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Assessing river flood risk and adaptation in Europe—review of projections for the future

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Abstract Flood damages have exhibited a rapid upward trend, both globally and in Europe, faster than population and economic growth. Hence, vigorous attempts of attribution of changes have been made. Flood risk and vulnerability tend to change over many areas, due to a range of climatic and nonclimatic impacts whose relative importance is site-specific. Flooding is a complex phenomenon and there are several generating mechanisms, among others intense and/or long-lasting precipitation, snowmelt, ice jam. Projected climate-driven changes in future flood frequency are complex, depending on the generating mechanism, e.g., increasing flood magnitudes where floods result of heavy rainfall and possibly decreasing magnitudes where floods are generated by spring snowmelt. Climate change is likely to cause an increase of the risk of riverine flooding

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across much of Europe. Projections of flood hazard in Europe based on climatic and hydrological models, reviewed in this paper, illustrate possible changes of recurrence of a 100-year flood (with probability of exceedance being 1-in-100 years) in Europe. What used to be a 100-year flood in the control period is projected to become either more frequent or less frequent in the future time horizon of concern. For a large part of the continent, large flooding is projected to become more commonplace in future, warmer climate. Due to the large uncertainty of climate projections, it is currently not possible to devise a scientifically-sound procedure for redefining design floods (e.g. 100-year flood) in order to adjust flood defenses. For the time being, we recommend to adjust design floods using a "climate change factor" approach.

Keywords Floods · Adaptation · Risk · Vulnerability · Climate projections · Climate change impacts

1 Introduction

The costs of damages caused by extreme weather events (among which floods are a major category) have exhibited a rapid upward trend, both globally and in Europe. Yearly material damage from large events has increased globally by order of magnitude within four decades, in inflation-adjusted monetary units. Damages caused by natural disasters, mostly weather and water-related have increased much more rapidly than population or economic growth (Mills 2005). Since flooding is the most common natural hazard in Europe, the climate signal in changing flood risk has been vigorously sought.

Human encroachment into floodplains and increase of damage potential appear to be the major causes for increased flood-related damages in most areas. For instance, in Japan half the total population and about 70% of the total assets are located on flood plains, which cover only about 10% of the land surface. An important factor influencing the flood risk is an unjustified belief in the absolute security provided by structural defenses. However, even a perfectly maintained dike designed to withstand, for example, a 100-year flood (river flow with probability of exceedance in any given year being one in 100 years, i.e. 0.01) does not, by definition, guarantee absolute

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protection. It is likely to be overtopped and possibly breached by an extreme flood (e.g. one with return period of 1,000 years). When a dike breaks, the damage may be greater than it would have been in a levee-free case, since existence of a dike is taken as a safety guarantee by the riparian population, so that the damage potential grows very strongly. Further, a short memory syndrome can be observed. During a flood-free interval, decision makers gradually reduce the funding of flood preparedness systems, and citizens become increasingly less risk-aware. This occurs, for river and coastal flooding, in developing and developed countries alike, including the United States, where the Katrina event unveiled the general inadequacy of the emergency preparedness system.

2 Observed development of climatic drivers

There has been an increasing body of evidence of the ongoing warming of the atmosphere at a variety of scales, including the global scale, with mean global surface temperature increasing by 0.65°C over the last 50 years (IPCC 2007). Precipitation changes are less regular, but increases over land north of 30°N over the period 1901–2005 and decreases over land between 10°S and 30°N after the 1970s were observed (Trenberth et al. 2007). Several studies lead to the conclusion that, over the last 50 years, there has been an increasing probability of heavy precipitation events for most extra-tropical regions; at the continental and global scales (cf. Groisman et al. 2005; Trenberth et al. 2007). Among changes detected in the UK (Wilby et al. 2008) are: increase in winter precipitation totals, larger N-day precipitation totals, and intensity of extreme (daily) events. It is likely that there have been widespread increases in the contribution to total annual precipitation from very wet days, i.e. days in which precipitation amounts exceed the 95th percentile value, in many land regions (Fig. 1), even in those areas where a reduction in total precipitation amount has been observed. This corresponds to the observed significant increase in water vapor amount in a column of the warmer atmosphere (consistent with the Clausius-Clapeyron law). However, only a few regions have sufficient data to assess trends in rare precipitation events in a reliable way (Trenberth et al. 2007). The

