Floods – vulnerability, risks and management

- a joint report of ETC CCA and ICM

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Executive summary

Floods are extreme events that can have large impacts on human societies and ecosystems. They arise from a multitude of causes and can have very different consequences depending on regional and local circumstances. Floods are part of the natural hydrological cycle, but adverse impacts arise when water masses inundate infrastructures and land that cannot cope with the excessive water. Major flood disasters in Europe have caused loss of lives and economic loss that amount to billions of euro, but aggregated over large areas small local floods also produce significant losses.

Analyses of trends of past flood events suggest flood hazard may have increased in parts of Europe. Available evidence suggests high flows have been increasing in northern Europe, especially in western Britain and coastal Scandinavia. Regional patterns are, however, diverse, with many weak negative trends occurring in northern Europe as well, and a very mixed pattern in central Europe. Across most of the continent, however, urbanisation and the accumulation of assets in flood prone areas have led to increasing trends in the damages and economic consequences of floods.

Global warming may reduce flood hazard in areas that are dominated by annual snowmelt floods, except in those regions where a sharp increase in winter snowfalls outweighs the effects of a warmer and shorter snow season. In other parts of Europe there is greater uncertainty in how flood hazard will change due to climate change. Increases in extreme river flows have, however, been predicted in several studies and may occur over relatively short time spans.

Flood risk management is a demanding task that requires careful analysis of flood hazards and their causes, assessments of the magnitude of the risks, systematic planning to reduce risks and adaptation in the face of possible change. Dam safety is a major issue in dealing with flood risks. Flood risk management requires appropriate institutions, technical solutions and functioning governance structures. Recently participatory approaches have opened up new avenues for the development of flood risk management. Promising examples of participatory flood risk management have been documented.

Flood risk management has been seeking new directions and needs to adapt to an uncertain future. Flood risk management needs to consider developments in exposure and vulnerability due to land-use change and infrastructure development. Due to the combined effects of climate change and socio-economic development flood risk is unlikely to remain stationary. Scenarios for flood risk management thus have to combine socio-economic scenarios, such as projections for population growth, urbanisation and industrial developments with projections of future flood hazards. Detailed scenario studies are still missing in many river catchments. Recent studies have suggested that climate change can add significantly to the expected damages in some parts of Europe over the coming decades. Adaptation to changes in flood hazards and risk is therefore an essential element in efforts to adapt to climate change.

1 Introduction

This report describes floods in a European context. Flooding in the sense of land being covered temporarily by water is a natural event. Many human activities and natural ecosystems benefit from and are even dependent on flooding. Adverse consequences arise when water masses cover or destroy structures and interfere with activities that do not cope with inundation. The EU Directive on the Assessment and Management of flood risks (Floods Directive, Directive 2007/60/EC) specifically addresses this problem at the EU level. The white paper "Adapting to climate change: Towards a European framework for action" (EC 2009a) also identifies flooding as one of the issues that need to be considered in planning for the future.

The occurrence of catastrophic flood events proves that our ability to manage floods is still limited. Furthermore, in the face of climate change the past is no longer a reliable guide to the future. Flood risk assessment, like natural hazards and disaster management more generally, cannot be based on an assumption of stationarity (Milly et al. 2008). Both the natural and the social conditions are changing and as a consequence also the risk and impacts of floods.

The purpose of this report is to highlight factors that contribute to the occurrence and adverse consequences of floods, and possibilities to reduce flood risks from inland waters and rainfall. It includes a discussion on changes in flood patterns and illustrates how different scenarios for climate change may affect vulnerability to floods and flood risks. The report provides illustrative examples of flood risk management from the local to European level.

2 Floods and their impacts

Floods are complex phenomena with respect to origin, predictability, risk and consequences. A flood event as defined by the EU Floods Directive is simply the temporary inundation of land not normally covered by water (Chapter 1, Article 2). Floods are often caused by extreme weather conditions leading into local accumulations of rainwater or overflowing of streams and other bodies of water. Impacts arise as a consequence of the spreading and movement of the water masses.

In the riverine environment, floods often have mixed impacts. They may produce benefits to some parts of the ecosystem and damages to other parts. Regular annual floods provide water resources for human use and carry nutrients supporting agricultural production on flood plains. Adverse impacts depend on the vulnerabilities of the area in question. The vulnerability of an area develops over long time frames but the impacts usually arise suddenly when the flooding passes critical thresholds. Flood risks could in principle be greatly reduced by avoiding building and other development close to rivers and other bodies of water, but there is often a high perceived value of living near water, and access water or water resources is a necessary part of many activities. Flood damages can furthermore arise due to localised extreme rainfall far from water bodies. A good understanding of flood damages is a pre-requisite for developing efficient disaster prevention policies (EC 2009b).

2.1 Types of flooding, exposures and vulnerability

The reduction of flood risks requires an understanding of the nature of the floods. A classification of different types of floods helps to identify certain characteristics that need attention in efforts to reduce flood risk.

Any classification of floods is somewhat arbitrary, but distinctions can usefully be made between the following types of floods:

- *Fluvial flooding* occurs when water levels in a channel, lake or reservoir rise so that water covers nearby areas, which normally are dry land. A fluvial flood may be caused by heavy or persistent rain, snowmelt or ice jam, sometimes also by debris jam, landslide or other blockage of the channel. Flooding can be a regular feature of the yearly hydrological cycle, but rivers have different patterns of flow and the severity of flooding varies. Antecedent conditions (soil moisture, groundwater stage) may also considerably affect the severity of the flood. Forecasting fluvial floods is generally easier than for other flood types.
- *Pluvial flooding* is caused by intense localised rainfall. Pluvial floods often cause damages in urban environments in combination with overflowing sewers and high runoff in small catchments. Urban pluvial floods often arise due to a combination of land sealing and insufficient capacities of sewers and drainage systems. They are difficult to predict due to the difficulty in predicting local rainfall patterns, lack of data on the actual hydrological status, and the short lead-times.
- *Coastal flooding* occurs when sea level exceeds normal levels due to storm surges, exceptional tides or tsunamis. Flooding in deltas and river mouths may be caused by a combination of fluvial flooding with storm surges or otherwise exceptionally high sea level. Forecasting is difficult but risk analyses can be performed using models. Coastal flooding due to sea level rise, storm surges or tsunamis is covered in the (forthcoming) EEA report on coasts.
- *Groundwater flooding* arise when underground water emerges in excessive quantities from either point or diffuse locations. This can be a consequence of e.g. persistent rains, high sea levels or land subsidence. If adequate data exist on groundwater flow forecasting is feasible.
- *Flash flooding* is characterised by very rapid inundation. Some pluvial floods can be classified as flash floods, particularly if heavy rain in the upper part of the catchment creates flood wave surges downstream where it may not have rained at all. In addition to pluvial origin, there are many other causes of flash floods: river

or lake outbursts (linked e.g. to landslides or ice jams), lahars and jokulhaups[1], overflowing of karstic formations, dam-breaks and snow-slush flows. The forecasting of flash floods is often extremely difficult due to the same factors as mentioned under pluvial flooding.

- *Dam failures* cause floods when man-made dams fail due to, for example, inadequate spillway design, geological instability, internal erosion, frost damage, poor maintenance or landslides to the reservoir. The flood may be devastating, often of a flash flood type. The flooding material may contain significant amounts of other substances than water such as harmful sludge. Dam failures can be modelled and assessed in advance through risk analysis, but not forecasted.

The first three flood types are characterised by their source and the two first may occur almost everywhere in Europe. Due to the topography and the patterns of rainfall the risk of flash floods is highest in Mediterranean and mountain areas, and coastal flooding has caused the largest damages in low-lying areas around the North Sea.

2.2 Factors affecting floods and flood risks

The hydrology and flood hazard (the magnitude and frequency of floods) of a catchment are strongly influenced by local factors such as the spatial-temporal distribution of rainfall, catchment topography, soil types and the proportion of lakes in the upstream area. In addition to these basic hydrological factors, human activities such as the development of land-use and infrastructure interventions (e.g. reservoirs and flood defences), also affect flood hazards. These are illustrated in the cases presented below.

Floods are determined by a combination of hydrological, climatological, and land-use conditions. Flood damages are strongly related to socio-economic conditions affecting land use. Few pan-European assessments of land-use impacts on catchment flood response have been undertaken, but general observations of the direction and magnitude of change can be made. The following sections describe how human activities in the form of urbanisation and land use changes have been found to affect flood risk. They also underline the importance of local conditions for flood risks.

2.2.1 Urbanisation

Urban areas are often particularly vulnerable to floods. Both pluvial and fluvial floods can cause significant impacts. The development of the urban form affects the vulnerability.

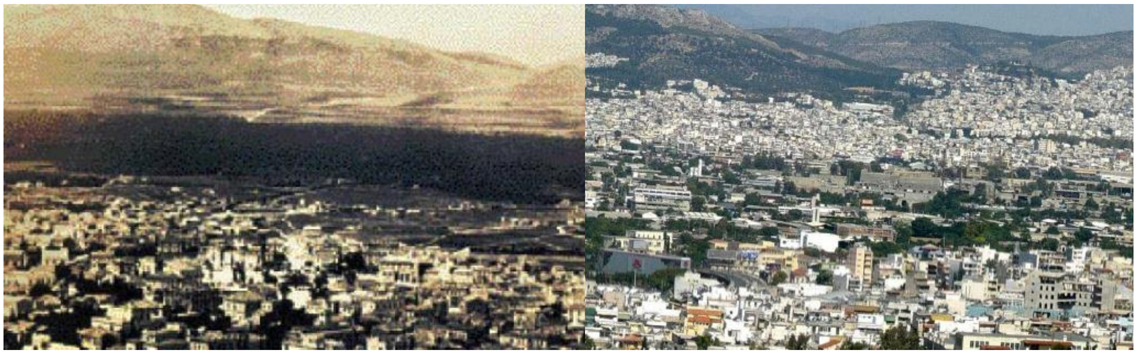
Increasing urbanisation often means an expansion of impermeable areas. In hydrological terms, the effects of urbanisation on catchment flood response is therefore generally

[1] lahar= A landslide or mudflow of volcanic fragments on the flanks of a volcano; jokulhaup = the flood of water etc. that occurs when a volcano erupts underneath a glacier.

considered to be an increase in runoff volume and a decrease in catchment response time, both resulting in higher peak flows. Analysis of flood data has confirmed this perception, and has also indicated that these effects are most prominent for small to medium size floods, whereas they become less important for large floods (Hollis, 1975). It is also clear that the effect of urbanisation depends on the pre-urban conditions of the catchment. For example, constructing impervious areas on already rapidly-responding soils and landscapes is likely to have a less dramatic effect on the downstream flood response than the equivalent impervious area in a catchment dominated by a non-responsive soil type (Kjeldsen, 2010). Urban floods also have elevated risks of adverse consequences such as the spread of diseases and pollution of water when sewers overflow and pollutants leach into the flood water.

