Service: Floods, which consists of EFAS and its global twin system, GloFAS.

Flood forecasts and flood risk maps have associated uncertainties and are useful if decision-makers can understand and act upon the information provided, so forecasting and mapping must be undertaken in harmony with user needs and requirements to bring added value to the whole process of flood hazard and risk management.

# 3.5 Hydrological risk: landslides

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## 3.5.1 Introduction

The term landslide encompasses a wide variety of phenomena, from the simple fall of rock blocks from vertical rock faces, through to topples and landslides that are dominated either by a sliding motion or by flows of soil and/or rock. Landslides are strongly correlated with other types of natural hazards, such as floods, droughts, wildfires, earthquakes, tsunamis and volcanoes, and are often involved in cascading events of multihazard disasters.

Climate change, the increased susceptibility of surface soil to instability, anthropogenic activities, growing urbanisation, uncontrolled land use and the increased vulnerability of populations and infrastructure contribute to the growing landslide risk. In the Thematic Strategy for Soil Protection (European Commission, 2006), landslides are considered one of the main threats to European soils. In this framework, landslide disaster risk reduction should be properly undertaken in order to reduce the impact of landslides on humans, structures and infrastructures. In areas with high demographic density, protection works often cannot be built owing to economic or environmental constraints, and is it not always possible to evacuate people because of societal reasons. Forecasting the occurrence of landslides and the risk associated with them, and defining appropriate EWSs, are, therefore, essential needs.

The societal and economic impact of landslide risk is difficult to assess and it is underestimated, since a relevant part of related damage is attributed to other natural hazards, in multihazard chains (e.g. seismically induced failures, rainfall induced debris flows, lahars and rock avalanches associated with volcanism).

An established worldwide scientific landslide community has flourished in the last decades, thanks to several international organisations, such as the International Consortium on Landslides and the Landslide Joint Technical Committee, which periodically organise the World Landslide Forums and the International Landslide Symposia, respectively. Regular landslide sessions are also organised at the General Assembly of the European Geoscience Union each year.

*The term 'landslide' describes a variety of processes that result in the downward and outward movement of slope-forming materials, including rock, soil, artificial fill or a combination of these.*

In this subchapter, the main causes and triggers of landslides and their socioeconomic impact at European

level are described, before some general concepts and methodologies on landslide zoning (inventory, susceptibility and hazard maps) and EWSs based on the analysis of landslide monitoring data and rainfall data are introduced.

## 3.5.2 Landslide causes and triggers

The most recent landslide classification is found in Hungr et al. (2014). It discerns five main types of movement: falls, topples, slides, spreads and flows. Many landslides consist of a variety of movement types occurring in sequence. For example, large landslides in high mountainous areas often start as rock falls involving freefalling rock that detaches from a cliff, which upon impact at the cliff toe may spontaneously transition into a very high-energy rock avalanche (Hutchinson, 1988). The properties of the flow change further as the landslide entrains or deposits debris and water.

Landslides vary greatly in size. At the largest scale, a single landslide can involve up to some cubic kilometres of rock and soils. At the other end of the scale, a small boulder has the potential to cause loss of life, if it strikes an individual, or to cause mass fatalities if, for example, it causes a train to derail. In general, the potential to cause loss scales with size of the landslide, largely because of the scaling of the kinetic energy and the affected area.

A key causal factor for landslides is the topographic setting of the potential site. In general, the propensity to failure usually increases as the slope angle increases, from essentially zero on a flat surface to a significantly higher level when slopes are steep. However, the relationship with geological factors is highly non-linear, and below a key gradient, any given slope is likely to be stable under most conditions. Slopes naturally evolve into a stable state under any given set of environmental conditions, primarily through landsliding processes. External factors disrupt the slope equilibrium to induce instability; thus, for example, a migrating river channel or an unusual flood may erode the toe of a slope, increasing the slope gradient and the likelihood of failure. The slope will then naturally evolve back to its stable gradient through time, perhaps by means of another landslide that removes the excess material.

A second set of causal factors relates to the type of material involved in the potential instability and its geotechnical properties, such as internal friction and cohesion. In hard rock masses, stability is usually defined not by the intact strength of the material but by the joints, fractures and faults. The strength of these discontinuities may be dramatically lower than the intact rock strength, especially where they are lined with a weaker material. Where such a discontinuity has an orientation that promotes failure, the resistance of the slope to landsliding can be dramatically reduced. Therefore, in many cases, analysis of susceptibility depends on an understanding of the role played by these discontinuities. Furthermore, the strength of slope materials degrades through the processes of weathering, which may physically and chemically alter the constituent minerals or may break an intact mass into smaller, weaker pieces. Therefore, the susceptibility of a slope to failure may increase with time.

Earth materials interact closely with hydrology and hydrogeology. Water is probably the most important factor that promotes slope instability. In many cases, water influences the strength parameters of geological materials, generally reducing strength when materials become saturated. Pore water pressure changes the effective stress state of a slope, typically reducing resistance to shear forces, and promoting instability. The lack of understanding of hydrological conditions is a frequent cause of failure in managed slopes; the 1966 Aberfan disaster in South Wales for example (Bishop et al., 1969), in which more than 140 people were killed by a landslide from a mine waste tip, was primarily the result of the construction of the tip on a spring and watercourse, which promoted conditions of full saturation after periods of heavy rainfall. However, water can also have more complex relationships with instability. For example, in some materials partially saturated conditions can provide additional strength through the generation of suction forces, while in others saturated conditions can promote soil liquefaction after failure, turning a slow landslide into a highly mobile and highly destructive flow.

Land use can also be a key factor in landslide causation. Some types of vegetation can improve stability by providing additional strength to the soil via root systems, and by regulating the infiltration of water and drawing

down pore water pressures through transpiration. In general, forested slopes are more stable than those left bare, and there is a large body of evidence to support the argument that there is increased mudflow activity after fires have removed vegetation (Cannon and Gartner, 2005; Shakesby and Doerr, 2006) and increased landsliding after careless logging (Jakob, 2000). In general, the removal of vegetation promotes instability. Growing new vegetation is a difficult (but effective where successful) way to restore stability. Deforestation highlights the action of humans as the final key factor. As people modify the landscape, the likelihood of landsliding changes. In many cases, humans promote instability by cutting slopes to steeper angles, removing vegetation, changing hydrology and increasing weathering rates.

*Landslide occurrence is related to causal factors, which create a propensity for a slope to fail, and triggers, namely the specific external event that induces landslide occurrence at a particular time.*

In most cases, the timing of failure is associated with a trigger event. This is not always true, however; there is increasing evidence that slopes can fail through progressive mechanisms that involve the weakening of slope through time until stability is compromised, but such events are rare, although they can be destructive. However, most landslides are associated with a clearly defined trigger. Heavy rainfall is a key factor in generating landslides, primarily through the generation of pore water pressures and thus a reduction in the effective normal stress. For example, the annual global landslide cycle is dominated by the effects of rainfall associated with the South Asian and East Asian monsoons (Petley, 2010). The impact of the South Asian monsoon on the southern edge of the Himalayas, allied with the topography and materials of the region, makes this the global hotspot for landslide occurrence. However, the same correlation holds true everywhere.

The second key factor, and possibly the most important in terms of loss of life, is the impact of seismic events. Large earthquakes in mountain chains can trigger extraordinary numbers of landslides. Recent events include the 2005 Kashmir (Pakistan) earthquake and the 2008 Sichuan (China) earthquake, both of which killed more than 20 000 people in landslides. The Sichuan earthquake alone triggered more than 100 000 landslides. At present, the nature of the interaction between seismic waves and slopes is poorly understood, and forecasting the impacts of a future earthquake in terms of landslides is fraught with difficulty. However, the high levels of loss suggest that this will be a key area of research in the future.

Humans can also be a key trigger of landslides. The construction of hydroelectric stations can be significant. The Three Gorges Dam in China, the world's largest hydroelectric project, is expected to lead to the ultimate relocation of 1.4 million people owing to the construction of a 650-km long reservoir and the increased landslide risk; similar problems can be also found in Europe but to a lesser extent. The Vajont rock slide (Italy) resulted in the deaths of more than 2 000 people in 1963, when rock fell into the reservoir impounded by the highest arch dam in the world at the time. Humans trigger landslides through slope cutting (especially for road construction), deforestation, irrigation, undercutting and changes in hydrology and blasting, among many other activities. Mining activities have a particularly large impact. In more developed countries, mining is therefore strictly regulated; sadly, in less affluent countries, regulation lags considerably, and losses are much higher.