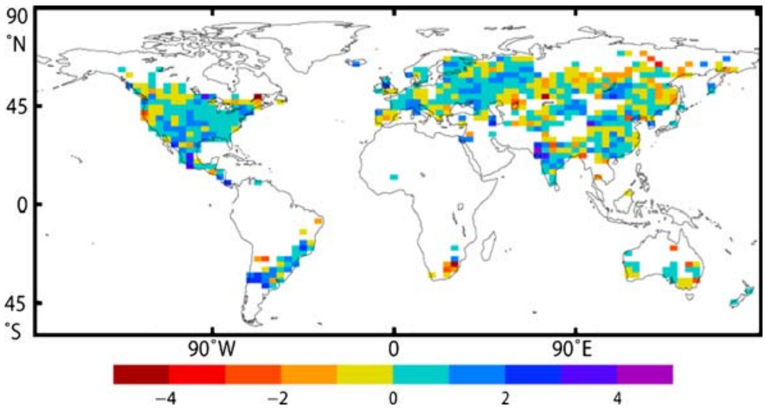

Fig. 1 Observed trends, in % per decade for 1951–2003, in the contribution to total annual precipitation from very wet days (95th percentile). Trends were only calculated for grid boxes where both the total and the 95th percentile had at least 40 years of data during this period and the data extended until at least 1999. Source: Trenberth et al. (2007)

rainfall statistics are strongly influenced by inter-annual and inter-decadal variability. There are problems with data homogeneity, e. g. related to changes in snowfall.

The effects of climate change on streamflow (equal to precipitation minus evapotranspiration minus change in water storage), which vary regionally, largely follow changes in the prime driver, precipitation, and changes in temperature in snow-impacted basins. However, temperature changes may be decisive also beyond basins with snowmelt-based flood generation mechanism, e.g. generally in mid latitudes, due to changes in potential evapotranspiration. Indeed, streamflow generation is a complex process, integrating influences of many climatic and non-climatic factors, such as volume and timing of precipitation, catchment storage, evapotranspiration and snowmelt, and whether precipitation falls as snow or rain, as well as watershed management practices and river engineering works (e.g. dikes and dams) that alter the water conveyance system over time. It is very difficult to disentangle the climatic effects on river flow from the effects of human interventions in the catchment. Several ongoing land-use changes, such as urbanization, deforestation, elimination of natural storage (floodplains, wetlands), can be regarded as adverse from the viewpoint of flood safety, resulting in growth of damage potential and amplification and acceleration of the maximum discharge of the flood wave.

Among observed climate-related phenomena impacting on floods in Europe are increase in precipitation intensity; increase in westerly weather patterns during winter; and shrinking snow cover. However, results of a global change detection study of annual maximum river flows (Kundzewicz et al. 2005) do not support the hypothesis of a ubiquitous increase of annual maximum river flows. Nevertheless, examining 70 time series for river discharge in Europe, Kundzewicz et al. (2005) found that the overall maxima (for the whole 1961–2000 period subject to study) occurred more frequently (46 times) in the second 20-year sub-period, 1981–2000, than in the first 20-year sub-period, 1961–1980 (24 times). A regional change in timing and nature of floods has been observed in many areas of Europe, and less snowmelt and ice-jam-related floods were recorded.

3 Projections for the future

Climate projections using multi-model ensembles show increases in globally averaged mean water vapor and precipitation over the 21st century. Yet, precipitation scenarios show strong regional differences. In Europe, there is a marked contrast between predicted future winter and summer precipitation change. Wetter winters are expected throughout the continent (in many places—less snow and more rain), while in summer, a strong difference in precipitation change between northern Europe (getting wetter) and southern Europe (getting drier) is projected (Kundzewicz et al. 2006). However, it has to be emphasized that various climate models do not consistently project precipitation change, disagreeing even as to the sign of change (Kundzewicz et al. 2007, 2008). This is in contrast to temperature projections where all the models agree as far as the sign of change (ubiquitous warming) is concerned (IPCC 2007). Generally, the extremes in precipitation are likely to be impacted more than the means. Multi-model climate projections for the 21st century show increases in average annual precipitation intensity defined as the annual total precipitation divided by the number of wet days (Fig. 2), which increases in most areas (Meehl et al. 2007). The behavior of precipitation extremes is projected to be notably different from the mean precipitation over much of Europe. The highest quartiles of daily precipitation amounts and annual maximum daily precipitation are anticipated to increase over many areas, also some of such areas where the mean precipitation is projected to