Urbanisation affects the vulnerability as shown by the following case of Athens. The rapid urbanisation of Greater Athens, peaking in the 1920s due to refugees and internal immigration, resulted in both an increase in flood occurrence and a socio-economic segregation of the population of Athens, which is, to some extent, still evident today (Evelpidou et al. 2009). This has increased flood risk precisely for the more vulnerable parts of the population.

Figure 2.1 Western Athens in 1870(a) and 2007(b). Photos from Laskaris (2008), used with permission of the author.



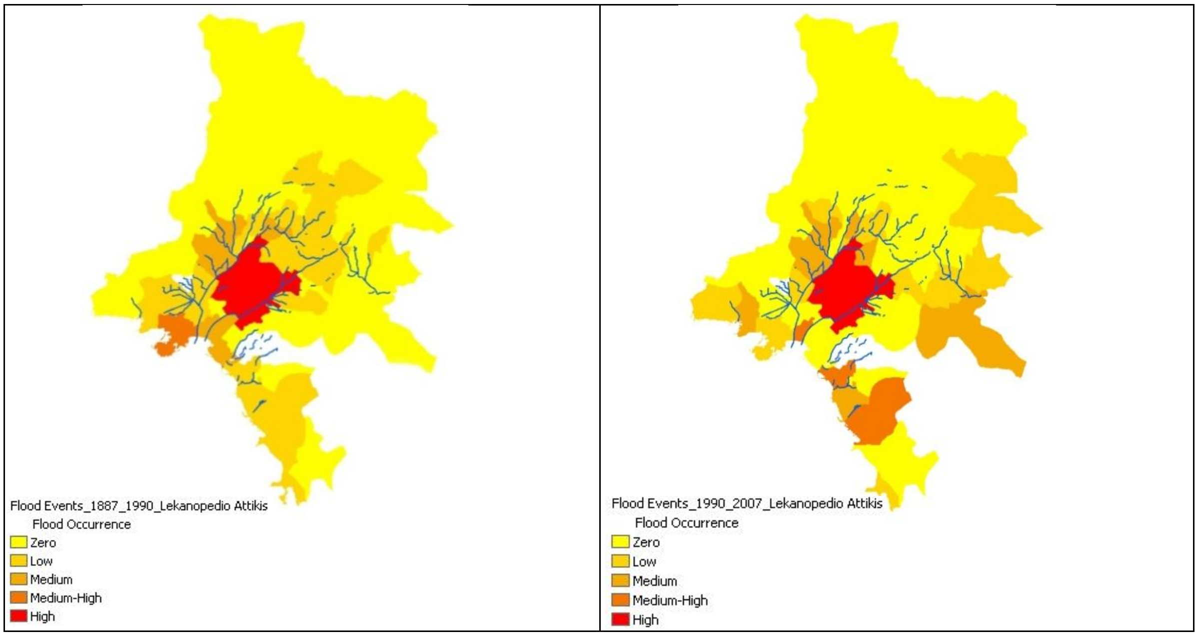
The intense development of the wider Athenian urban complex (Figure 2.1), led to the degradation of many tributary streams, with the Kephisos River being the most important (Evelpidou et al., 2009). Although the river still drains 70% of its natural catchment, it suffered much due to a significant decrease in its width as a result of illegal dumping and illegal construction/industrial development on its banks (Figure 2.2).

Figure 2.2 Structures (a) and roads and houses (b) on the river bed. Photos from Laskaris (2008), used with permission of the author.

Furthermore, due to its topography (steep slopes) and climate (intense, short duration rainfall) Athens is often subject to flash floods. This increases risk - particularly in view of its significant population density: 3.000.000 people live within the 300 km^2 catchment of the Kephisos River. A total of 145 significant flood events have been reported between 1887-2007 in which more than 250 people have died, and with damage estimates in the order of hundreds of millions of euro with a surprising consistency in their location and recurrence. As can be seen in Figure 2.3, the implementation of flood management measures in the 1990s resulted in small decrease of flood risk in some upstream areas but did not manage to eliminate main problems close to the Kephisos. Furthermore, the continuous urbanisation of the eastern suburbs and the coast increased flood risk in new areas (Kandilioti and Makropoulos, 2011).

The most recent flood event that resulted in loss of human life was in 1994 (with 9 deaths reported and a state of emergency declared for the city of Athens). Despite improvement in emergency planning, flood protection and awareness raising such catastrophic events could happen again (Papathanasiou et al., 2009). This is because major flood management interventions in the main urban rivers (such as Kephisos) are still wanting. However, community hubs, such as the Kephisos River Managing Authority are attempting alliances at the local level between local authorities, business and general public initiatives and pressure groups to raise the profile and reveal the true nature of the problems pushing for control of illegal activity coupled with economic and environmental regeneration of the area.

Figure 2.3 Flood hot-spots between 1887-1990 (left) and 1990-2007 (right). From Kandilioti and Makropoulos (2011), used with permission of the corresponding author.



2.2.2 Land use management: Agriculture and forestry

Historical land use changes that have converted forests and wetlands to agricultural land have affected the hydrology of catchments. The influence of specific agricultural land-use management practices on the flood generating processes is however difficult, if at all possible, to detect in observed flood series.

The role of forests in controlling flooding is a contentious issue spanning a variety of sectors in society with conflicting aims (Calder and Aylward, 2006; Laurance, 2007; with reply from Calder et al., 2007). As with more general land-use management issues, the discussion often concerns at what spatial scale and severity of flooding an impact can be detected. Forests constitute a major, but diverse, land-use component across Europe, conditioned by geographical and climatological factors as well as national differences in management practices. In a study of 28 forested catchments from across Europe, Robinson et al. (2003) concluded that on a broad European or regional scale, the effects of forests on extreme flows are relatively small. They furthermore concluded that except for the particular cases of managed plantations on poorly drained soils in northwest

Europe and eucalyptus plantations in Southern Europe, specific forestry practices appear to play only a minor role in managing regional or large-scale flood risk across the continent. This supports the finding that changes in land use or land use management practices with the aim of reducing storm runoff are only feasible at sites where infiltration and wetting can be significantly enhanced (Naef et al. 2002).

In the UK, Defra (2008) concluded that there was little or no evidence linking agricultural land-use change to changes in catchment flood response. Similarly, Pfister et al. (2004) and O'Connell et al. (2006) both concluded that while land-use change might affect flooding in small catchments (headwaters), no evidence could be detected in observations on the larger river basin scale such as that of the rivers Meuse and Rhine (Pfister et al. 2004). Given the importance of agriculture and food production in Europe, more scientific research is needed on the link between flood risk and land-use from a larger sample of catchments covering a wider range of geographical and climatological conditions as well as agricultural practices within Europe.

2.3 Impacts of major floods

Catastrophic floods have occurred in Europe throughout history, affecting thousands of people. They have caused fatalities and the economic losses have been significant. Total flood damages have increased in Europe over the last few decades. This trend can, however, mainly be attributed to socio-economic, rather than climatic, factors.

Across Europe, damaging floods have been an ever-present peril. Several studies have documented historical flood events in Europe going back several centuries (e.g. Brázdil et al., 2006; Burger et al., 2006; Macdonald and Black, 2010; Elleder, 2010; Glaser et al, 2010). Most of the large-scale disastrous events have been caused by prolonged periods of heavy rainfall, often coinciding with ice-breaking or snow melt (Glaser et al., 2010).

Recent floods have been documented by EEA (2001) and EEA (2010a). Details on damages have been compiled in the EM-DAT[2] Database, which contains floods fulfilling at least one of the following criteria:

- ten or more people reported killed
- one hundred or more people reported affected
- declaration of a state of emergency
- call for international assistance.

The EM-DAT Disaster Database has documented 266 flood disasters in Europe (excluding Russia, but including Turkey) from 2000 to 2011. These floods have caused 1080 fatalities, affected more than 2.8 million people and caused economic damages amounting to more than 48 billion euro.

[2] http://www.emdat.be/database (Accessed October 29 2012)

In economic terms, the two worst events in this millennium have been the Elbe and Danube flood of 2002 and the UK floods in 2007, which caused damages of several billions euro. Variations from year to year are large; in 2001, 2004, 2006, 2008 and 2009 total flood damages in all the countries that currently are members of the EU (EU27) were below one billion euro. Examples from outside the EU include floods in the Krasnodar region of Russia in summer 2002 which killed 258 people and affected almost 400,000 and flooding in Switzerland in August 2005, causing six fatalities and 2.5 billion Swiss francs or roughly 1.6 billion euros of damages.[3]

In the period of 2000-2010 European countries have been unevenly hit by floods (Table 1). The Mediterranean region, UK and the Black Sea have been most frequently exposed to flood disasters. In this period Romania had the worst floods in terms of fatalities with more than 220 deaths directly caused by flooding. The costs of the damages strongly reflect affected assets. In general total flood damages have increased in Europe over the last few decades. This trend can be attributed to socio-economic, rather than climatic, factors, such as changes in population, wealth and inflation (Barredo, 2009). Improved data collection and better reporting may also have contributed to the overall trend.

The flooding experienced in the UK in the summer of 2007 illustrates how flooding can affect multiple aspects of society (Marsh and Hannaford 2007). The flood events were in large part caused by three storms of record-breaking magnitude and spatial extent. For example, the storm of 19-20 July produced up to 140mm of localised rainfall, estimated to have an annual probability of approximately 1 % (a “100-year flood”). The resulting river flood peaks exceeded previous maximum recorded flow in numerous locations, and in several places the levels exceed those to be expected for a 1 % annual probability.

The extensive flood damages caused by the unusual conditions in the UK are well-documented. Over 55,000 homes and 6,000 businesses were flooded; the related insurance claims were approaching 3.5 billion euro by late-2007. Total costs were estimated to be up to 6.5 billion euro. A breakdown of the total economic costs (Environment Agency 2010) showed that households and businesses accounted for the bulk (66%) of the overall damages; followed by power and water utilities (10%); public health costs (9%); communications (7%); local government costs (7%); agriculture (2%); and emergency services (1%). Most of the health impacts were mental health costs based on estimates of people’s willingness to pay to avoid exposure to the distress caused by flooding. Other health impacts of floods typically include direct injuries and outbreaks of communicable diseases and infections. Indirect effects caused by the disruption of health care services, water treatment or sewage disposal, may in some cases be more serious than the direct impacts.

[3] http://www.bafu.admin.ch/hydrologie/01834/02041/02043/index.html?lang=en (Accessed Oct 27 2011)

Table 2.1 Number of flood disasters documented in the EM-DAT-data-base for 2000-2011 in Europe, excluding Russia but including Turkey (Oct-29-2012 - Data version: v12.07).

