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.

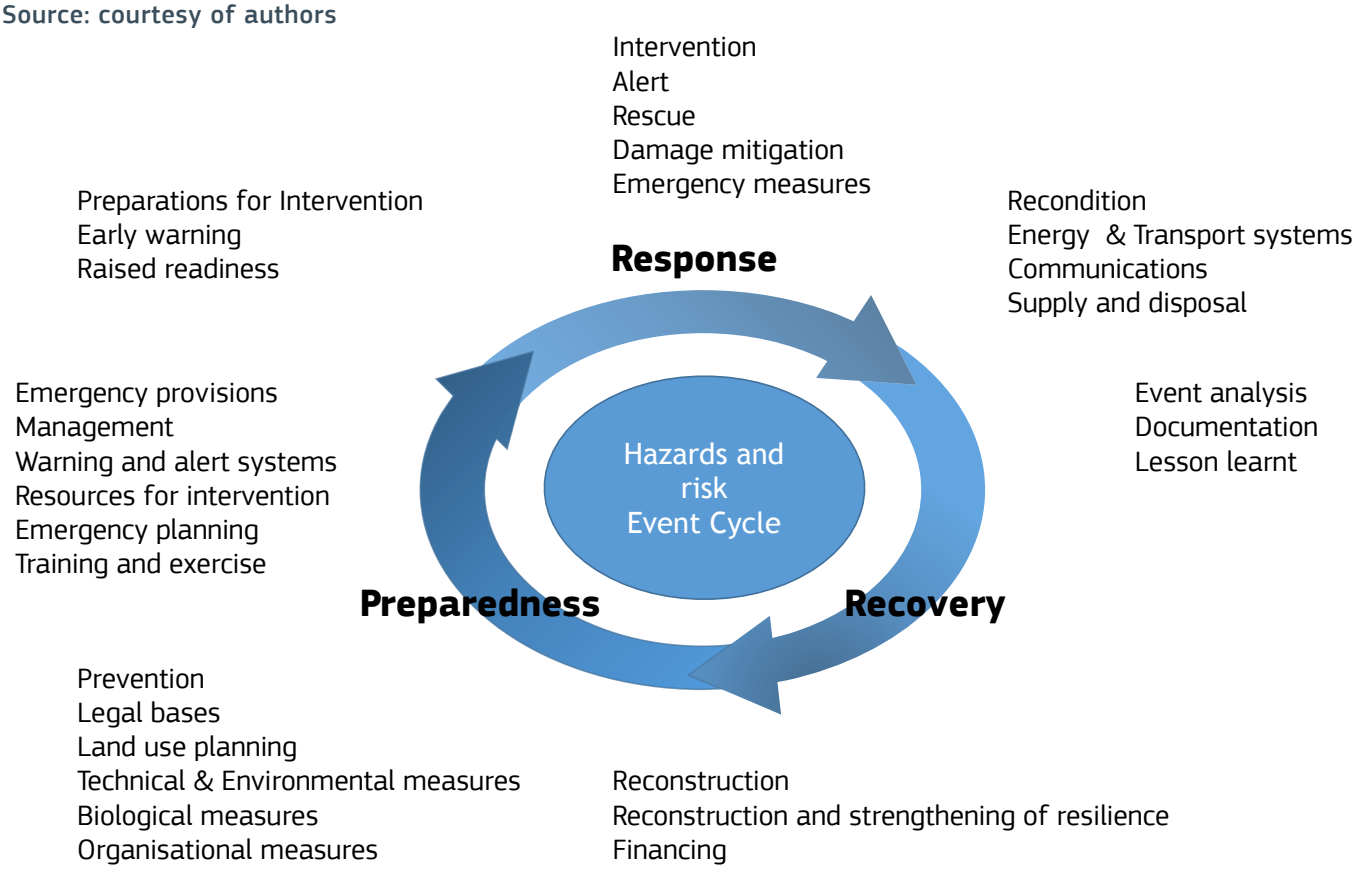
In this subchapter, the main drivers of flood hazard are introduced and flood hazard and risk mapping are discussed, particularly at the regional scale. Flood predictability is then considered, along with a review of the added value of flood monitoring, flood forecasting and EWSs.

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

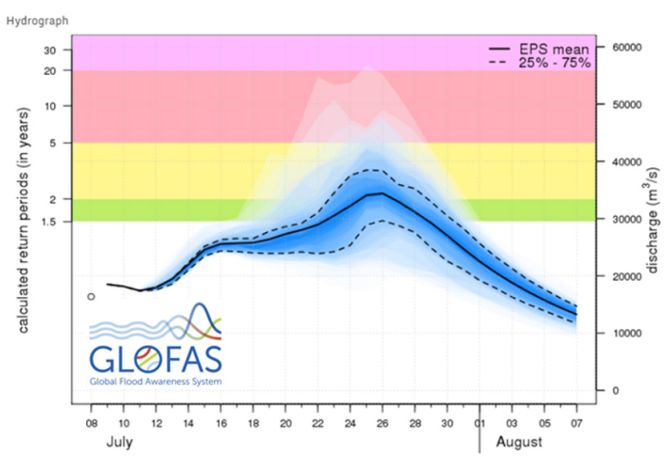
GloFAS forecasts of the River Ganges floods in July/August 2016.

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.

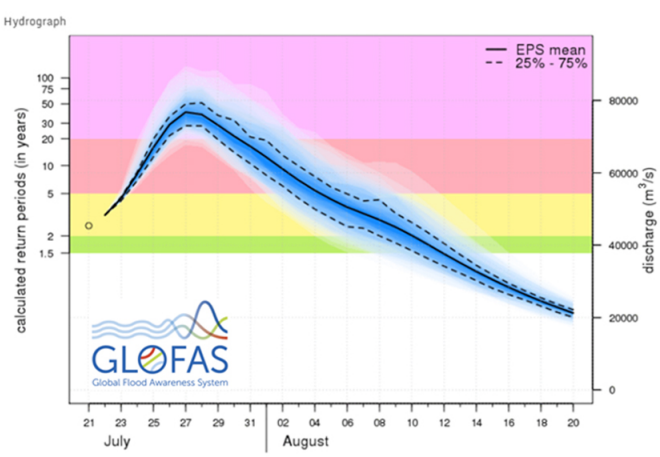
Source: GloFAS (2017)

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.

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