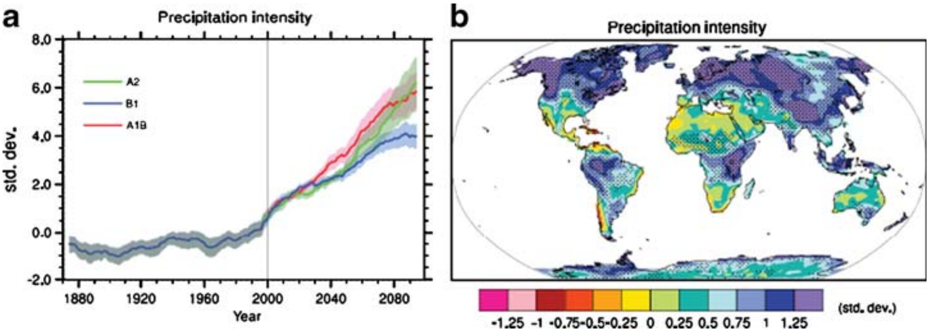

Fig. 2 Changes in spatial patterns of precipitation intensity (defined as the annual total precipitation divided by the number of wet days) over land, based on multi-model simulations from nine global coupled climate models. (**a**) Globally averaged changes in precipitation intensity for a low (SRES B1), middle (SRES A1B) and high (SRES A2) scenario (**b**) Changes in spatial patterns of simulated precipitation intensity between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. *Solid line* in (**a**) is the 10-year smoothed multi-model ensemble mean; the envelope indicates the ensemble mean standard deviation. *Stippling* in (**b**) denotes areas where at least five of the nine models concur in determining that the change is statistically significant. Each model's time series was centred on its 1980 to 1999 average and normalised (rescaled) by its standard deviation computed (after de-trending) over the period 1960 to 2099. The models were then aggregated into an ensemble average, both at the global and at the grid-box level. The changes are given in units of standard deviations. Source: Meehl et al. (2007)

decrease (Christensen and Christensen 2003; Kundzewicz et al. 2006). Yet, existing climate models are not good at reproducing local climate extremes, due to, *inter alia*, inadequate (coarse) resolution. Hence, projections of extreme events for future climate are highly uncertain.

Palmer and Räisänen (2002) projected a considerable increase in the risk of a very wet winter in Europe (and a very wet monsoon season in Asian monsoon region). For example, for CO_2 doubling (61–80 years from present), an over five-fold increase of the risk of a very wet winter is projected over Scotland, Ireland and much of the Baltic Sea basin, and even over seven-fold increase for parts of Russia.

Changes in river flows due to climate change depend primarily on changes in the volume and timing of precipitation and, crucially, whether precipitation falls as snow or rain. A robust finding is that warming would lead to changes in the seasonality of river flows where much winter precipitation currently falls as snow, with spring flows decreasing because of the reduced or earlier snowmelt, and winter flows increasing, with likely consequences to flood risk. In regions with little or no snowfall, changes in runoff are much more dependent on changes in rainfall than on changes in temperature, and studies often project an increase in the seasonality of flows, with higher flows in the peak flow season (Meehl et al. 2007).

Due to the uncertain precipitation projections, projected direction of change of long-term average annual runoff is not consistent across different climate models. Over large areas, even for large river basins, running the same greenhouse gas emissions scenario on different climate models may result in very different projections of future runoff change. Comparison of projections of mean annual runoff corresponding to the same emissions scenario but to different climate models (Arnell 2003; Meehl et al. 2007) clearly demonstrates that even the direction of change over many areas may differ among models.

The expected increase in heavy precipitation has multiple adverse consequences, such as: increased floods, landslides and mudslides (possibly leading to flow obstructions), increased soil erosion; increased pressure on government and private flood insurance