Country	Number of documented flood disasters	Deaths	Flood damage costs (USD ‘000)	Number of affected people
Albania	5	4	17,673	90,484
Austria	6	14	3,300,000	61,416
Belgium	8	5	238,146	3,300
Bosnia-Hercegovenia	8	3	87,000	328,740
Bulgaria	12	52	458,000	13,350
Canary Is	2	23	79,923	700
Croatia	6	0	80,000	3,160
Czech Rep	9	49	2,977,560	220,165
Finland	1	0		400
France	20	72	4,322,350	55,961
Germany	8	36	1,1840,000	331,450
Greece	15	16	605,659	12,330
Hungary	9	2	578,000	47,814
Ireland	3	2	325,000	900
Italy	19	115	10,444,000	58,150
Lithuania	2	4		
Macedonia FRY	6	2	3,600	109,750
Moldova Rep	4	5	8,584	23,000
Montenegro	4	0		7,886
Norway	2	0		2,100
Poland	7	49	3,880,000	120,550
Portugal	6	52	1,350,000	948
Romania	31	222	1,548,790	213,575
Serbia	5	2		20,480
Serbia Montenegro	6	2		46,545
Slovakia	8	8	34,000	1,180
Slovenia	1	0	5,000	
Spain	10	38	576,285	8,460
Switzerland	3	7	2,450,000	5,600
Turkey	18	216	932,000	110,870
Ukraine	7	55	1,040,755	578,665
United Kingdom	15	26	14,949,150	350,830

2.4 The risk of dam failures

Dams and reservoirs play a vital role in flood management. Especially in multipurpose projects, dams are frequently built to support flood management and not only for hydropower production or irrigation. However, devastating floods have also been caused by dam failures.

A dam failure is defined by the International Commission on Large Dams (ICOLD) as the collapse or movement of part of a dam or its foundation, so that the dam cannot retain water. There are several data bases on dam failures. The Data Station for Dam Failures DSDF-VIENNA has information on 323 failures of large dams, 445 failures of small dams and 133 failures of tailing dams since 1980[4] (EEA 2010b) Analyses of dam failures can be very difficult, with many historical events not completely understood. According to the ICOLD[5], the most common cause of failure of earth and rockfill dams is overtopping (31%), followed by internal erosion in the dam itself (15%) or in its foundation (12%). With masonry dams, the most common cause is overtopping (43%) followed by internal erosion in the foundation (29%). Hydrotechnically speaking, inadequate spillway capacity is often the factor which triggers the chain of events leading to a dam failure.

Dam breaks can cause domino-like failures of downstream dams. Catastrophic consequences downstream are also possible with only a minor damage to the dam itself, e.g. if a landslide hits a reservoir. This was the case in Italy in 1963, when a huge landslide caused 50 million m^3 of water to overtop the Vaiont Dam, killing around 2,000 people in the river valley. The dam with a height of 260 m was damaged only slightly at the top.

2.5 Have flood hazards changed over time?

An important question for flood risk managers is to establish if the flood hazard has changed in recent decades. Available evidence suggests different patterns across Europe with increasing high flows in northern and western Europe. Regional patterns are, however, diverse, with many weak negative trends occurring in northern Europe as well, and a very mixed pattern in central Europe.

Detection of a climate signal in hydrological observations of flood magnitude and frequency is difficult due to the confounding effects of long-term natural variability in climate, human disturbance of catchments and river systems, as well as the relatively short period of observation in most rivers. Global warming is expected to cause changes in intense rainfall although local variation can be significant (Huntington, 2006). According to Min et al. (2011), an intensification of heavy precipitation events has

[4] http://www.risk-assessment.at/en/we/services_bhdf.asp [6.7. 2011]
[5] http://www.icold-cigb.net/ [6.7. 2011]

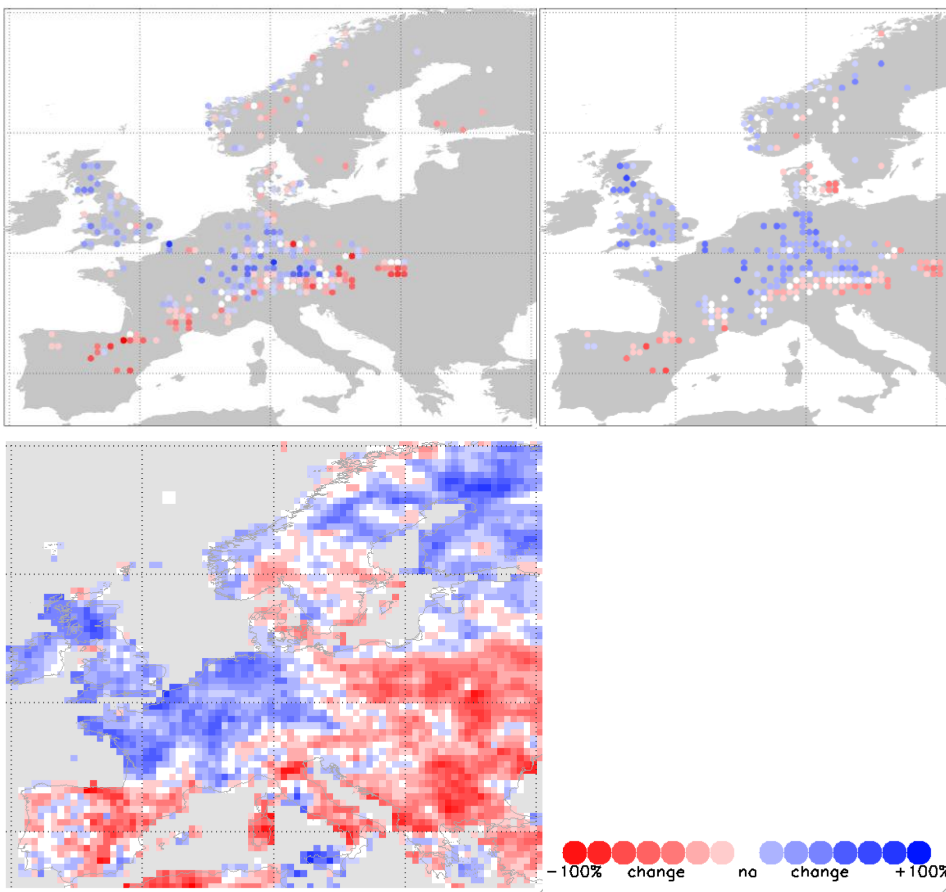
already been observed over parts of the Northern Hemisphere during the second half of the twentieth century (including parts of Europe), and human-induced increases in greenhouse gases may have contributed to this trend. Trends in flood frequency and magnitude have been examined at the national scale in many European countries (see for example the national overviews presented in the various chapters of Kundzewicz et al., 2012).

A European-wide comparison by Stahl et al. (2010), based on 441 catchments with near natural flow regimes from 15 countries with data from 1932, 1942, 1952,1962 and 2004, found evidence of increasing annual runoff in northern Europe, and decreasing runoff in southern Europe. A follow-up study by Stahl et al. (2012) analysed trends in 7-day maximum flows using the same dataset, and also examined trends in an ensemble of large-scale hydrological models validated by using these same observations. The overall pattern found largely confirms the results of national studies – increasing high flows in northern Europe, with steepest trends in western Britain, parts of Scandinavia and mainland northwest Europe, contrasting with decreases in southern Europe – but regional patterns are very mixed, with many weak negative trends also occurring in northern Europe, and a very mixed pattern in central Europe (Fig.2.4).

In many of the regional or national studies, trends in hydrological records are associated (either qualitatively or quantitatively) with changes in atmospheric circulation patterns. Recent observed trends in central Europe are linked to changing circulation types, in particular an increase in westerly airflows (Petrow and Merz, 2009). Floods have been linked to circulation types in a number of studies (Petrow et al., 2009; Bouwer et al., 2008) and evidence suggests patterns of higher and lower flood frequency may be driven by changes in circulation patterns over long timescales (Schmocker-Fackel et al., 2010a,b; Jacobeit et al., 2003). The North Atlantic Oscillation (NAO) has long been recognised as one of the primary drivers of European climate, and a number of studies have shown links between the NAO Index (NAOI) and streamflow at a European scale (Shorthouse and Arnell, 1999; Bouwer et al., 2008; Wrezinski and Paluszkiewicz, 2011).

Climate variability associated with the NAO has been cited as a likely driver of observed high flow trends in some national-scale studies. In the UK, Hannaford and Marsh (2008) found relationships between the NAOI and high flow indicators in western Britain, which is likely to influence the upward trends seen in these areas; Maraun et al. (2011) reached a similar conclusion in studies of extreme rainfall in the UK. The NAO has also been posited as a mechanism for influencing streamflows in central Europe. Villarini et al. (2012) found the NAO to be a significant factor explaining patterns of extreme flooding in Austria, although other studies of NAO influences on flooding in central Europe have been less conclusive (e.g., Bouwer et al., 2008; Schmocker-Fackel et al., 2010a,b). The association of flooding with modes of large-scale atmospheric circulation raises the question whether recent changes in flood frequency reflect anthropogenic climate change or the influence of multi-decadal variability. These two factors are not mutually exclusive, though, since modelling studies suggest that the recent evolution of large-scale patterns such as the NAO is also driven by anthropogenic forcing (e.g., Gillet et al., 2002; Dong et al., 2011).

Figure 2.4 The 7-day maximum trends across Europe, 1963 – 2000 (Stahl et al. 2012). Blue denotes positive trends, red negative. Units are in % of the average 7-day flow for the respective catchment or model grid for the period 1963–2000. Top left: observations; top right: ensemble mean for eight models at location of observations. Bottom: ensemble mean from eight models for Europe. Modified from Stahl et al., 2012, used with permission of author.



A recent analysis of the floods in England and Wales in autumn 2000, based on several thousand climate simulations, has shown that anthropogenic climate change due to twentieth century greenhouse gas emissions very likely increased the risk of flood occurrence (Pall et al., 2011). The precise magnitude of this contribution remained uncertain, but in nine out of ten cases the model results suggested it was at least 20%. It is important to note, though, that many factors, anthropogenic and natural, contribute to the development of a particular flood event, and that attributing an individual event solely to climate change is not appropriate (Pall et al., 2011).