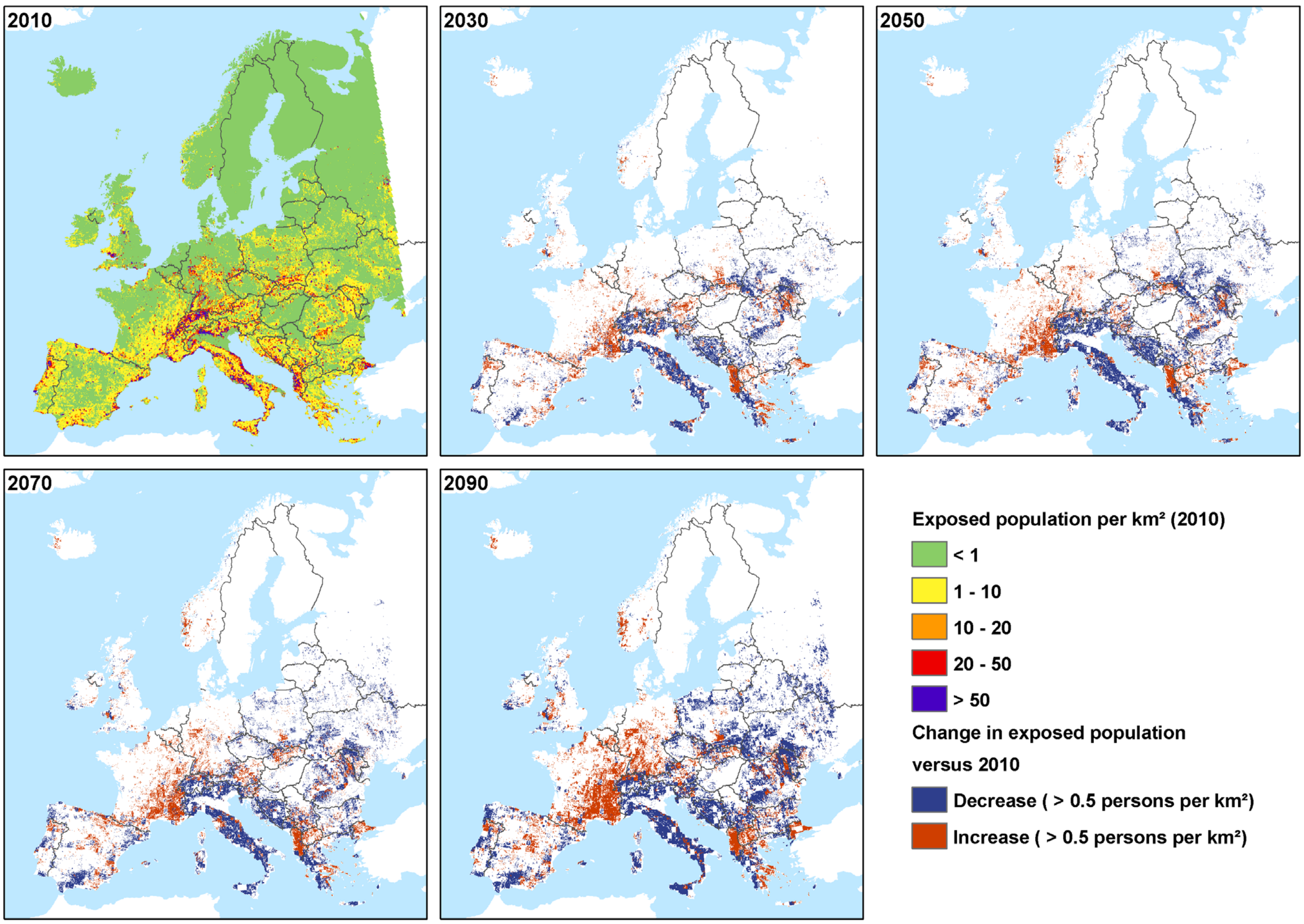
Finally, in active volcanic areas, landslides can be a major problem. Some of the highest levels of loss have occurred as a result of the high-mobility volcanic landslide known as a lahar, and volcanic flank collapses, which can be tsunamigenic, may be the largest terrestrial landslides possible. Some of the deadliest landslide events on record have occurred in volcanic areas. Active volcanism promotes instability (the 1980 Mount St Helens eruption started with a landslide that depressurised the volcano), and dome collapse is common. Volcanic deposits regularly mobilise into high-energy flows, and hydrothermal activity can cause material strength degradation over large areas. Major debris avalanches, partially submarine, were triggered by the 2002 eruption of Stromboli volcano (Italy) and they caused tsunamis, in a typical multihazard domino effect (Tinti et al., 2006).

## 3.5.3 The socio-economic impact of landslides in Europe and climate change

The fast-paced changes in society, climate change and the human impact on the environment have a major impact on the frequency and spatial distribution of landslides. Annual climate data in Europe for the last two centuries demonstrate a shifting pattern in frequency and intensity of extreme weather events (IPCC, 2012, 2013). Along with the changes in climate and weather patterns, demography, land use and other factors driving the landslide risk are changing rapidly (UN, 2015). Indeed, projections through the 21st century for Europe indicate that societal changes may lead to a larger increase in the impacts from landslides and other natural hazards than climate change. Therefore, the changes in the socioeconomic impact of landslides should be considered at two different timescales. The influence of climate change on the spatial and temporal characteristics of landslide risk will be noticeable by the end of the century. At a shorter timescale of one to two decades, the rapid changes in anthropogenic factors such as urbanisation and land use change drive the dynamic risk pattern that we face today.

**FIGURE 3.26**

**Estimate of changes in the exposure of Europe's population to landslides in the 21st century**
**Source: SafeLand (2013)**



Regional climate model (RCM) simulations from the EU FP6 project ENSEMBLES (Van der Linden and Mitchell, 2009) predicted a consistent large-scale pattern of heavy precipitation changes in Europe. The simulations generally showed an increase in heavy precipitation over northern and central Europe in winter, although some inconsistencies were found among the predictions from different models in mountainous regions and at the foothills of the mountains. In summer, most models agree on an increase in heavy precipitation over Scandinavia and reduced precipitation in southern Europe. The largest inconsistencies were found in the transition zone across central Europe, which separates areas with positive trends in the north and areas with negative trends in the south. Considering both the expected changes in patterns of extreme precipitation events and changes in other factors driving the landslide risk, the EU FP7 project SafeLand assessed the expected changes in climate-driven landslide activity (magnitude, frequency) in Europe in the next 100 years.

*It must be emphasized that any prognosis of the changes in the socio-economic impact of landslides due to climatic change involves a high level of uncertainty.*

The SafeLand study estimated that landslide hazard threatens about 4 % of European citizens today. In addition to the people directly threatened in their homes, 8 000-20 000 km of roads and railways are exposed to high landslide hazard, causing additional direct threats to life and economic assets as well as problems for emergency response and recovery operations (Jaedicke et al., 2013). The SafeLand prognosis was that about 0.7% of the total European population will experience an increase in landslide risk by the end of the century, although in some parts of Europe the risk will be reduced. The spatial pattern of the expected change in the European population exposed to landslide risk is depicted in Figure 3.26. The main changes in landslide risk at the European scale shown in the figure are due to the changes in population pattern caused by migration and urbanisation.

The SafeLand project also made a detailed study of the changes in landslide risk pattern at local scale for selected sites in Europe for the period 1951-2050. For these studies, the climate simulations were downscaled to simulate localised heavy precipitation events in regions where rain-induced landslides occur on a regular basis. The downscaled climate models predicted an increase in landslide hazard at all sites. These results differed from the predictions provided by larger scale climate models at some locations. These differences might be explained by the refinement in the climate model used, which, for example, considered the influence of local topography on precipitation. This demonstrated that large-scale models are useful to evaluate the relative spatial variations of landslide activity, while local scale models are necessary for urban planners and local authorities to estimate the future risks associated with landslides and other hydro-meteorological hazards in their communities or regions of interest.