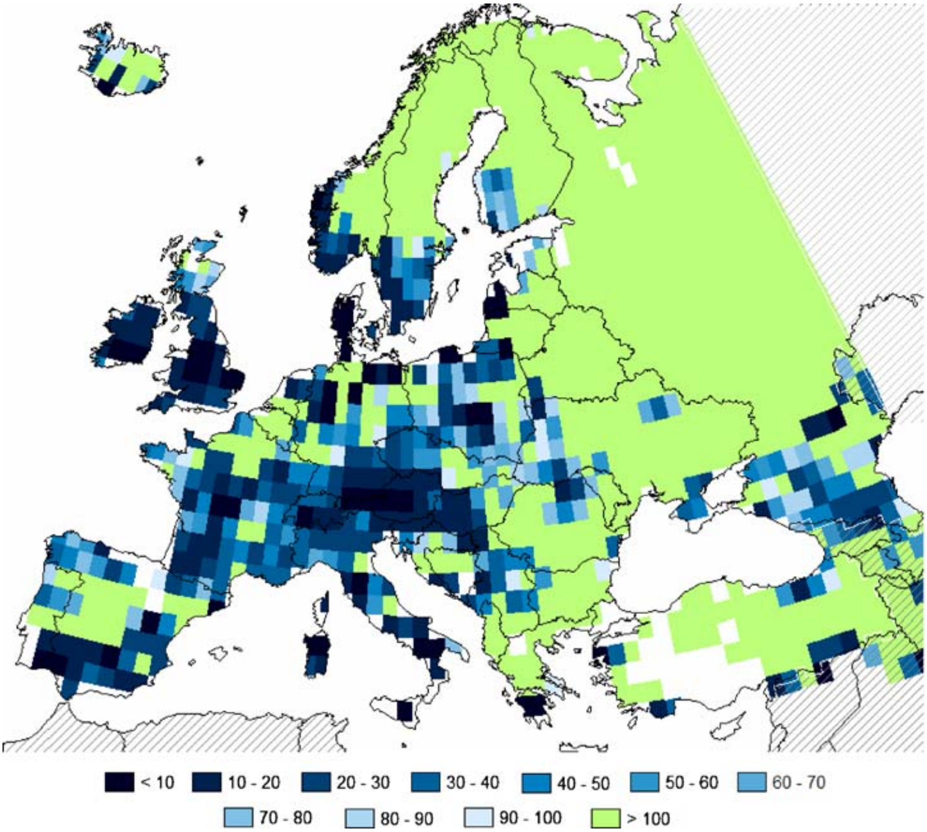

Fig. 3 Recurrence interval (return period) of today's 100-year flood (i.e. flood with a recurrence interval of 100 years during the period 1961–1990) at the end of the 21st century (2071–2100), in case of scenario SRES A1B. (Map prepared using results from Hirabayashi et al. 2008)

systems and disaster relief. Milly et al. (2002) demonstrated changes in the flood risk over several large basins, worldwide, based on monthly flow values. The control 100-year flood was projected to be exceeded more frequently as a result of CO_2 quadrupling, in some areas even every 2 to 5 years, on average. Kleinen and Petschel-Held (2007) and Hirabayashi and Kanae (2009) project a considerable increase in flood-affected population in the future climate.

Lehner et al. (2006), Hirabayashi et al. (2008), and Dankers and Feyen (2008) developed projections of flood hazard in Europe based on climatic and hydrological models. They produced maps of changes of recurrence of a 100-year flood, comparing the control period with scenarios. Figures 3 and 4 show that for much of Europe, what used to be a 100-year flood in the control period becomes either more frequent or less frequent in the future time horizon of concern. For a large part of the continent, a 100-year flood becomes more commonplace, occurring every 50 years, or even more frequently. However, comparison of Figs. 3 and 4 (resulting from studies based on different assumptions—different models, different resolutions, different scenarios, different control periods); should not be directly compared. It is known (cf. Kundzewicz et al. 2007, 2008), that there is a considerable uncertainty and large discrepancies between model results.

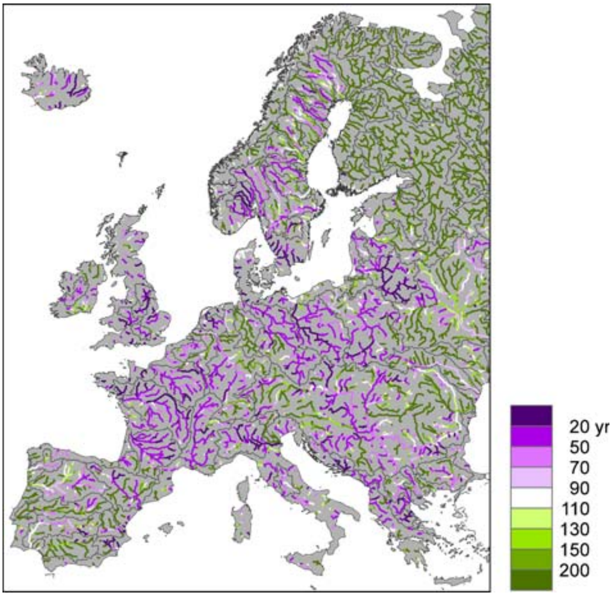

Fig. 4 Recurrence interval (return period) of today's 100-year floods (i.e. flood with a recurrence interval of 100 years during the period 1961–1990) at the end of the 21st century (2071–2100), in case of emissions scenario SRES A2. Source: Dankers and Feyen (2008)