2.6 Projections of flood hazards

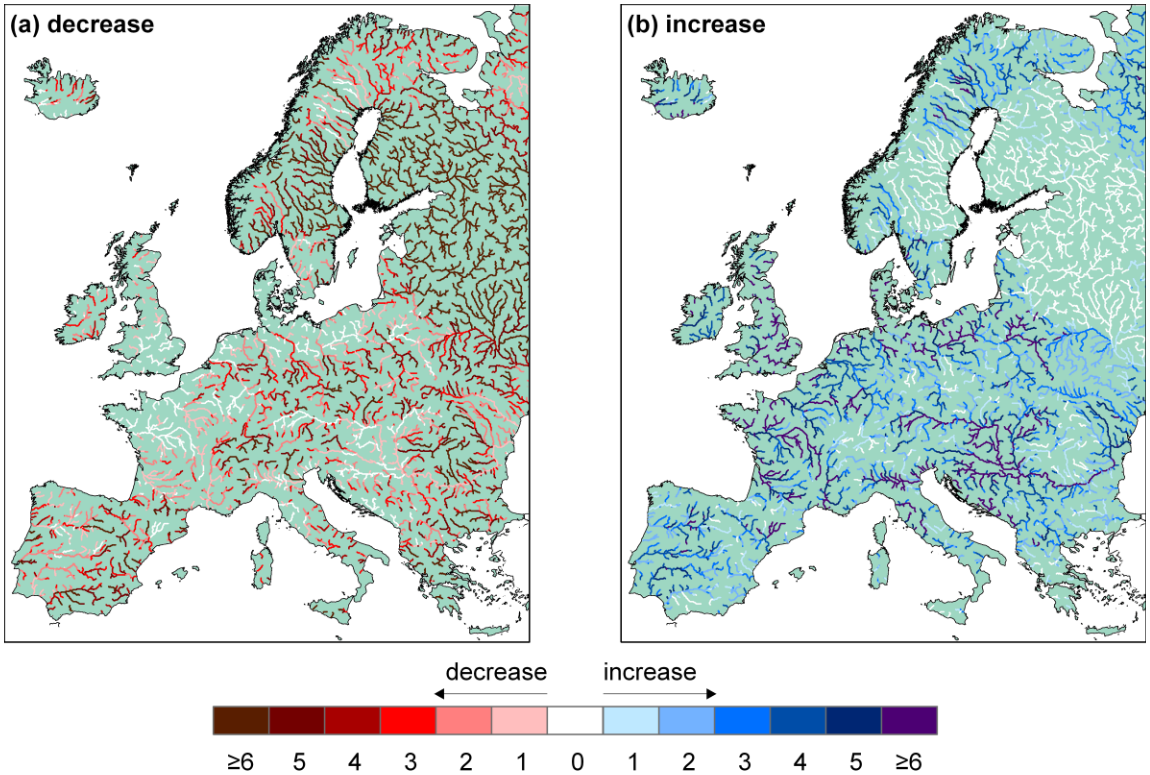
Recent analyses suggest that global warming is likely to reduce flood hazard in areas that are dominated by annual snowmelt floods, except in those regions where a sharp increase in winter snowfalls outweighs the effects of a warmer and shorter snow season (Dankers & Feyen, 2009). In other parts of Europe there is considerably more uncertainty in how flood hazard will change due to climate change. Increases in extreme river flows have, however, been predicted in several studies and may occur over relatively short time spans (Kay & Jones, 2011).

It is widely accepted that heavy precipitation events will become more frequent and/or intense under global warming (Allen and Ingram, 2002; Hegerl et al., 2007). An increase in rainfall intensity may occur even in areas that are getting drier on average (Christensen and Christensen, 2004). However, this is a general pattern that may work out differently at the local scale. Climate model projections of changes in extremes are less robust than for changes in average conditions, and present-day characteristics of climate extremes are difficult to reproduce (Meehl et al., 2007). Furthermore, changes in flood hazard do not only depend on changes in heavy rainfall but also on other processes such as snow accumulation and melt, and antecedent soil moisture conditions.

A European scale study by Dankers and Feyen (2009) found some patterns of change to be robust across different climate models and scenarios. Especially in north-eastern Europe a general decrease in extreme river discharge was projected by the end of this century, due to a reduction in the hazard of extreme snowmelt floods. Elsewhere, a consistent tendency toward a higher flood hazard in at least the majority of the model experiments was found in several major European rivers such as the Loire, Garonne and Rhone in France, the Po in Italy and the Danube in central and eastern Europe (see Fig. 2.5).

At the scale of individual river basins, using a different combination of climate models or assuming a different emissions scenario sometimes resulted in a very different or even opposite climate change signal in flood hazard. Much of this uncertainty could be traced back to the driving Global Circulation Model (GCM) that had a larger influence on the results than the choice for a particular Regional Climate Model (RCM) or even the emissions scenario. Importantly, Dankers & Feyen (2009) also found that some of the changes in simulated flood hazard can partly be attributed to large, decadal-scale natural variability in the simulated climate. This underlines the fact that there is still considerable uncertainty in future projections of changes in climatic extremes.

Figure 2.5 Number of scenarios (out of total eight experiments) showing either a (a) decrease or (b) increase of more than 5% in the 100-year return level in the scenario period (2071-2100 compared to 1961-1990). (Dankers & Feyen 2009, used with permission of the corresponding author).



National and catchment-scale studies provide a more detailed and nuanced picture, in areas where more data and better models are available. A national assessment for Finland by Veijalainen et al. (2010) found important regional differences in the impact of climate change across the country due to different climatic conditions and catchment properties. In snowmelt-flood dominated areas, annual floods decreased or remained unchanged due to decreasing snow accumulation. In contrast, a projected increase in precipitation led to an increase in floods in the major central lakes in Finland and their outflow rivers.

Many studies have made projections of changes in river flooding for the UK, most recently by Kay & Jones (2011). Their results suggest an increase in flood risk across much of the country, particularly in East Anglia and the Upper Thames. Negative trends in flood risk, present in a small number of places, were not significant. These changes, which were derived over the period 1950-2099 under the A1B emissions scenario, are however unlikely to occur linearly over the coming century, partly because of natural variability, but possibly also due to the non-linear response of hydrological systems. The implication is that changes in flood frequency, whether caused by long-term climate change or medium-term natural variability, may potentially happen in a relatively short time span (Kay & Jones, 2011).

In addition to national studies, there have been many climate impact studies in individual river basins. For example in the Elbe basin, Hatterman et al. (2008) projected a shift in the occurrence of flood events from early spring to early winter due to less retention of runoff in snow. In a modelling study of the Rhine basin, Hurkmans et al. (2010) found that future annual maximum river flows at nearly all return periods were generally higher than in the reference period (1950-2000) under three different emission scenarios (B1, A1B and A2). In the most extreme scenarios, an event with the magnitude of the most extreme flooding events in the last half century occurred on average every 5-6 years in the future (Hurkmans et al., 2010). Likewise, Te Linde et al. (2010) projected a basin-wide increase in peak discharge by 2050 of 8%-17% for discharge levels with annual probabilities between 1/10 and 1/1250. For the Seine River in France, Ducharne et al. (2011) found a slight decrease in high flow levels. In their simulations the flood levels with a 10% and 1% annual probability did not change significantly throughout the 21st century. Similar results were found for the Loire River by Moatar et al. (2010). Very few regional or national-scale modelling studies of changes in flood hazard under climate change have been undertaken in southern Europe.

3 Flood risk management – risk analysis, assessment and governance

Flood risk management entails careful analysis of flood hazards and their causes, assessments of the magnitude of the risks, systematic planning to reduce risks and adaptation in the face of possible change. This process requires appropriate institutions, technical solutions and functioning governance structures. The need for adaptation to climate change has increased the interest in finding effective and cost-efficient approaches to flood risk management.

3.1 Flood risk management

Floods have to be addressed in a risk management framework as they always include elements of probability and uncertainty. Such a risk management framework for floods includes planning and implementation of preventive measures, crisis management and also post-flood management. Historical flood events but also scenarios provide feedback that lead to the readjustment of measures and actions in all parts of the management process.

Flood management and its regulatory base have evolved along different tracks in Europe. The Floods Directive of the EU seeks to achieve some harmonisation (see box 3.1) and uses a three-step approach to floods risk management:

1. Carry out ***preliminary flood risk*** (analysis and) ***assessment*** (PFRA) by 2011 for "*those areas for which they [the member States] conclude that potential significant*

flood risks exist or might be considered likely to occur" (Article 5.1). This assessment should also determine acceptable levels of risk and risk reduction as a function of the effort and money that can be spent (Merz 2006). Historical data (Chapter 2), modelling, quantification of uncertainties, scenarios (Chapter 4), and governance need to be considered.

2. Preparation of ***flood hazard maps*** (FHMs) and ***flood risk maps*** (FRMs) by 2013. These maps will be part of the flood risk management plans and should identify areas areas with a high (where appropriate) and medium (at least 1% annual probability) likelihood of flooding, as well as the risk of extreme (i.e. low likelihood but high impact). In areas identified as being at high risk, the number of inhabitants potentially at risk, the economic activity and the environmental damage potential must be indicated.

3. Establishment of ***flood risk management plans*** (FRMPs) for areas with a significant high risk by 2015. The FRMPs should include and prioritise measures to reduce the probability of flooding and its potential consequences by addressing all phases of the flood risk management cycle, particularly focusing on prevention, protection, and preparedness. Due to the nature of flooding, much flexibility on objectives and measures are left to the Member States in view of subsidiarity. Risks should be assessed with reference to individual and collective perceptions and weighing of the acceptance / tolerability of certain risks. This complements the description of the physical flood processes (Wachinger & Renn 2010, Schanze 2006). Objectives and different evaluation criteria are ideally identified and selected in this phase.

Integrated approaches to flood management have been developed in, for example, Switzerland, the UK, the Netherlands and some German States (Defra 2005, , StMUGV 2005, Müller 2010).

A central element in flood risk management is the identification of ***Preventive measures*** (DKKV 2004, Schanze et al. 2008, FLOODsite 2009), which can include actions such as:

- Spatial planning: keeping constructional development out of floodplains as far as possible;
- Constructional measures: ensuring appropriately adapted construction methods in areas prone to flooding;
- Risk acceptance: own financial provisions (backed by insurance);
- Behavioural adaptation: explaining, preparing for and practicing how to cope with flood-related danger situations;
- Information systems: alarming, warning and informing about impending events;
- Increasing natural water retention in catchment areas and reduced land sealing;
- Technical flood protection: constructional facilities for water retention (dams, storage, reservoirs, dykes, flood polders).

The highest costs are usually associated with technical flood protection measures. More cost efficient measures can often be achieved through combinations of spatial planning, constructional measures, behavioural adaptation and catchment management.

A real time early warning system is an important prerequisite for effective management. It enables authorities to start implementing contingency plans, such as evacuations of inhabitants and the mobilisation of rescue forces. Several countries have developed systems for flood warning at national, regional and local level that are connected with systems for initiating evacuation actions. For example, Finland has a real time web based Catchment simulation and forecasting system which provides information on floods and flood warnings.[6]

When floods occur the focus is on c*risis management.* Contingency plans have to ensure that information flows between all responsible actors, bringing the information together to support operational actions. Many actors are involved including water managers, the police, fire brigade, volunteers and those responsible for infrastructures and their maintenance. Flood event management includes forecasting and the provision of warnings, deployment of temporary flood protection structures and emergency response.

After a flood disaster relief, reconstruction actions and financial compensations become part of the management activities. Flood events may also change past risk assessments, put pressure on developing flood defences and lead to the adjustment of regulations and norms (Merz et al. 2010). Careful documentation of the event is necessary in order to learn from the experiences. General flood impact databases such as EM-DAT[7] or NEDIES[8] exist to give a general overview, but for true learning more detailed documentation is needed. The development of such detailed flood impact data bases is going on in several EU member states and also at the European level (EEA, ETC CCA and JRC 2012).