In addition, the large uncertainties in population and traffic evolution scenarios, land use changes and political decisions regarding urban development require that the key parameters driving landslide risk are accurately monitored and that the prognosis of landslide risk is continuously updated as new information becomes available and more accurate and refined climate change models are developed.

## 3.5.4 Landslide zoning: inventory, susceptibility and hazard maps

The mapping of landslides underpins disaster risk reduction strategies, integrating socio-economic impacts, and therefore the challenge is to analyse their causes and triggers in our changing environments. Owing to the extraordinary breadth of the spectrum of landslide phenomena, no single method exists to identify and map landslides and to ascertain landslide susceptibility and hazard.

In addition to predicting 'where' a slope failure will occur, landslide hazard forecasts 'when' or 'how frequently' it will occur, and 'how large' it will be (Guzzetti et al., 2005).

The simplest form of landslide mapping is a landslide inventory map, which shows the location and, where known, the date of occurrence and the types of landslide that have left

discernible traces in an area (Guzzetti et al., 2012). Landslide inventory maps can be prepared by different techniques, depending on their scope and the extent of the study area. Small-scale inventories (≤1:200 000) are compiled mostly from data obtained from the literature, through inquiries to public organisations and private consultants, by searching chronicles, journals, technical and scientific reports, or by interviewing landslide experts. Medium-scale landslide inventories (1:25 000 to 1:200 000) are most commonly prepared through the systematic interpretation of aerial photographs at scales ranging from 1:60 000 to 1:10 000, and by integrating local field checks with historical information. Large-scale inventories (>1:25 000) are prepared, usually for limited areas, using both the interpretation of aerial photographs at scales greater than 1:20 000, very high-resolution satellite images or digital terrain models, and extensive field investigations.

An archive inventory shows information on landslides obtained from the literature or from other archive sources. Geomorphological inventories can be further classified as historical, event, seasonal or multitemporal inventories. A geomorphological historical inventory shows the cumulative effects of many landslide events over a period of tens, hundreds or thousands of years. In a historical inventory, the age of the landslides is not distinguished, or is given in relative terms (i.e. recent, old or very old). An event inventory shows landslides caused by a single trigger, such as an earthquake, rainfall event or snowmelt event, and the date of the landslide corresponds to the date (or period) of the triggering event. Examining multiple sets of aerial or satellite images of different dates, multitemporal and seasonal inventories can be prepared. A seasonal inventory shows landsides triggered by single or multiple events during a single season, or a few seasons, whereas multitemporal inventories show landslides triggered by multiple events over longer periods (years to decades).

*Landslide susceptibility is the probability of spatial occurrence of slope failures, given a set of geo-environmental conditions. Landslide hazard is the probability that a landslide of a given magnitude will occur in a given period and in a given area.*

Conventional methods to prepare landslide inventory maps rely primarily on the visual interpretation of stereoscopic aerial photography, aided by field surveys. New and emerging techniques, based on satellite, airborne and terrestrial remote sensing technologies, promise to facilitate the production of landslide maps, reducing the time and resources required for their compilation and systematic update. These can be grouped in three main categories, including the analysis of surface morphology, chiefly exploiting very-high-resolution digital elevation models captured for example by LiDAR (light detection and ranging) sensors, the automatic or semi-automatic interpretation and analysis of satellite images, including panchromatic, multispectral and synthetic aperture radar (SAR) images, and the use of new tools to facilitate field mapping.

Qualitative and quantitative methods for assigning landslide susceptibility can be classified into five groups (Guzzetti et al., 1999):

1. geomorphological mapping, based on the ability of an expert investigator to evaluate and map the actual and potential slope instability conditions;
2. analysis of landslide inventories, which attempts to predict the future landslide spatial occurrence from the known distribution of past and present landslides (typically, this is obtained by preparing landslide density maps);
3. heuristic or index-based approaches, in which investigators rank and weight the known instability factors based on their assumed or expected importance in causing landslides;
4. process-based methods that rely on simplified physically based landslide modelling schemes to analyse the stability/instability conditions using simple limit equilibrium models, such as the 'infinite slope stability' model, or more complex approaches;
5. statistically based modelling contingent on the analysis of the functional relationships between known or inferred instability factors and the past and present distribution of landslides. Regardless of the method used, it is important that the susceptibility zonations are validated using independent landslide information,

and that the level of uncertainty associated with the zonation is given (Rossi et al., 2010).

Landslide hazard is more difficult to obtain than landslide susceptibility, since it requires the assessment of the temporal frequency of landslides and the magnitude of the expected failures (Guzzetti et al., 2005). The temporal frequency (or the recurrence) of landslides, or of landslide-triggering events, can be established from archive inventories and from multitemporal landslide maps covering sufficiently long periods. Furthermore, where a landslide record is available, an appropriate modelling framework needs to be adopted (Witt et al., 2010). Alternatively, for meteorologically triggered landslides, one can infer the frequency of landslide events from the frequency of the triggering factors, for example the frequency (or the return period) of intense or prolonged rainfall periods. The uncertainty inherent in the prediction of triggers that may result in landslides adds to uncertainty inherent in the prediction of occurrence of landslides.

To determine the magnitude of an expected landslide, investigators most commonly revert to determining the statistics of landslide size (area or volume). Accurate information on landslide area can be obtained from high-quality geomorphological inventories. Determining the volume of a sufficiently large number of landslides is more problematic, and usually investigators rely on empirical relationships linking landslide volume to landslide areas (Guzzetti et al., 2009; Larsen et al., 2010; Catani et al., 2016). Finally, when determining landslide hazard as the joint probability of landslide size (a proxy for magnitude), the expected temporal occurrence of landslides (frequency) and the expected spatial occurrence (landslide susceptibility), great care must be taken to establish if, or to what extent, the three probabilities are independent. In many areas, given the available information and the local settings, this may be difficult to prove (Guzzetti et al., 2005). We expect that the quantitative assessment of landslide hazard will remain a major scientific challenge in the next decade.

Such identification of areas susceptbible to landslide hazard is essential for the landslide risk assessment and possible implementation of effective disaster risk reduction strategies. These strategies (Dai et al., 2002) include land-use planning, development control land, the application of building codes with different engineering solutions, acceptance, and monitoring and early warning systems. Land planning control reduces expected elements at risk. Engineering solution is the most direct and costly strategy for reducing either the probability of landsliding or the probability of spatial impact of a landslide. One approach is correction of the underlying unstable slope to control initiation of landslides (such as stabilisation of slope, drainage, retaining walls or planting), and the other is controlling of the landslide movement (such as barriers/walls to reduce or redirect the movement when a landslide does occur). The acceptance strategy defines acceptable risk criteria (Fell, 1994;Fell and Hartford, 1997); and the monitoring and warning system strategy reduces expected elements at risk by evacuation in advance of failure.

## 3.5.5 Landslide monitoring and early warning

These systems require a fine assessment of the socioeconomic impact of landslides, which must be based on accurate landslide mapping, as well as an understanding of their causes. EWSs for landslides are based on the reliable continual monitoring of relevant indicators (e.g. displacements, rainfall, groundwater level) that are assumed to be precursors to triggering landslides or reactivations. When values for these indicators exceed predefined thresholds, alarms are transmitted directly to a chain of people in charge of deciding the level of warning and/or emergency that must be transmitted to the relevant stakeholders, following a predefined process (Figure 3.27). In some cases, warnings can also be automatically transmitted. Usually, one to five alert levels are used (Blikra, 2008; Intrieri et al., 2013): the highest level may lead to emergency warnings to the population, evacuations or the use of sirens and loudspeaker messages in several languages to force people to move to a safer place, as in the case of tsunamis induced by landslides.

An EWS needs to be set up with specific requirements. First, the potential impacts must be defined based on a risk analysis informed by hazard mapping, including the impact of global changes (Corominas et al., 2014). In addition, the causes and triggers of disasters must be thoroughly analysed and the development of local coping capacities must be included (Dash

and Gladwin, 2007).