Box 3.1 International Floods and Disaster Prevention Policies

The Hyogo Framework for Action (UN/ISDR, 2007) emerged from the World Conference on Disaster Reduction in 2005 to promote a strategic and systematic approach to reducing vulnerabilities and risks to hazards. In the EU the Floods Directive responds to the framework for action. . At a national level, one major activity has been the establishment of national strategies and national platforms for disaster risk reduction. National Platforms are multi-stakeholder national mechanisms that serve as an advocate for disaster risk reduction at different levels, from communities to the national institutions. So far, 16 European countries have established such a platform, and many more countries have established official Hyogo Framework Focal Points. In Europe, representatives of National Platforms and HFA Focal Points regularly meet at the regional level at least once a year. The meetings are hosted by a European country and are supported by UNISDR and the Council of Europe European and Mediterranean Major Hazards Agreement (EUR-OPA) (CoE, 2010). In November 2009, European HFA Focal Points and National Platform coordinators agreed to establish a European Forum for Disaster Risk Reduction (EFDRR).

[6] http://www.ymparisto.fi/default.asp?node=11776&lan=en [Sept 20 2011]
[7] http://www.emdat.be/ [30.10. 2011]
[8] http://nedies.jrc.it/index.asp?ID=91 [30.10. 2011]

3.2 Dam safety as part of risk management

Dam safety is one of the practical issues in flood management and regulation of dam safety plays an important role in avoiding disasters. Dam safety concerns not only pluvial or fluvial floods but is also an essential element in industrial operations that use tailing dams. Risk management plans need to pay attention to the governance of dam safety.

Many countries have a long history of regulatory frameworks for dam safety (Bradlow et al., 2002). Important aspects include the legal form of the regulation, the institutional arrangements for regulating dam safety, the powers of the regulating entity, and the contents of the regulatory scheme. The contents of the regulations relate to factors like the obligations of the regulating entities, the scope of the regulations, and the consequences of non-compliance with the stipulated obligations.

The scope of the regulatory scheme is essential as it determines what issues can be addressed. Historically some countries have focused on the safety aspect only, whereas others have also included dam construction, operation, maintenance, and surveillance. Legal systems have evolved and generally become stricter. The concern for dam safety has also resulted in the creation of organizations devoted to dam safety, for example, the Association of State Dam Safety Officials in the US[9] in addition to organizations with a broad agenda such as the International Commission on Large Dams (ICOLD)[10].

In dam safety the hazard potential is defined as the possible adverse incremental consequences that result from the release of water or stored contents due to failure of the dam or its misoperation. In many countries dams have been classified according to the hazard potential; the class 'high' generally indicates that the failure or misoperation will probably cause loss of human life. These dams should fulfil very strict technical and hydrological criteria in their construction and maintenance. Emergency Action Plans and Early Warning Systems are necessary non-structural tools to minimize the impacts of dam failures.

The EU Floods Directive (2007/60/EC) does not specifically refer to flooding resulting from dam breaks and dike breaches and it does not deal with the technical aspects of dam safety. However, it does require flood hazard maps to be produced for floods with a low probability, implying consideration of extreme event scenarios, such as dam breaks. There are no EU wide regulations devoted exclusively to dam safety, but the Directive 96/82/EC on the control of major accident hazards involving dangerous substances (SEVESO II), as extended by Directive 2003/105/EC, addresses aspects that are relevant to dam safety, by demanding, for example, emergency plans.

[9] http://www.damsafety.org/ [6.7. 2011]
[10] http://www.icold-cigb.net/ [6.7. 2011]

3.3 Urban flood management

Urban floods emphasise the complex interactions between hydrology and societal processes as shown by the example of Athens (Section 2.2.1). The management of urban areas requires long-term planning and development of robust measures to deal with the possibilities of extreme flood events.

Many cities and towns are situated in locations such as deltas and flood plains that are prone to flooding**.** However, also cities that are far away from water bodies prone to flooding may experience pluvial urban flooding because of intense rainfall, and often in combination with extensive land sealing and drainage networks with insufficient capacity.

Urban floods affect infrastructure, assets and urban activities, including transport. They cause health risks due to overflowing sewers and intrusion of surface water into water supply systems. Urban floods also increase the risk of pollution of water courses into which storm water and flood water drains. Management measures preparing for urban floods therefore have to address a wide range of different aspects of urban floods.

There is a general need to make urban areas more resilient to flooding. Flood-proofing of buildings is a well-known measure in this respect, sustainable urban drainage another. Green infrastructure can also provide opportunities for addressing problems caused by land sealing in urban areas (The Civic Federation for the Center for Neighborhood Technology 2007, EPA 2010, EEA 2010c, EEA 2012).

The reduction of the vulnerability of urban areas to floods requires detailed knowledge of local conditions. Measures have to deal with water supply, waste water treatment, rain water runoff and special conditions such as snow melt. There is a need for research into the effects of extreme weather events on urban drainage, water management and water treatment.

Urban water management have to be developed taking into account risks but also all positive aspects of water in the urban environment. Water is a necessary element in a sustainable urban environment, but climate change may change conditions for current practices related to urban drainage, water management and treatment. These issues are dealt with extensively in the EEA report on cities (EEA 2012).

3.4 Participatory management and private action

Modern flood risk management stresses the involvement of societal actors. This has raised the need to develop participatory approaches and tools that can be used in flood risk management. Private instruments for risk management such as flood insurance also change the role of different actors and can contribute to an interest in participatory approaches.

In many countries flood risk management has been considered to be a task mainly for the government. Historical counterexamples exist, for example in the Netherlands water boards have been organised and maintained by stakeholders for many decades. Currently the involvement of multiple public and private parties is encouraged or even demanded (Christoplos et al. 2001, Walker et al. 2010). This change underlines the relevance of communication (Renn 2008) and principles of "good governance", including openness, participation, accountability, effectiveness and coherence (McFadden 2009). It leads to a 'governance of preparedness' in which key players are brought together in new configurations (Medd and Marvin 2005).

More inclusive management of floods builds trust between the public, administration and research (Wachinger and Renn 2010, see also Moser 2010, Mosert et al. 2008, Höppner et al. 2011). It may also raise people's awareness and motivation for taking actions to mitigate the impacts of hazards (Stanghellini and Collentine 2008 and Slinger et al. 2007). When people become more aware of floods, they are more motivated to initiate protective action in participatory exercises (Wachinger and Renn 2010; Jonoski, 2002; Evers, 2008; White et al., 2010) (Box 3.2).

The inclusion of tacit or local knowledge can improve the effectiveness of the measures for flood risk management. Many residents have had personal experience of flood events and hence may have good understanding of flooding issues in their local area (White et al. 2010). There are possibilities to incorporate valuable local knowledge into modelling procedures leading to potentially improved flood risk maps (EXCIMAP 2007, LAWA 2010, Meyer at al. 2011)

Box 3.2
Collaborative modelling as a way of managing flood risk: the case the Cranbrook (UK)

The **Cranbrook** catchment (Figure 1) is located within the London Borough of Redbridge in the Northeast part of Greater London. Several flood events have been reported since 1926 with a recent example being the event of February 2009, where coincidental fluvial and pluvial flooding occurred due to heavy rainfall that caused rapid snowmelt that was still lingering in large quantities following snowfall the week before. The amount of water in the river exceeded the capacity of the channel and surface water overwhelmed the local drainage systems. Over 200 calls were received at the emergency control centre during the event. After the event, new drainage work was carried out and a new flood warning scheme was put in place. The need for more collaboration between stakeholders was identified as a means to improve resilience (Ochoa et al., 2011).

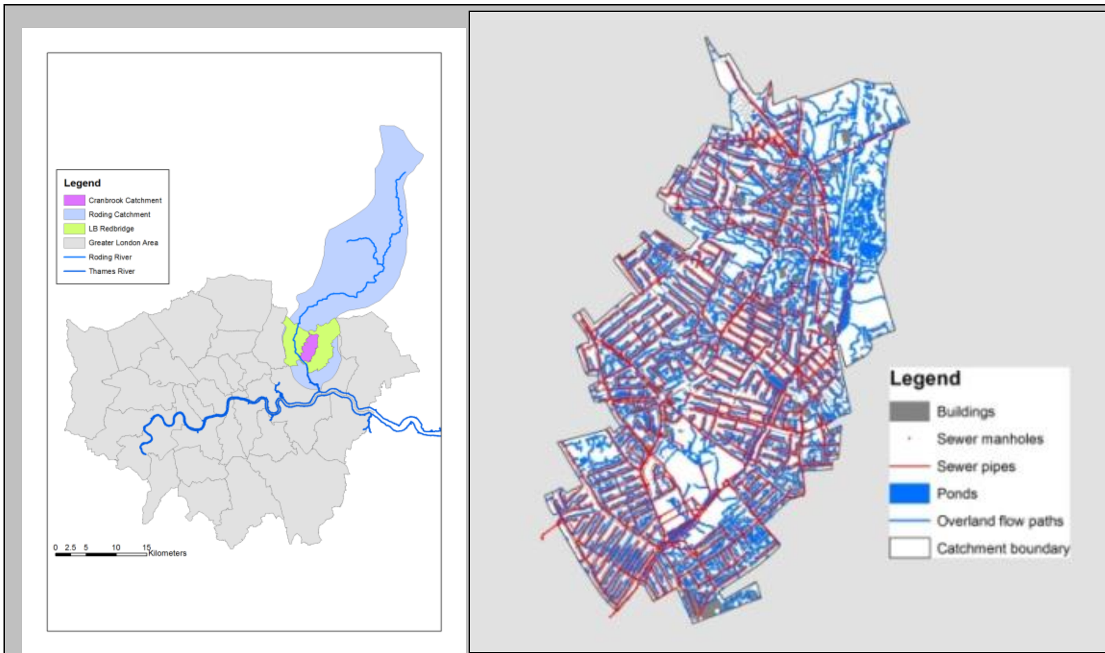


Figure 1: The Cranbrook catchment. From Ochoa et al., 2011, used with permission of the authors.

A formal stakeholder identification approach was undertaken (Figure 2) to map the links between stakeholders that would take part in a collaborative modelling exercise. The process of identifying stakeholders and their links resulted in a much improved understanding of the social-administrative system and its critical points for improvement. The stakeholders were presented with alternative flood management interventions and explored their effects using online simulation tools. The interventions included: "Do nothing", Rainwater harvesting, Improved and targeted maintenance regimes for the sewer system, Improved resistance for preventing water from entering properties and Improved rainfall and flood forecasting and warning.

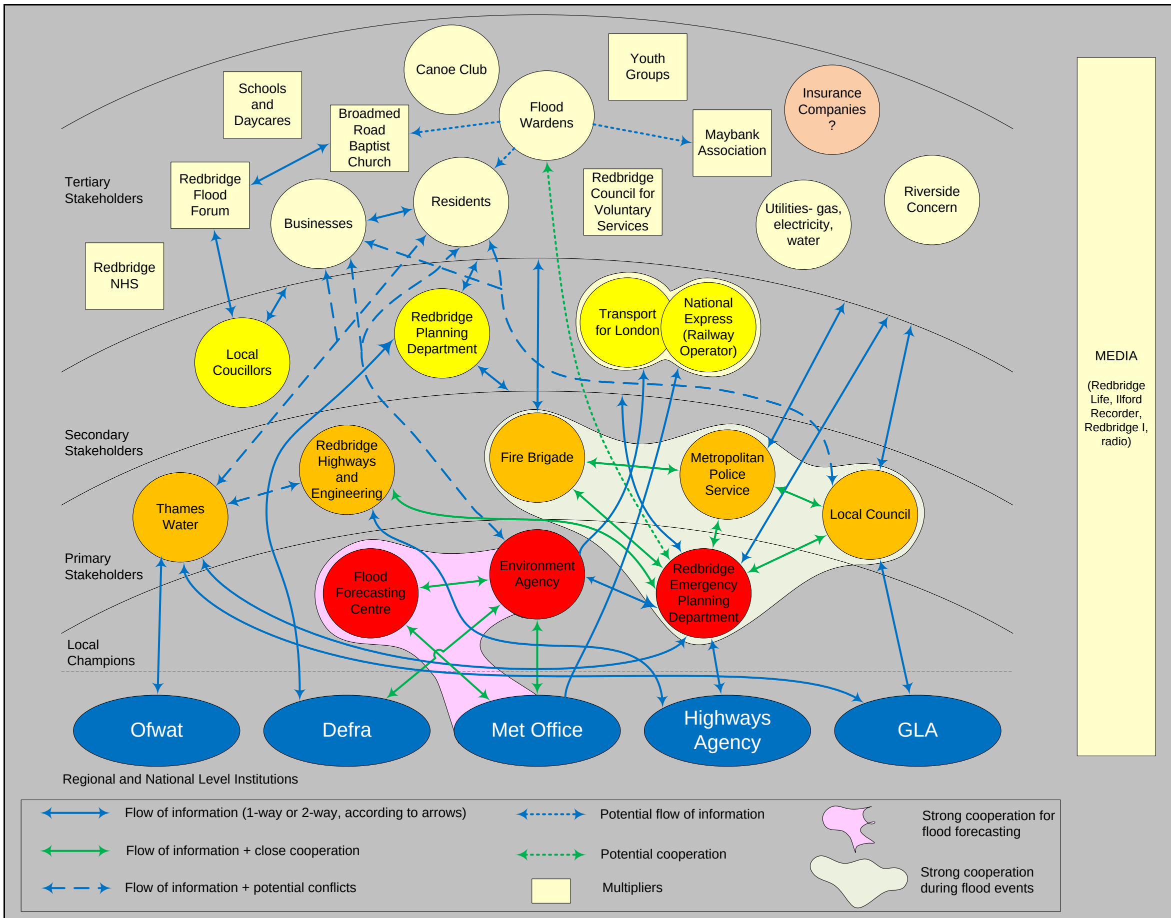


Figure 2: Stakeholder organi-sociogram, London Borough of Redbridge (UK) from Ochoa et al., 2011, used with permission of the authors.

This engagement of a wide variety of stakeholders in the decision-making process for flood risk management proved to make them more aware of the situation and increased their personal responsibility towards this issue and their understanding of each other's attitudes and perspectives on risk.

Flood insurance and compensation systems are important parts of strategies for dealing with flood risks (Association of British Insurers 2002). The development of flood risk insurance is an example of close links between public and private actors in the management of environmental issues. The private insurance and re-insurance industry has for a long time been involved as an actor in the management of risk. Insurance arrangements and the relation between market and public measures are determined at a national level and as a consequence a great diversity exists across EU member states. For example, in the UK there has been an ever increasing trend towards individualisation of flood risk, segmentation of the market and differentiation between insurance premiums depending on degrees of assessed risk at a particular location. The UK Environment Agency works with the Association of British Insurers to support the insurance industry's commitment to continue offering flood risk insurance to the vast majority of homes and businesses in flood risk areas. However, in other parts of Europe exactly the opposite trend is observable. For example in France and similarly in Belgium, Spain and Norway, compulsory cover for disaster risk is shared amongst all policy holders with an identical additional percentage premium paid on top of the assessed premium for fire insurance (French Disaster Reduction Platform 2007). In both cases public-private partnerships have been central – in the UK an agreement between the government and insurance companies to ensure the continued provision of flood insurance cover even in high risk locations (although at very high prices); in France a consensual setting up and on-going monitoring of the shared risk arrangement linked to a public risk prevention policy. But importantly the outcomes of these public-private partnerships remain quite divergent and ideologically distinct (Walker et al. 2010).

Increasingly insurers and reinsurers use sophisticated probabilistic catastrophe models to price flood risk. For instance the Parameter Trigger Concept is based on the principle of a pay-out mechanism which includes a parameter that can be measured or modelled. The advantage is that funds can be made quickly available after the event because no laborious proof of damage has to be given. There is no explicit link to the loss suffered by the insured. The main challenge is to capture the majority of damaging events by the trigger definition.

3.5 Developing governance for flood risk management

Resilience and adaptation demand flood management that is robust and flexible. Combinations of measures can reduce vulnerability and are generally cost efficient. This requires integrated strategies and recognition of the role of local authorities, non-governmental and private actors (Section 3.4). A tipping point approach may be a useful base for adaptive flood management.

Management strategies relying exclusively on cost-intensive technical measures and reactive top-down approaches based on large-scale engineering are regarded as an out-dated way of dealing with floods (Samuels 2006, Coninx 2008). With the increasing awareness of the links between large-scale interventions, society and the ecosystems, there has been a general call to view flood defence emphasizing sustainability (Kundzewicz, 2002, AFPM 2009).

The concept of resilience deals with inherent uncertainties of management strategies (Berkes 2007, Klein et al. 2003, Kuhlicke and Kruse 2009, Merz et al. 2010). The challenge is to better understand (1) the amount of disturbance a system can absorb without major disruption; (2) the degree to which the system is capable of self-organization; (3) the degree to which the system can build and increase the capacity for learning and adaptation (Klein et al. 2003).

Integrated approaches to flood management are increasingly reflected in many policies, strategies and projects. On a practical level there is a growing awareness that ***combination of measures*** should be used to reduce vulnerability and disastrous flooding.

Effectiveness and costs and benefits need to be considered together with practical applicability and intangibles such as socio-cultural preferences and environmental consequences. Evaluation criteria for strategies and measures furthermore include ***robustness, flexibility, and acceptance*** (de Bruijn et al. 2008).

The EC (2009a) has suggested a number of guiding principles for new measures:

- Perform a climate check;
- Choose robust and flexible measures (focus on non-structural measures, a mixture of measures, focus on "no regret" and "win-win" measures, etc.);
- Use a catchment approach;
- Take long-term developments into account;
- Consider other adaptation measures and their impact on flooding.

There are a number of approaches that combine technical measures with new modelling and participatory approaches in order to better deal with changing conditions. The Cranbrook case (Box 3.2) shows that it is possible to improve the resilience of communities and cities to flooding through stakeholder involvement. Such involvement deepens the understanding for and acceptance of measures that can and have to be taken. Other novel initiatives include "Making Space for Water" (Defra, 2005) and "Room for the River" (Programme Directorate Room for the River - Netherlands, 2007, see box 3.3). These can also accommodate changing conditions related to climate change as in the German KLIWAS programme (see box 3.4). In many parts of Europe transnational actions have to be taken in order to improve flood management.

New approaches need to be supported by adequate legislation. Current European and national legislation does not cover all aspects of integrated flood risk management. For example spatial planning is not as such covered by the Floods Directive. The management of flood generation areas and land-use changes that affect the magnitude of risks are only marginally covered. Flash floods and pluvial flooding in urban areas are not explicitly referred to in existing legislation, and their management depends more on evolving planning practice than on specific policies. There is thus a need to further develop policies at all levels of governance recognising the multifaceted nature of flood protection.

Sustainable flood risk management must strike a balance between preparedness (considering the long lead times for certain types of measures combined with the pace of relevant changes) and economic considerations (avoiding investments in measures which by hindsight were not necessary). A promising approach is the adaptation tipping point method combined with the development of adaptation pathways (Kwadijk et al., 2010). In this approach the focus is on the flood risk management system and its ability to deal with extreme events.

Box 3.3
Construction of artificial side channels / flood bypasses, reconnecting old river branches and increasing the water discharge capacities (Room for the River)
After two consecutive flood peaks in 1993 and 1995 in the Netherlands, where the dikes only just held, it was decided that flood prevention was inadequate. But instead of raising the dikes, as was done so many times in the past, the Dutch government decided to create more room for the river in order to lower maximum water levels during flood peak events. The Room for the River project is a good example of a combination of a resistance and a resilience-based strategy. By lowering the floodplain, realigning the dikes and reconstructing secondary channels, the water regains more space and this leads to a reduction in high water levels.

Since the mid-nineteenth century, the loss of floodplains in the Netherlands has been approximately 65% of the total floodplain surface area in 1850, and urban development has created several bottlenecks in the floodplain. Giving more room to rivers substantially lowered flood levels, but also help to sustain a more attractive environment, both urban and natural. This greatly influenced public and political opinions.

Room for the River was officially adopted by the Dutch government to achieve the required safety level for the river systems. In 2005, specific targets were set at the national level and local authorities became responsible for the design and construction of individual measures along the Rhine, Scheldt and Meuse rivers (http://www.ruimtevoorderivier.nl/).

Box 3.4
Adopting a climate factor when reinforcing existing dikes (KLIWAS)
Up to 30 climate model runs (including those of the EU-FP6-Project ENSEMBLES), as well as different bias correction methods and hydrological models, were evaluated against the background of the interdisciplinary research programme KLIWAS (http://www.kliwas.de), which integrated ecological, economical, water quality and water quantity aspects of climate change for rivers and coastal waters which are used as waterways. The purpose was to account for different sources of uncertainty and provide a reliable basis for the assessment of various adaptation options. Historical data bases were extended for model validation and monitoring of climate change effects. A model chain was established, which couples climate models to hydrological/oceanographic, hydrodynamical / sedimentological, water quality, and ecosystem models. At each step, uncertainty was analysed in detail to assess the level of understanding of the aquatic systems and their sensitivity to low flow, floods, and other aspects of "historical" and future climate change. As a result, the design level of protection structures (e.g. against a flood of 1 % annual probability) is multiplied with a climate change factor between 1.15 and 1.25, or a generally higher freeboard is chosen (e.g. in Saxony).

Tipping points for adaptation are events where the magnitude of change of one of the relevant drivers (extreme river discharge, land use, etc.) is such that current flood risk management strategies will no longer be able to meet their objectives. When these adaptation tipping points have been identified, scenarios are used to indicate under what conditions they may be reached, and thus, when alternative strategies are needed. The trigger for taking action is therefore not climate change per se, but a high likelihood of conditions under which set objectives for flood protection can no longer be achieved.

When an adaptation tipping point is expected to be reached, a switch to a new strategy is needed. Each new strategy has its own future tipping point which, again, requires a switch to be made. In the long run water management is thus a succession of strategies. Several successions are possible, together forming adaptation pathways.

In this approach, adaptation follows pathways of strategies that are influenced by current and future climate, socio-economic developments and societal perspectives. It addresses uncertainty over future developments by incorporating flexibility and by increasing resilience to tolerate a wider range of conditions. Strategies can be designed to implement small, incremental changes which are common to all the strategies first, leaving the major irreversible investment decisions as far as possible in the future.