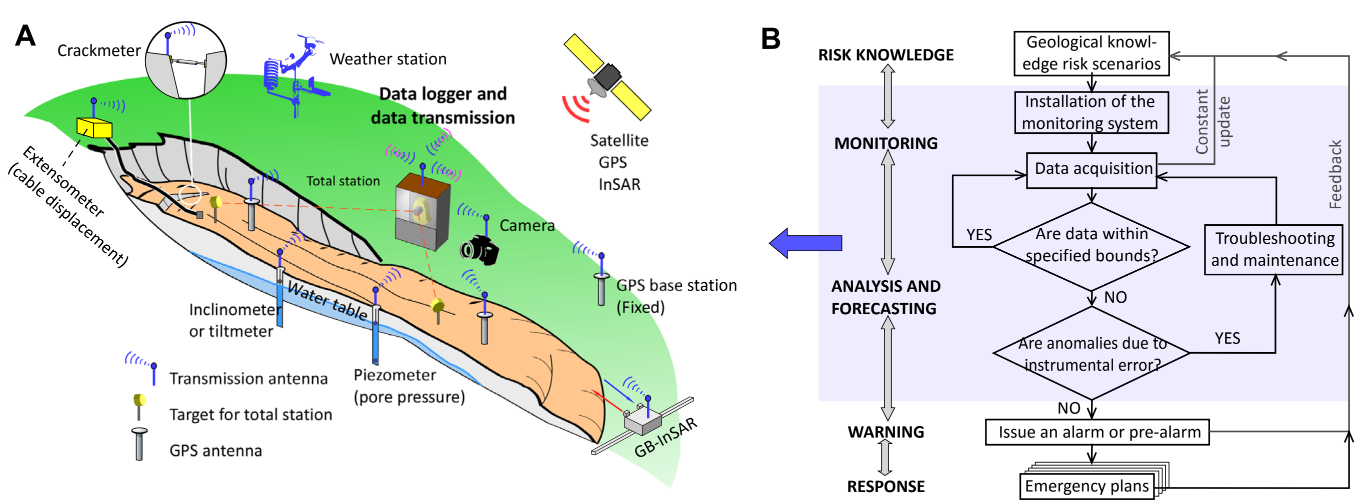
The number of EWSs dedicated to landslides has greatly increased since the beginning of the 21st century because of the progress made in electronics, communication and computer programs for monitoring and imaging. In addition, the innovations in satellite technologies and ground remote sensing have greatly improved the capacity of remote imaging measurements versus in situ point measurements (Tofani et al., 2013). Implementing an EWS depends on the context, namely (1) the type of landslide (Hungr et al., 2014), (2) the disaster scenarios considered, (3) the degree of awareness of the stakeholders, including populations, and (4) the allocated resources (e.g. budgetary, human).

Landslide types determine, first, if the appropriate EWS must be site specific or regional (Intrieri et al., 2013), and also if it is dedicated to identifying triggering conditions and/or to detecting an ongoing event (Sättele et al., 2016). For example, monitoring systems of debris-flow or shallow landslide EWSs are usually based on thresholds of rainfall amount over a period of time. These thresholds are based on rainfall intensity-duration, cumulated event rainfall-duration (Guzzetti et al., 2008), or antecedent precipitation (including snow depth) measures and soil moisture (Baum and Godt, 2010; Jakob et al., 2012). An extended monitoring of those indicators usually makes it possible, therefore, to set regional alarms. Landslide types also constrain the maximum lead time or time of reaction after the alarm transmission (Sättele et al., 2016). In some specific cases, debris-flow catchments are equipped with monitoring systems such as ultrasonic and seismic sensors that detect the debris-flow movements (Marchi et al., 2002) and automatically send a warning message to shorten the reaction time as much as possible.

For site-specific systems, displacements measured by different sensors and pore water pressure and/or precipitation are usually used (Michoud et al., 2013). Various sensors can be set to monitor displacements, including extensometers (cable or laser) and crackmeters that measure the distances between two points, and total stations that are also used to provide distances and 3D positions using targets positioned on site. Moreover, GPSs

**FIGURE 3.27**

**(A) Illustration of the components of a modern EWS that does not show the energy sources and the two or three levels of redundancy. (B) Flow chart of the activities of the implementation and operation of an EWS (modified from Intrieri et al., 2012). The blue box in (b) indicates the action linked to the monitoring system. Source: courtesy of authors**



are nowadays widely used, which can give the real 3D position of a point (Gili et al., 2000). All the above techniques usually provide data only at specific point locations; thus, several of them must often be set up in a network to monitor areal deformations. Inclinometers give deformations at depth along boreholes, providing essential data on the changes in depth of landslide behaviour (Blikra, 2008). For the last few years, ground-based interferometric radar (GB-InSAR) has been used for the most critical landslides (Casagli et al., 2010; Blikra, 2012; Rouyet et al., 2016). It provides a map of the distance changes, from the GB-InSAR to the landslide surface, at a millimetre scale and with a time resolution of a few minutes. Satellite InSAR images are also used to monitor long-term displacement trends, with results being strongly dependent on the type of treatment. In optimal cases, the time resolution is about 6 days, with millimetre precision and metre spatial resolution (Berger et al., 2012). Finally, as landslides react to water infiltration, many instruments are dedicated to monitor water: rain gauges, piezometers, thermometers, barometers, moisture content sensors and other meteorological data. Pore water pressure changes monitored with piezometers usually have a good correlation with slope movements (Michoud et al., 2013).

Behind the implementation of the monitoring part of EWSs is the understanding of the landslide mechanisms, that is, the identification of the main parameters controlling the movements of the landslide (Intrieri et al., 2012 and 2013). For this purpose, the design of a landslide conceptual model (LCM) is fundamental, since it will guide the type and the location of the sensors to install, and it is required to forecast landslide failure scenarios. The updating of an LCM must be continual during the whole life of an EWS. In addition, landslide failures may trigger other hazardous events in a cascade effect, such as tsunamis or dam breaks, that have to be considered in the EWS. The reasons why an EWS is implemented are either the identification of an unacceptable risk level or an increase in, or abnormal, landslide activity. Although the LMC implementation process provides reasons to fix appropriate sensors that will monitor the most significant failure initiation indicators, there are usually many practical constraints, such as topography, access, visibility and available resources.

*Landslide monitoring and EWSs are tools to forecast the potential occurrence of disasters, thus contributing to the implementation of effective disaster risk-reduction strategies.*

Ideally, the first data from a monitoring system are used to calibrate and fix alarm thresholds usually based on displacement velocities or accelerations, or pore water pressure or precipitations (Cloutier et al., 2015). This approach can be supported by failure forecast models, such as the Fukuzono method, or by more complex models (Crosta and Agliardi, 2003; Federico et al., 2012). The alarm thresholds will be used to trigger chains of actions that will involve different levels of people depending on the alert level, from technicians and experts to officers and politicians who will be involved in the assessment of the abnormal situations and who will have to make decisions (Froese and Moreno, 2014). This starts from the initial check of the situation and the coherence of the movement detection of the sensors (to avoid false alarm), and it can end with an evacuation decision. It requires that the monitoring system is reliable and is therefore redundant in terms of sensors, communication and the stakeholders involved. Pre-defined crisis units must follow decision trees to propagate or stop the warning at each level. This also necessitates the requirement to verify constantly that the observed landslide behaviour is still following the expected course, which also implies that the threshold and alarm levels can be reassessed by the crisis units.

The most important actions that can be prompted by EWS high-alert levels are evacuations and a rapid set-up of protection measures. They imply that all stakeholders, including the relevant population, must be prepared through education and training to implement the appropriate response.

In addition, the methods used to emit and communicate the emergency situation must be adapted to the local population culture. It must be stressed that all stages of implementation or operation must include feedback to the other stages. Frequent feedback and updates are a key point. They must also include the reappraisal of the indirect effects (cascade). A final problem relates to communication to

the general population, which, to be effective, needs trust and training and must be an efficient means by which to communicate and emit warnings and actions within the noise of our 'connected world'. It appears that only 38 % of the EWSs have more than one communication vector to inform the population (Michoud et al., 2013).

## 3.5.6 Conclusions and key messages

### Partnership

Understanding landslide risk requires a multihazard approach, based on networking and partnership between different scientific disciplines, with transdisciplinary research that aims to identify those socioeconomic and institutional elements that require attention in landslide DRM.

### Knowledge

Knowledge of landslide risk is a multidisciplinary task that requires an understanding of processes and mechanisms, spatial and time prediction, vulnerability assessment, monitoring and modelling of the effects related to environmental and climate change.

### Innovation

The effectiveness of landslide risk mitigation measures critically depends on scientific innovation and technological development for rapid mapping, monitoring and early warning.

# 3.6 Hydrological risk: wave action, storm surges and coastal flooding

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## 3.6.1 Overview of coastal flood risk

Coastal flooding is one of the most significant risks to life and infrastructure both globally and for Europe, with wide-ranging social, economic and environmental impacts. For example, in the United Kingdom alone, it is estimated that GPB 150 billion (EUR 177 billion) of assets and 4 million people are currently at risk from coastal flooding (Environment Agency, 2009). In Europe, long-term investment in operational flood warning systems has largely ensured that fatalities due to coastal flooding are avoided; however, the damage to infrastructure and clean-up costs are still significant. For example, during storm Xaver (4-8 December 2013) which brought the highest ever observed water levels to many European coastlines, there was no loss of life due to coastal flooding (although there were 15 fatalities directly associated with falling trees and vehicles). However, the financial impact of the severe coastal flooding was estimated by Credit Suisse to be more than EUR 1.5 billion.

In contrast to European weather systems, tropical cyclones can cause storm surges of up to 10 metres, which continue to cause devastating loss of life in parts of South-East Asia. In 1970, a devastating storm surge resulted in approximately a quarter of a million deaths in Bangladesh. Over the past decade, there has been considerable activity in the development of crucial flood warning systems for vulnerable tropical areas such as Bangladesh (DMB, 2010; WMO, 2010), resulting in the saving of tens of thousands of lives. However, despite the improving availability of coastal warning systems, tropical cyclones continue to cause havoc when this is a lack of preparedness. On 8 November 2013, Typhoon Haiyan (known as typhoon Yolanda in the Philippines) caused catastrophic damage throughout the Philippines, with the majority of the death toll (estimated to be more than 6 000 people) attributable to the storm surge that struck Tacloban City.

*Coastal flooding is caused by a combination of high tides, storm surges and wave conditions. Development on floodplains increases the risk as do coastal erosion and sea-level rise.*

Coastal flood risk is growing because of long-term mean sea-level rise and possible future changes in storminess (Church et al., 2013), as well as continued population growth and development in flood-exposed areas (Hallegatte et al., 2013). Irrespective of any future change in storm climate (which would affect storm surges and waves), mean sea-level rises will result in more instances of extreme sea-lev-

el thresholds being reached.

Coastal flooding occurs when a combination of high tide, storm surges and wave conditions is sufficiently severe to overtop or breach coastal defences and cause inundation of low-lying areas. Extreme high waters around Europe are normally caused by a combination of high tides and severe weather events (with the exception of the Mediterranean Sea where tides are small). Extra-tropical cyclones (the prevailing European weather systems) produce storm surges that can increase tidal levels by 3-4 metres in exceptional cases. The still water level (defined as the sea level before short-period waves are taken into account) can be further elevated at the coast by wave set-up caused by wave breaking. Storms then also produce large wind and swell waves, which can overtop coastal defences/beaches and cause flooding and erosion. A further factor that drives coastal flood risk is socioeconomic change (Thorne et al., 2007). Changes in land use and increasing asset values in floodplain areas have led to increased exposure to flooding (Horsburgh et al., 2010). Changes in coastal morphology can also influence flood pathways and thus flood risk (Thorne et al., 2007; Nicholls et al., 2015). As erosion is expected to dominate coastal morphological change in the future because of mean sea-level rises, this will add to the overall flood risk.

Waves and storms are a significant feature of global climate and have been included in many assessments of climate, including the latest assessment (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013). Recently, recognition of the central role of waves in atmosphere–ocean interactions has led to an initiative to include wave models more directly into climate model projections (Cavaleri et al., 2012; Hemer et al., 2012). The largest waves in European waters are found on the Atlantic boundaries, where waves can propagate over large fetches from the Atlantic Ocean. Many factors affect the height of waves in European waters, but for the Atlantic margin, the persistence and strength of westerly winds are particularly important (Wolf and Woolf, 2006), as are the intensity and frequency of storms. Waves are affected by currents and water depth and are locally modified by coastal geometry and man-made structures. Waves decrease in height in shallow water as a result of energy dissipation by bottom friction and wave breaking; this reduction in wave energy at a particular location may reduce over time, if the sea level rises, unless the coastal morphology in areas of mobile sediment can adapt at a similar rate (Woolf and Wolf, 2013). Extreme waves represent a hazard for any offshore operation or construction. Hazards may be due to, for example, large individual or significant wave heights, steep waves, crossing seas, or rapidly developing sea states (Toffoli et al., 2005). At the coast, wave overtopping or the impact of the waves on structures may become important. On longer timescales, changes in coastal wave climate may cause changes in the sedimentation and erosion patterns that in the long run will have impacts on sediment and shoreline dynamics (Wong et al., 2014). As sea levels rise and the rate of rise accelerates, low-lying coastal regions may be inundated, allowing waves to penetrate further inland, thus causing further damage.

## 3.6.2 Natural variability of waves, storm surges and mean sea level

All components of sea level display considerable natural variability, which influences the frequency of flooding on all timescales. Natural variability in the wave, storm surge and mean sea-level components ranges from variability associated with stochastic processes, to those displaying seasonal and longer period changes associated with regional climate (e.g. the quasi-decadal cycle known as the North Atlantic Oscillation - NAO). Europe experienced an unusual sequence of extreme storms over the winter of 2013-2014, resulting in some of the most significant coastal flooding since the catastrophic North Sea storm surge of 1953 (Matthews et al., 2014; Haigh et al., 2016).

Sea-level change at any particular location depends on many regional and local processes as well as global climate drivers, so regional sea-level change will differ from the global average. The fifth assessment report (AR5) of the IPCC concluded that it is very likely that the average rate of global averaged sea-level rise was 1.7 mm per year between 1901 and 2010 (IPCC, 2013). For the more recent period 1993-2010, this had risen to 3.2 mm per year, with consistency between tide-gauge and satellite altimeter data. It is likely that similarly high rates occurred between 1920 and 1950. Although there is a great deal of local variability in the measured values, mean sea levels around Europe (from tide gauge records) mostly exhibit

20th century rises that are consistent with the global mean value, although the central estimate around the United Kingdom is slightly lower than that of the global value (Woodworth et al., 2009). There is high confidence that the rate of observed sea-level rise increased from the 19$^{th}$ to the 20$^{th}$ century (Bindoff et al., 2007; Woodworth et al., 2011) and there is evidence of a slow long-term acceleration in the rate of sea-level rise throughout the 20$^{th}$ century (Church and White, 2011).

*All components of sea level exhibit natural variability. There is no convincing evidence of observed changes in European storminess. Changes in extreme levels are driven by mean sea-level change.*

Whether the faster rate of increase in sea level during the period from the mid-1990s reflects an increase in the longer-term trend or decadal variability is still not clear. For planning and engineering purposes, it is sea level with respect to the local land level that is of primary interest; furthermore, the Earth itself is moving as it recovers from ice loading during the most recent ice age. A key process that affects vertical land motion is the viscoelastic response of the solid Earth to deglaciation, termed glacial isostatic adjustment (GIA). An accurate understanding of regional sea-level change is a particular area that involves combining the global models of eustatic sea-level change (i.e. sea-level rise due to volume changes as well as geological changes to ocean basins) with local models of GIA modified localised effects at the coast (e.g. Smith et al., 2012). A further complication is that sea-level change is affected by large-scale gravitational adjustment in response to polar ice melt. Mitrovica et al. (2001) showed how rapid melting of major ice sources gives rise to spatial changes in the Earth's gravity field (as well as to the volume of water in the oceans); their model predicts a fall in relative sea level close to the source of melting as the gravitational interaction between ice and ocean is reduced, but a correspondingly larger rise in sea level further from the melt source.

Storm surges are the large-scale increases in sea level due to a storm. They can increase sea levels by 3-4 metres in European coastal seas and may last from hours to days and span hundreds of square kilometres. They are caused by wind stress at the sea surface and the horizontal gradient of atmospheric pressure (Pugh and Woodworth, 2014), although the magnitude of any particular storm surge is influenced by many factors, including the intensity and track of the weather system, bathymetry and coastal topography. The same factors control storm surges caused by mid-latitude weather systems (extra-tropical cyclones) and tropical cyclones (hurricanes). In regions of high tidal range, storm surges represent the greatest threat when they coincide with tidal high water: most operational forecasting centres now systematically refer to the combination of a storm surge and tidal high water as a storm tide.