Learning and monitoring is essential to the adaptation tipping points approach. When monitoring reveals that changes happen more quickly than originally envisaged, the implementation of a new strategy can be brought forward in time. Likewise, under a slower change decisions can be put back in time.

4 Scenarios for flood risks in Europe

Scenarios provide a means to explore potential future developments. Rather than making predictions of what will happen, they paint a picture of how alternative futures might unfold, describing plausible trajectories of climate, environmental, socio-economic and technological conditions. Scenario studies can be driven by an interest in the uncertainty, probability or desirability of future developments. The key question to be addressed is: What futures should European flood management be prepared for?

The aim of scenarios is to facilitate decisions that are robust under a wide range of possible futures (Moss et al., 2010). As a consequence of climate change as well as socio-economic developments, the non-stationary dynamics of flood risk has already been recognised. The direction and magnitude of future changes are, however, uncertain. Scenarios of flood risk can be used to better understand the consequences of these uncertainties and are therefore a useful tool in flood risk management.

Scenarios should identify the key drivers that determine flood risk. Flood risks change when the hazard changes or when vulnerabilities change. A change in hazard may entail a change in the frequency (or probability) of flooding, or a different pattern of flooding (see section 2.6). A change in vulnerability may arise from developments in land use and infrastructure, economic conditions and economic activities that are sensitive to floods.

Societal factors, for example the different role authorities can play relative to private actors, may also need to be considered.

This chapter briefly reviews current research on scenarios and presents available scenarios of how flood risk may develop in Europe in the future.

4.1 Research supporting the development of scenarios for flood risks in Europe

The development of scenarios of future flood risk requires input on all the different aspects of flooding at different spatial and temporal scales, from climate conditions such as precipitation pattern and intensity to hydrological processes and societal vulnerabilities.

Comprehensive, integrated scenarios of flood risk need to include projections of:

- The climate conditions, which are based on global or regional climate models, or ensembles of models, providing projections of rainfall and its spatiotemporal distribution, temperatures and other climate variables. Note that these projections are themselves dependent on scenarios of greenhouse gas emissions assuming different trajectories of future socio-economic development.
- The hydrological processes and (their) variables: river flow and its variation, snow melt, soil moisture, evaporation, water levels in lakes and reservoirs.
- Land cover, which directly interferes with hydrological processes. This includes aspects such as land sealing, dykes, dams and reservoirs.
- Patterns of land use, which affect the physical location of infrastructures such as buildings, transport routes, harbours and airports, and activities vulnerable to floods such as agriculture, aquaculture and transport.
- Economic activities that affect the value of the assets and activities at risk from flooding.
- Measures and responses that affect the hazard (e.g. flood defences) and vulnerabilities and the ability to cope with flood risks, including general adaptation to natural hazards and climate change.

The EU has funded several large research projects on flood risk, some of which focus on the basic methodological aspects such as the development and comparison of models and scenarios, whereas others explore in particular the possible future developments in flood risk, or certain key elements of it such as climate and hydrology. Many projects have combined several aspects (Table 4.1). The results of these projects have been synthesised in scenarios for future flood risks in Europe (See Section 4.2). A general overview has also been provided in the EEA SOER report (EEA 2010a).

The projects listed below differ in geographical scale. The ones selected here are mainly Europe-wide, although some use a case study approach focusing on particular regions or trans-boundary catchments. Many of the projects are closely linked. For examples, the results of the ENSEMBLES project and the LISFLOOD model studies are extensively used in other projects to provide projections of climate or hydrological change. In addition to the studies included in Table 2 there have also been projects with a national or local focus, although the extent to which flood risk scenarios have been developed differs from country to country.

Table 4.1 suggests that although several projects have developed scenarios of changes in climate and hydrology, few studies have specifically included changes in land use, exposure and adaptive capabilities. Only recently studies have started to develop fully integrated scenarios of flood risk that take into account adaptive capacity as well as climate drivers and hazards (e.g., ClimWatAdapt, see section 4.2). There is still a need for European-wide scenarios of land use and other socio-economic changes. One of the difficulties with European-wide scenarios is that flood hazards and vulnerabilities are context dependent. For effective and efficient flood protection it is not sufficient to make broad brush analyses. One also needs to understand relevant interactions between economic, technical, political and hydrological processes.

The large gap in time horizon between climate studies (which typically provide projections until the end of the century) and socio-economic studies (which usually do not look further ahead than 2030/40) creates further difficulties. At short time scales much of the projected climate change is still obscured by natural variability. Short-term (decadal-scale) climate projections are, however, in great demand. Meaningful long-term socio-economic scenarios would in principle be useful from a strategic point of view, but it is a difficult task due to large uncertainties caused by potential structural changes in socio-economic conditions.

Table 4.1. Overview of major projects contributing information to the development of flood scenarios for Europe with indicative information on the focus of the project: ***=major focus; ** = important aspect; *=issue taken into account

Project acronym	Project title	Project period	Scenarios: Climate	Hydro-logy	Land use	Exposure	Adaptive capacity	Geographical scale	Reference (www-page and/or key publication)
Main focus on European wide flood issues									
LISFLOOD	LISFLOOD climate change impact assessments	Since 2005	**	***		*		Europe	http://floods.jrc.ec.europa.eu/climate-change-impact-assessment.html
ClimWatAdapt	Climate Adaptation – modelling water scenarios and sectoral impacts	2010–2011	**	**		**	**	Europe	http://www.climwatadapt.eu/
ADAM	Adaptation and Mitigation Strategies: Supporting European climate policy	2006–2009	*	**		*		Europe	http://www.adamproject.eu/
PESETA	Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis	2006–2007	**	**		*		Europe	http://peseta.jrc.ec.europa.eu/
WATCH	Water and global Change	2007–2011	*	***				Global; 4 case study catchments across Europe	http://www.eu-watch.org/
FLOODSITE	Integrated flood risk analysis and management methodologies	2004–2009	*	*		*	*	Europe; several case study areas	http://www.floodsite.net/
Main focus on climate drivers									
ENSEMBLES	ENSEMBLE-based Predictions of Climate Changes and their Impacts	2004–2009	***	*	*			Europe	http://www.ensembles-eu.org/
CORDEX	COordinated Regional climate Downscaling EXperiment	Since 2009	***					Europe (and other regions across the globe)	http://www.euro-cordex.net/
AVOID	Avoiding Dangerous Climate Change	2009–2012	***	**		*		Global	http://www.avoid.uk.net/
PRUDENCE	Prediction of regional	2001–2004	***	*				Europe	http://prudence.dmi.dk/ , Christensen et

	scenarios and uncertainties for defining european climate change risks and effects								al. 2007
STARDEX	Statistical and regional dynamical downscaling of extremes for european regions	2002–2005	***					Europe	http://www.cru.uea.ac.uk/projects/stardex/
				Regional analyses					
CLAVIER	Climate Change and Variability: Impact on Central and Eastern Europe	2006–2009	***	**				Central and Eastern Europe	http://www.clavier-eu.org/
CECILIA	Central and Eastern Europe Climate Change Impact and Vulnerability Assessment	2006–2009	***	**				Central and Eastern Europe	http://www.cecilia-eu.org/
ACQWA	Assessment of climatic change and impacts on the quantity and quality of water	2008–2013	**	**		*		European mountain regions	http://www.acqwa.ch/
VERIS-Elbe	Changes and management of risks of extreme flood events in large river basins - the example of the Elbe River	2005–2008	**	***	**		**	Elbe	http://www.veris-elbe.ioer.de/
AMICE	Adaptation of the Meuse to the Impacts of Climate Evolutions	2008–2013	**	***	*	*	*	Meuse	http://www.amice-project.eu/en/index.php
Rheinblick2050	Impact of regional climate change on discharge in the Rhine River basin	2008–2010	**	***				Rhine	http://www.chr-khr.org/projects/rheinblick2050

4.2 Integrated scenarios of flood risk in Europe

Flood risk management needs to consider developments in exposure and vulnerability due to land-use change and infrastructure development. Scenarios for flood risk management thus have to combine socio-economic scenarios, such as projections for population growth, urbanisation and industrial developments with projections of hazards (Section 2.6). Recent studies have suggested that climate change can add significantly to expected damages in some parts of Europe over the coming decades.

To estimate future flood risks, the ClimWatAdapt project used hydrological simulations of the LISFLOOD model (van der Knijff et al., 2010) that was also used in the earlier studies of Dankers and Feyen (2008, 2009). To simulate climate change impacts on river flows the LISFLOOD model was forced with the bias corrected output of 11 different RCM simulations origination from the ENSEMBLES project. (For details see Flörke et al. 2011). These scenarios of changes in flood hazard were then combined with projections of socio-economic change. The results showed that the combination of climate change and economic growth will likely result in a strong increase in European flood risks (Flörke et al. 2011).

The ClimWatAdapt project focused on floods with an annual expected probability of exceedance of 1%. These "100-year floods" are extreme events, which tend to cause especially great financial damage. The level is also frequently used as an indicator for the development flood protection infrastructure. The LISFLOOD scenarios showed that the occurrence of a 100-year flood event is strongly affected by climate change. However, the uncertainty related to the spatial distribution is still large. Different climate models gave very different results. Using the ensemble mean, floods were projected to increase especially in the northwestern part of Europe (UK, western France, Belgium, Netherlands, western Germany) and on the Iberian peninsula (Portugal and Spain).

When accounting only for climate change, some regions dominated by snowmelt (for example the Vistula and Odra catchments in Poland) are likely to see a reduction in annual flood damages due to the strong reduction in snowmelt-driven and ice-jamming floods, which compensates for the increase in summer flood damage in these regions. The total number of people affected by floods (assuming protection up to a current 100-year flood event) was expected to increase by 80% in the EU27 due to the impact of climate change alone. This happened in all European countries except Denmark and Poland. The changes in people affected by flooding varied between the different European countries and were the highest in Belgium, Italy, Slovenia, and UK.