In a strongly tidal region such as the European shelf, it is important to understand the interaction between storm surges and tides. Such interactions have been extensively studied (e.g. Rossiter, 1961; Prandle and Wolf, 1978). The dominant mechanism for tide-surge interaction is increased water levels as a result of meteorological forcing that induce a phase shift in the tidal signal (Horsburgh and Wilson, 2007); many properties of a non-tidal residual time series (i.e. the time series of sea-level observations minus tidal predictions) are simply artefacts of small changes to the timing of predicted high water. The most useful measure of storm surges is the skew surge, which is the difference between the maximum observed sea level and the maximum predicted tidal level, regardless of their timing during the tidal cycle (de Vries et al., 1995). Hence, each tidal cycle has one predicted high water value and one associated skew surge value. The advantage of using the skew surge is that it is a simple and unambiguous measure of the storm surge. Williams et al. (2016) have now shown that the magnitude of high water exerts no influence on the size of the most extreme skew surges. This is the first systematic proof that any storm surge can occur on any tide, which is essential to understand worst-case scenarios. The lack of surge generation dependency on water depth emphasises the dominant natural variability of weather systems. Weak seasonal relationships between skew surges and tidal high waters have been identified, and the inclusion of these in statistical methods will improve the estimates of extreme sea levels.

Storm surges are, of course, generated by storms, and there has been much

recent research aimed at understanding past and future changes in storminess over Europe due to the changes in mid-latitude storms over the North-East Atlantic. Trends in severe wind storms around the United Kingdom are difficult to identify, owing to the low numbers of such storms, their decadal variability and the unreliability of direct wind speed observations (Wang et al., 2009).

Wang et al.'s analysis shows that storminess conditions in this region have undergone profound decadal or longer timescale fluctuations, with considerable seasonal and regional differences. The most notable differences are seen between winter and summer, and between the North Sea area and other parts of the region. Over the last century the number of winter storms has decreased and then increased again. The observational evidence indicates that the strength of mid-latitude sea-level pressure (SLP) gradients and associated westerly circulation has increased in the northern hemisphere, especially during winter, since at least the late 1970s (Woolf and Wolf, 2013). The behaviour of North Atlantic storm tracks is key to understanding present and future changes in storminess. Future climate model projections have a large variability between models and a low signal-to-noise ratio for Europe compared with other mid-latitude regions (Hawkins and Sutton, 2009). Woollings (2010) identifies future European climate as particularly uncertain because (1) the spread between the predictions of current climate models is still considerable and (2) Europe is particularly strongly affected by several processes, which are known to be poorly represented in models, such as the small-scale structure of storms. Some of this variability seems to be related to the large-scale atmospheric patterns such as the NAO, which is related to the SLP difference between Iceland and the Azores. However, it is not clear that this relationship will persist into the future.

Wave climate in the North-East Atlantic and in European seas is to a large extent determined by the large-scale atmospheric circulation, the statistics of large-scale extra-tropical storms and smaller scale regional and local wind systems. Natural climate variability or anthropogenic changes in such factors will affect the wind climate, which results in corresponding changes to the wave climate. Changes in local wind climate will affect the wind sea, while changes in remote storm statistics will have an effect on the swell component of the wave climate. For the North-East Atlantic, Wolf and Woolf (2006) performed a number of sensitivity experiments with a numerical wind–wave model. By using synthetic wind fields, varying the strength of the prevailing westerly winds and the frequency and intensity of storms, as well as the location of storm tracks and the storm propagation speed, they found that variations in the strength of the westerly winds was most effective at changing mean and maximum significant wave height, while variations in other parameters had little effect on the mean wave height. Intensity, track and storm propagation speed, however, significantly affected maximum wave height. Generally, in all European Shelf seas and in the North-East Atlantic, pronounced seasonal variability in wave climate is seen with the highest waves in autumn and winter (e.g. Dodet et al., 2010; Arkhipkin et al., 2014).

Based on the assessment of literature analysing data from in situ measurements, satellite altimeter observations and wave model hindcasts, the IPCC AR5 concluded that it is likely that mean significant wave heights have increased in regions of the North Atlantic over the past half-century and that it is likely that these trends largely reflect natural variations in wind forcing (Church et al., 2013). For the North Sea and Baltic Sea, recent work is summarised in Huthnance et al. (2016) and Hünicke et al. (2015), indicating that wave height in these seas varies substantially on inter-annual and decadal timescales but does so far not show significant long-term trends. Using 20 years of buoy data for the Bay of Biscay, Dupuis et al. (2006) reported a tendency towards decreasing wave heights, which is consistent with the findings published in Dodet et al. (2010). For the Mediterranean Sea, Lionello and Sanna (2005) reported decreasing mean winter values of significant wave height in the period 1958–2001, while for the Black Sea, Arkhipkin et al. (2014) reported no significant change in corresponding storm activity.

The IPCC (2013) confirms that at most locations mean sea level is the dominant driver of observed changes in sea-level extremes, although large-scale modes of variability such as the NAO may also be important. There is evidence of increases in extreme water levels over the past 100-200 years around many parts of the global coastline, including Europe (e.g. Menendez and Woodworth, 2010). While changes in storminess could contribute to changes in sea-level extremes,

there is little or no evidence for either systematic long-term changes in storminess or any detectable change in storm surges (IPCC, 2012). The scientific consensus is that any changes in extreme sea levels at most locations are caused by the observed rise in mean sea level (e.g. Woodworth and Blackman, 2004; Menendez and Woodworth, 2010; Wahl and Chambers, 2016).

## 3.6.3 Datasets for coastal flood hazard analysis

The importance of having long time series data for assessing the statistics of extremes is well known (e.g. Weisse et al., 2009). A long time series of wave observations (at least 10 years and, ideally, 30 years) is required to describe the wave climate (Wolf et al., 2011). Such knowledge is required to characterise coastal vulnerability and to plan coastal management strategies. We know that there is also a large amount of inter-annual and inter-decadal variability, which can obscure any observation of long-term trends. There are few long-term wave datasets for European waters. One example is the United Kingdom Met Office Marine Automatic Weather Station (MAWS) system, which consists of various met-ocean recording systems, some of which have been maintained for several decades. A review by Hawkes et al. (2001) assessed the data available and led to the establishment of the CEFAS Wavenet network (n.d.). Data collected from the Seven Stones Light Vessel since 1962 led to the earliest observation of an increase in wave height in the North Atlantic (Bacon and Carter, 1991). This observation has since been validated and extended using altimeter wave data and models and attributed largely to changes observed in the North Atlantic atmospheric circulation patterns, principally the NAO (Woolf et al., 2002, 2003; Wolf and Woolf, 2006). Owing to the lack of long-term datasets, numerical models are often used to extend the time series, and many global and regional wave hind-casts and reanalyses are now available (e.g. ERA-Interim, ERA-20C from the European Centre for Medium-range Weather Forecasts (ECMWF, n.d.).

*Datasets covering more than 30 years of wave observations are essential for flood hazard analysis. All coastal European countries store sea-level data. There are fewer wave datasets but satellite data are increasingly useful.*

Long time series are increasingly available from satellite observations, although these are less reliable in the coastal zone. Improved algorithms now allow these data to be used closer to the coast (e.g. Gommenginger et al., 2010). Long time series data can also be generated using proxy data from time series of other variables (e.g. SLP data can be used as a proxy for storminess or can be generated from long hindcasts of dynamical models). Projections of future impacts that the relationships between proxy variables will remain the same in a future climate or may be made by running dynamic models into the future. Local impact models are highly dependent on the accuracy of projections of storminess in global climate models (where storminess may be defined as a measure of the frequency and intensity of storms).

Sea-level data from most European nations are archived and made available through their national data repositories. For instance, the British Oceanographic Data Centre is responsible for the remote monitoring and retrieval of sea-level data from the tide gauge network. These are then processed and quality controlled prior to being made available for scientific use. Several other European nations offer a similar facility (e.g. Système d'Observation du Niveau des Eaux Littorales, SONEL, in France and National Oceanographic Data Committee, NODC, of the Netherlands). For long-term sea-level analysis, a global record of sea levels is available from the Permanent Service for Mean Sea Level, which is responsible for the collection, publication, analysis and interpretation of sea-level data from the global network of tide gauges (PSMSL, 2017).

In order to better understand historical magnitudes and footprints of coastal flooding events for the United Kingdom, a systematic database of extreme sea level and coastal flooding has been compiled, covering the past 100 years (Haigh et al., 2015; www.surgewatch.org). Using records from tide gauges, all sea levels that reached or exceed the 1 in 5 year return level were identified. These were attributed to 96 distinct storms, the dates of

which were used as a chronological base from which to investigate whether historical documentation exists for a concurrent coastal flood. For each event, the database contains information about the storm that generated that event, the sea levels recorded during the event, and the occurrence and severity of coastal flooding that resulted. This database is continuously updated. Similar databases for Europe-wide flooding could be conceived and created.

## 3.6.4 Future climate projections of waves, storm surges and mean sea level

The IPCC (2013) has projected global sea-level rise for the period 2081-2100, compared with 1986-2005, to be 0.29-0.82 metres. The precise range varies with the assumed Representative Concentration Pathway (RCP) scenario, which describes the radiative imbalance in Earth's atmosphere due to greenhouse gas emissions. Unlike in the previous IPCC report, these projections now include a contribution from changes in ice-sheet outflow, for which the central projection is 0.11 metres (it should be noted that there is only medium confidence in the range of projected contributions from models of ice sheet dynamics). Nevertheless, these new projections are broadly similar to those in the earlier AR4 assessment (IPCC, 2007). It is very likely that the rate of global mean sea-level rise during the 21st century will exceed the rate observed during the period 1970-2010 for all RCP scenarios. Regional patterns of sea-level change in the 21st century still differ between models. However, about 70 % of the global coastlines are projected to experience a sea-level change within 20 % of the global mean sea-level change.

Some studies use simple statistical, so-called 'semi-empirical', models that relate 20th-century (e.g. Rahmstorf, 2007) or earlier (e.g. Vermeer and Rahmstorf, 2009; Grinsted et al., 2010) temperature or radiative forcing (Jevrejeva et al., 2010) with sea-level rise, in order to extrapolate future global mean sea level. These models are motivated by evidence in the palaeo record of a connection between global mean sea level and temperature over glacial/interglacial timescales.

These models result in wider ranging, and typically larger, projections of sea-level rise than those obtained from physical process-based models. For example, Rahmstorf (2007) has projected sea-level rise by 2100 under a range of climate scenarios to be between 0.50 and 1.40 metres, and Vermeer and Rahmstorf (2009) suggested the higher range of 0.75 to 1.90 metres. Church et al. (2011) note that these models may overestimate future sea levels because of the exclusion of key non-linear processes and climate feedback mechanisms. In addition, future rates of sea-level rise may correlate less well with global mean temperature if ice sheet dynamics play an increased role in the future. Many national authorities have introduced high-end scenarios to aid contingency planning, the value of which justifies the numerous assumptions made. For the United Kingdom (Lowe et al., 2009), this low-probability but high-impact value was estimated to be 1.9 metres, which is consistent with physical constraints on glacier movement (Pfeffer et al., 2008); this value also encompasses the majority of semi-empirical model projections. For comparison, Katsman et al. (2011) used an alternative method to develop a high-end scenario of a 0.40- to 1.05-metre sea-level rise (excluding land subsidence) on the coast of the Netherlands by 2100. More recently, Jevrejeva et al. (2014) obtained a probability density function of the global sea level in 2100, suggesting that there is a 5 % or smaller probability of a global sea-level rise greater than 1.8 metres; this low probability upper limit combined expert opinion and process studies and also indicates that other lines of evidence are needed to justify any larger sea-level rise this century. It is very likely that global mean sea-level rise will continue beyond the 21st century. The thermal expansion of the ocean as a result of increased temperatures takes place over centuries to millennia; therefore, thermal expansion will continue beyond 2100, even if greenhouse gas concentrations are stabilised immediately (which is unlikely). Contributions to sea-level rise from ice sheets are expected to continue beyond 2100, but glacier contributions will decrease as the amount of glacial ice diminishes. Some models suggest sea-level rises of between 1 metre and 3 metres in response to carbon dioxide ($CO_2$) concentrations above 700 parts per million. Studies of the last interglacial period (e.g. Kopp et al., 2009) indicate a very high probability of a sea-level rise of 2 metres over 1 000 years, and cannot rule out values in excess of 4 metres.

Overall there is low confidence in

future storm surge and wave height projections because of the lack of consistency between models, and limitations in the model capability to simulate extreme winds (IPCC, 2012). Numerous studies have used regional climate model forcing to drive storm surge and wave models to infer changes in extreme sea level for the Mediterranean (Conte and Lionello, 2013; Jordà et al., 2012; Marcos et al., 2011), North Sea (Debernard and Røed, 2008; Gaslikova et al., 2013; Howard et al., 2010; Woth et al., 2006), as well as the Atlantic coast of Europe (Lowe et al., 2001; Lowe et al., 2009; Lowe et al., 2010; Marcos et al., 2012) and Baltic Sea (Gräwe and Burchard, 2012; Meier, 2006; Meier et al., 2004), while the first pan-European study was by Vousdoukas et al. (2016a). Some of these studies suggested increasing levels of storm surge along parts of northern Europe.

While extreme sea levels could change in the future, both as a result of changes in atmospheric storminess and of mean sea-level rise, it is very likely that mean sea-level rise will continue to be the dominant control on upwards trends in extreme future coastal water levels. Vousdoukas et al. (2017; 2016a) concluded that that by the end of this century the 100-year extreme sea-level along Europe's coastlines is on average projected to increase by 57 cm for RCP4.5 and 81 cm for RCP8.5. The North Sea region is projected to face the highest increase in ESLs, amounting to nearly 1 m under RCP8.5 by 2100, followed by the Baltic Sea and Atlantic coasts of the UK and Ireland. Mean sea-level rise is shown to be the main driver of the projected rise in extreme sea-level, with increasing dominance towards the end of the century and for the high-concentration pathway. Changes in storm surges and waves enhance the effects of sea-level rise along the majority of northern European coasts, locally with contributions up to 40 %. In southern Europe, episodic extreme events tend to stay stable, except along the Portuguese coast and the Gulf of Cadiz where reductions in surge and wave extremes offset sea-level rise by 20-30 %.

*Global mean sea level will rise between 0.3 metres and 0.8 metres this century. Larger rises are possible. There is low confidence in storm surge and wave projections due to climate model limitations.*

Regarding possible future wave climate changes, the IPCC AR5 notes low confidence in projections of future storm activity and hence in projections of wind waves (Church et al., 2013). For the Baltic Sea, Groll et al. (2017) found changes in the wave climate towards higher significant wave height for most regions that were consistent across their ensemble simulations. They noted that these changes result not only from higher wind speeds but also from a shift towards more westerly winds. In a comparable study for the North Sea, Groll et al. (2014) found a robust signal in eastern areas, where wave height was projected to increase towards the end of the 21$^{st}$ century in most of the analysed projections. For the west European Shelf, Zacharioudaki et al. (2011) found an increase in mean and extreme winter significant wave height south-west of the United Kingdom and the west of France. Elsewhere, decreases were found. This is consistent with the results provided by Charles et al. (2012), Mentaschi (2017) and Perez et al. (2015) who projected a general decrease in wave heights in the Bay of Biscay and Atlantic Europe by the end of the 21st century. Zacharioudaki et al. (2011) further emphasised that swell and wind sea may show different developments. For the north-west Mediterranean Sea, Casas-Prat and Sierra (2013) found some increase in mean and extreme projected wave heights but noted that these changes were very much dependent on changes in wave direction and thus on wind direction in the global models that were not uniform. The findings are consistent with those for the Mediterranean Sea reported by Lionello et al. (2008, 2010), who projected a shift in the wave height distribution towards lower values. Similar changes are reported in Perez et al. (2015), who further noted that the decreases were larger for long-term and high-emissions scenarios.