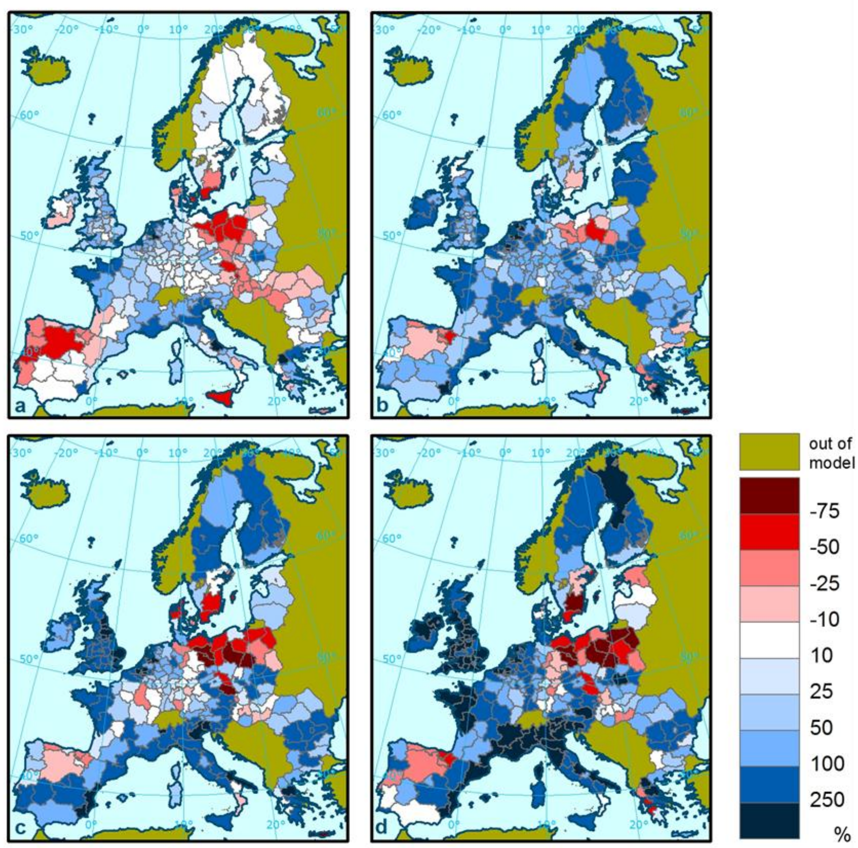
Within the EU FP7 project Climate Cost[11] the LISFLOOD model was also used in an assessment of future changes in the cost of floods in Europe. To achieve this, changes in the frequency of floods were combined with information on exposed assets, depth-damage relations and population density to estimate economic damages as well as the number of people living in flood risk areas. Under current conditions, the Expected Annual Damage (EAD) was estimated to be ~€5.5 billion for the EU27. On average higher flood damages were projected for all countries within the EU (Fig. 4.1). Taking into account both climate and socio-economic changes under the A1B scenario, the EAD was projected to increase to €20 billion by the 2020s (2011-2040), €46 billion by the 2050s (2041-2070), and €98 billion by the 2080s (2071-2100) for the ensemble mean results. A significant part of this rise will be

[11] http://www.climatecost.cc/ [Accessed Oct 29 2012]

due to socio-economic change. Nevertheless, the isolated effect of climate change alone amounted to €9 billion by the 2020s (2011-2040), €19 billion by the 2050s (2041-2070), and €50 billion by the 2080s (2071-2100).

The highest increases in climate change-related flood damage (over and above socio-economic change) were projected for the UK, Italy, Slovenia, Belgium and the Netherlands. This is due to a strong increase in the frequency of current high return period floods (e.g., the current 100-year return level was projected to become a 10- or 20-year flood by the end of this century). For several eastern European countries (e.g., Hungary and Czech Republic) the projected increase in flood damages was only related to economic development. In other words, in these areas the risk of damage per flooding event is increasing while the flood hazard itself is not changing much.

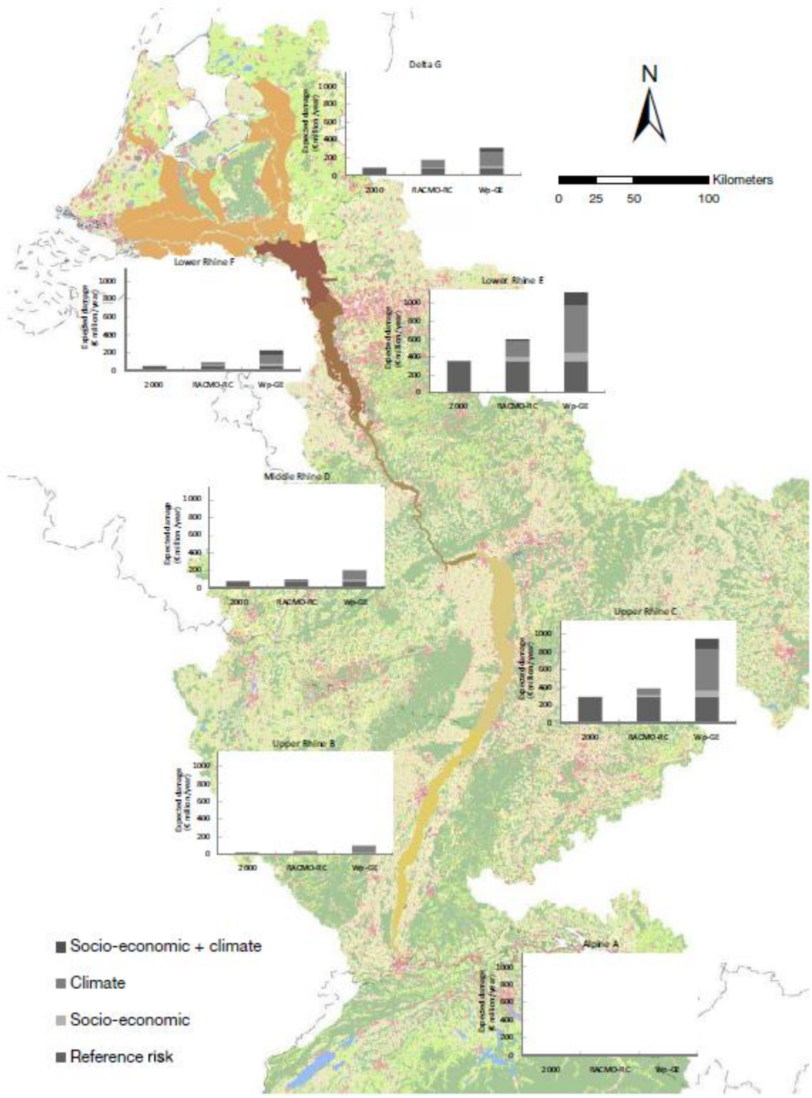
Figure 4.1. EU27 relative change in direct flood damage from floods due to climate change only (no socioeconomic change) for (a) current (1981-2010), (b) 2020s (2011-2040), (c) 2050s (2041-2070) and (d) 2080s (2071- 2100) relative to the baseline period (1961-1990), for the A1B scenario on LISFLOOD simulations driven by 12 regional climate models. Produced by JRC for the FP7 project ClimateCost, Feyen and Watkiss 2011, used with permission of the authors.



In addition to the European-wide analysis in ClimWatAdapt, a number of studies on specific areas have started to explore how changes in climate compare to changes in land use, and particularly in exposed assets, when it comes to future changes in flood risk. Te Linde et al. (2011) projected that by 2030 the annual expected damage from flooding over the entire

Rhine basin may increase by between 54% and 230%, of which the major part (~ three-quarters) could be accounted for by an increase in flooding due to climatic variables (Fig. 4.2). The remaining increase was due to projected changes in exposure which were based on land-use projections under two different socio-economic scenarios. In contrast, a small-scale case study in Belgium by Poelmans et al. (2011) found that although climate was the main source of uncertainty associated with projected future changes in peak flow and flood extent, the projections of potential damage were dominated by future land cover changes that occur in the floodplain.

Figure 4.2 Annual expected flood damage, for the reference situation and projections for 2030, aggregated into seven regions along the Rhine. From Te Linde et al. 2011, used with permission of the corresponding author.



5 Conclusions

Floods are extreme events that can have a large impact. They arise from a multitude of causes and can have very different consequences depending on regional and local circumstances. Major flood disasters in Europe have caused loss of lives and economic loss that amount to billions of euro, but aggregated over large areas small local floods also produce significant losses.

Analyses of trends of past flood events suggest flood hazard may have increased in parts of Europe. Available evidence suggests high flows have been increasing in northern Europe, especially in western Britain and coastal Scandinavia. Regional patterns are, however, diverse, with many weak negative trends occurring in northern Europe as well, and a very mixed pattern in central Europe. Across most of the continent, however, urbanisation and the accumulation of assets in flood prone areas have led to increasing trends in the damages and economic consequences of floods.

Global warming may reduce flood hazard in areas that are dominated by annual snowmelt floods, except in those regions where a sharp increase in winter snowfalls outweighs the effects of a warmer and shorter snow season. In other parts of Europe there is greater uncertainty in how flood hazard will change due to climate change. Increases in extreme river flows have, however, been predicted in several studies and may occur over relatively short time spans.

Flood risk management is a demanding task that requires careful analysis of flood hazards and their causes, assessments of the magnitude of the risks, systematic planning to reduce risks and adaptation in the face of possible change. Dam safety is a major issue in dealing with flood risks. Flood risk management requires appropriate institutions, technical solutions and functioning governance structures. Recently participatory approaches have opened up new avenues for the development of flood risk management. Promising examples of participatory flood risk management have been documented.

Flood risk management has been seeking new directions and needs to adapt to an uncertain future. Flood risk management needs to consider developments in exposure and vulnerability due to land-use change and infrastructure development. Due to the combined effects of climate change and socio-economic development flood risk is unlikely to remain stationary. Scenarios for flood risk management thus have to combine socio-economic scenarios, such as projections for population growth, urbanisation and industrial developments with projections of future flood hazards. Detailed scenario studies are still missing in many river catchments. Recent studies have suggested that climate change can add significantly to the expected damages in some parts of Europe over the coming decades. Adaptation to changes in flood hazards and risk is therefore an essential element in efforts to adapt to climate change.

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Appendix

Terminology

The terminology mainly follows UNISDR: UN International Strategy for Disaster Reduction Sec, 15 January 2009, http://www.unisdr.org/eng/library/lib-terminology-eng.htm. In addition aspects emphasised by the climate change assessments have been included. Important concepts include the following:

Adaptation: The adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

Coping capacity: The ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters.

Disaster: A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources.

Disaster risk: The potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period.

Disaster risk management: The systematic process of using administrative directives, organizations, and operational skills and capacities to implement strategies, policies and improved coping capacities in order to lessen the adverse impacts of hazards and the possibility of disaster.

Exposure: People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses.

Hazard: the magnitude and probability of occurrence of a flood event.

Preparedness: The knowledge and capacities developed by governments, professional response and recovery organizations, communities and individuals to effectively anticipate, respond to, and recover from, the impacts of likely, imminent or current hazard events or conditions.

Resilience: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.

Risk: The combination of the probability of an event and its negative consequences. The concept "captures uncertainty in the underlying processes of climate change, exposure, impacts and adaptation" (Schneider et al. 2007, p. 781).

Risk assessment: A methodology to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend.

Risk management: The systematic approach and practice of managing uncertainty to minimise potential harm and loss.

Scenario: A scenario is a coherent, internally consistent and plausible description of a possible future state of the world. It is not a forecast; rather, each scenario is one alternative image of how the future can unfold. A set of scenarios is often adopted to reflect, as well as possible, the range of uncertainty in projections. (IPCC-TGICA, 2007)

Storyline: A narrative description of a scenario (or a family of scenarios), highlighting the main scenario characteristics and dynamics, and the relationships between key driving forces. (IPCC-TGICA, 2007)

Vulnerability: The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. IPCC defines vulnerability as the degree to which a system is susceptible to, and unable to cope with, the adverse effects of climate change, including climate variability and extremes. It is measured as a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC 2007, p.883).