The effect of sea-level rise on tides remains an open scientific question, since previous studies are not reaching consensus. There is observational evidence of changes in tidal constituents in the 20$^{th}$ century (Mawdsley et al., 2015) however the significance of the driving processes remains yet unresolved (Woodworth, 2010). Regional modelling efforts have shown that sea-level rises exceeding 2 m can

affect tidal amplitudes and phases (Pickering et al., 2012). For smaller sea level rises (~1 m) some studies find significant tidal changes (Arns et al., 2015; Idier et al., 2017; Pelling and Green, 2014) whilst others report negligible effects (Lowe et al., 2001; Sterl et al., 2009; Vousdoukas et al., 2017).

## 3.6.5 Tools and methods for assessing coastal flood hazard

Downscaling from global to regional climate change projections is vital for the study of meaningful local impacts (Wolf et al., 2015). Downscaling is generally taken to refer to the generation of locally relevant data from the output of Global Circulation Models (GCMs). The aim is to use global-scale projections, using accepted greenhouse gas emissions scenarios, to generate regionally specific and useful forecasts, with increased spatial and temporal resolution, and including processes that are not resolved in the coarser resolution model. Downscaling can be done in several ways: (1) using process models, (2) using empirical/statistical relationships, and (3) using hybrid methods (e.g. pattern recognition). Nesting an RCM into an existing GCM is an example of the first method, termed dynamical downscaling. An RCM is a dynamic model that gives higher resolution results than a GCM. Downscaling can also be done using statistical regression. This aims to capture the essential relationships (often calibrated using relationships in the current climate) between the global model and local variables.

Extreme events are linked to coastal flooding and for that reason inundation maps are a crucial element for coastal management and engineering practices (Ferreira et al., 2006), and evaluation of adaptation options (Cooper and Pile, 2014; Hinkel et al., 2010). The most common and simple way to obtain inundation maps is the static inundation approach considering as flooded all the areas with elevation lower than the forcing water level, extensively used for studies of different scales (Hinkel et al., 2014; Hinkel et al., 2010; Vousdoukas et al., 2012b).

*Statistical or dynamical downscaling methods can be used to derive local information from global climate models. Reducing uncertainties and connecting physical models to decision tools will assist coastal management.*

However, given the high complexity of coastal flooding processes, several recent studies showed that that the static approach resulted in substantial overestimation of the flood extent compared to dedicated hydraulic models, especially in flatter terrains (Breilh et al., 2013; Gallien, 2016; Ramirez et al., 2016; Seenath et al., 2016; Vousdoukas et al., 2016b).

Intermediate approaches have been developed which are capable of reducing the computational cost by taking into consideration either only water mass conservation (Breilh et al., 2013), or aspects of flooding hydrodynamics (Dottori et al., 2016), or the presence of obstacles (Perini et al., 2016; Sekovski et al., 2015). More elaborate and more computationally intensive are dynamic models like LISFLOOD-FP (Bates et al., 2010), which despite being originally developed for simulating river flow processes, have been proven to be reliable also for coastal flooding applications, such as the reproduction of storm surge events (Ramirez et al., 2016; Smith et al., 2012) and the evaluation of future scenarios of sea level rise (Purvis et al., 2008). Finally, process-based models specialized for coastal hydro- and morpho-dynamics (Lesser et al., 2004; McCall et al., 2010; Roelvink et al., 2009; Vousdoukas et al., 2012a) would appear as the optimal option, however they come with the disadvantages of (i) increased computational costs, which are almost prohibitive for large scale application; and (ii) the fact that they require information about the nearshore topography in detail which is often not available.

Outputs from climate models of various resolutions are often used to force hydrodynamic impacts models such as wave and storm surge models (leading to models of coastal impacts such as flooding and erosion). Issues for these model couplings are (1) quantification of model accuracy for past events and (2) understanding the uncertainty for future projections. This uncertainty consists of (1) uncertainty in greenhouse gas emissions,

(2) uncertainty in climate model projections of sea level and storms and (3) uncertainty in the surge and wave models. As models improve, the model uncertainty may be reduced but there remains uncertainty in the emissions and some of the model physics. Increasingly, the outputs of physical models such as those described above are combined with socioeconomic data to provide a set of decision tools that allow coastal managers to assess and mitigate risk.

These so-called 'broad-scale assessment tools' (e.g. Gouldby et al., 2008) connect marine science to engineering and economics and are now widely used in national analyses of coastal flood hazard, helping to define the scale of the problem and the potential mitigations.

## 3.6.6 Conclusions and key messages

### Partnership

There is a need for improved multidisciplinary connections between oceanographers, coastal engineers and coastal planners to deliver decision tools based on sound physical and economic models.

### Knowledge

Flood severity analysis would benefit from a community-wide European database and analysis of historic storm events that resulted in coastal flooding, building on the model of Haigh et al. (2015).

### Innovation

There are a number of priority knowledge gaps that need to be addressed to improve the ability of the scientific community to assess the hazard-related risk associated with sea-level extremes, storm surges and waves. First, we require an improved understanding of the processes controlling time mean regional sea-level rise, in order to provide accurate regional projections. This implies a more sophisticated combination of ocean and solid Earth models, as well as sustained and accurate monitoring of sea level so as to better analyse regional variability. Sea-level projections also demand improved modelling of physical processes that couple the ocean and the cryosphere in order to explore the plausibility of rates of sea-level rise outside that suggested by the current models.

*Improved process understanding of regional sea-level change is essential, as are improvements to the representation of weather systems in climate models. Multidisciplinarity is needed to deliver economic planning tools.*

To better understand the possibility of changes to future storminess and, therefore, storm surges and waves, requires improved high-resolution modelling of mid-latitude weather systems in climate models. This would lead to a more complete assessment of future changes in the wave and storm surge climate with reduced uncertainty.

# Recommendations

A set of recommendations relating to the abovementioned hazards has been identified, based around the three pillars of the Disaster Risk Management Knowledge Centre (DRMKC):

## Partnership

**Recommendation 1**: Improving preparedness for hydrological risks requires contributions from many different disciplines of knowledge. Efforts are needed to improve (1) risk governance, including institutional governance, legal provisions and financial instruments for planning, prevention and crises management; (2) our understanding of hazard modelling; (3) forecasts and predictions, from short to long lead time ranges; and (4) emergency response recovery, including coordination of local operations, assistance to affected communities and recovery of disrupted services. Communication with and engagement of the public and decision-makers is key to effectively integrate these layers and to improve preparedness.

**Recommendation 2**: Risk-based decision-support frameworks have to be tailored to the problem in question but also need to be flexible to allow different situations to be dealt with as well as often unprecedented hydrological events. Warnings need to be tailored to the specific circumstances so that responders and the public can act accordingly. Information sharing and increased communication with all stakeholders is therefore essential and needs to be fostered further.

## Knowledge

**Recommendation 3**: Hydrological hazard and risk maps should be developed using probabilistic methods to reflect the uncertainty in the underlying data and models and to produce more robust estimates of risk. This is especially relevant considering the sensitivity of hydrological risks to a changing environment such as land use changes or climate change.

**Recommendation 4**: Forecasting and EWSs are identified as key preparedness actions for hydrological risk management and can be implemented at local scales as well as at continental and global scales. Continued efforts to improve these systems are necessary to increase preparedness and society's resilience to hydrological risks.

**Recommendation 5**: Hydrological forecasts and risk maps have associated uncertainties that require adaptive management approaches in the design of flood risk management policy and infrastructure. The large uncertainty in the impacts of climate change projections requires flexible adaptation pathways to be considered.

**Recommendation 6**: An improvement of the understanding of the processes controlling hydrological risk including a better representation of weather systems in climate models is necessary, in order to improve regional projections of hydrological risk under a changing climate.

## Innovation

**Recommendation 7**: Operational flood EWSs currently have the capability to produce coarse-scale discharge forecasts in the medium-range and to disseminate forecasts and, in some cases, early warning products in real time across the globe, in support of national forecasting capabilities. With improvements in seasonal weather forecasting, future advances may include more seamless hydrological forecasting at the global scale alongside a move towards multimodel forecasts and grand ensemble techniques, responding to the requirement of developing multihazard EWSs for disaster risk reduction.

**Recommendation 8**: Improved decision-support systems need to be developed that can integrate the different stages of flood risk management, without losing information on uncertainty, warning time, forecast accuracy and reliability. This will help decision-makers to understand the strengths and weaknesses of a forecasting system for different scales and events.

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