Dankers and Feyen (2008) project that in several major European rivers, such as the Odra (Oder), Labe (Elbe), Po, Loire, and parts of the Danube, what used to be a flood with exceedance probability being 1 in 100 years (so called 100-year flood) in the control period, will become more frequent by the end of the century under the IPCC A2 scenario. In these rivers, the average return period of such a flood reduces to once every 50 years, or even every 20 years, on average. However, in NE of Europe, and in several rivers in Central and Eastern Europe, and in the Iberian Peninsula, probability of exceedence of a control design flood decreases.

Projections by Hirabayashi et al. (2008) also indicate that over much of Russia and Scandinavia, floods corresponding to 100-year return period in the control period may become less frequent in the future. In much of Poland, Germany, Austria, Switzerland, France, and Italy the floods corresponding to the return period of 100 years are expected to become considerably more frequent. In aggregate terms, over 40% of the area of Europe the control 100-year flood is projected to become more frequent. Over 30% of the area of Europe, the mean recurrence interval of the 100-year flood in the control period is projected to decrease to below 50 years in 2071–2100. Results of the study by Dankers and Feyen (2008) show that at 52% of the total number of river cells shown in Fig. 4, the return period for a flood corresponding to 100-year event in the control period becomes longer (>100 years); i.e. there is an decrease in flood frequency. At 48% there is an increase in frequency, i.e. 100-year flood in the control period is exceeded, on average, more frequently than once in 100 years. At 31 % and 9%, respectively, the future return period is shorter than 50 and 20 years, respectively.

Comparing broad features of Figs. 3 and 4 one can find areas of agreements of results, e.g. today's 100-year flood projected to occur less frequently in 2071–2100 over most of Finland, and European part of the Russian Federation, while it is projected to occur more frequently in much of Poland, France, UK, Southern Sweden, and Northern Italy. Differences between broader features of Figs. 3 and 4 one can find over Greece, Southern

Spain, much of Belarus and Lithuania, where one model projects an increase of frequency of the 100-year flood between the control and the future time horizon, and another model projects a decrease.

Most studies involving models show increasing risk of flooding in the UK under warming climate (Wilby et al. 2008).

Additionally, the projections of Fig. 3 have been used as input to the damage estimation model described elsewhere in this volume (Lugeri et al. 2010), taking a simplifying assumption of no change in vulnerability and exposure. The Hirabayashi's data have been imported and interpolated, In order to fill gaps and discrepancies due to the different resolution; the projected change of the 100-years return period has been applied proportionally to the other return periods in the model. The output has been aggregated according to the administrative boundaries at regional level (NUTS2)[1] by simple sum, and the results are shown in Fig. 5. Both absolute damage values and relative change with the present conditions are shown.

Due to the quite large difference in spatial resolution and to the broad assumptions described above, these projections may only serve as illustrations of broad features of possible futures. Uncertainty makes it difficult to formulate a meaningful message that could be conveyed to practitioners and decision makers, interested in flood defenses in a particular locality, yet they seem useful to provide, in a broad-brushed sense, a snapshot of future flood risk over Europe.

Regional studies devoted to the impact of climate change on flood damages in Europe are scarce. Actually, the only study on the pan-European scale, known to the authors, is the work by Feyen et al. (2009), which arrived at averaged expected annual damages at the EU and country level. It was assumed that the flood protection level depends on the country's GDP (protection up to 100-year, 75-year, and 50-year flood for countries with GDP above 110%; in the range from 55% to 110%; and below 55% of the average EU 27 GDP level, respectively). Also a simplifying assumption of no adaptation to increasing flood levels and no growth in exposed values was made. Under these assumptions, useful and interesting indicative results were obtained. The present expected annual damage of 6.5 billion Euro was projected to rise to 18 billion Euro in 2071–2100 under SRES A2 scenario. In five countries the expected annual damage in the future horizon was projected by Feyen et al. (2009) to exceed 1 billion Euro, with highest value being 4 billion Euro. Among 27 countries of the EU in 25 there were non-zero flood damages in the control period. Out of these 25 countries, increase (up to 80%) is projected in 20 and decrease (even by 85%) is projected in five countries.

Among regional studies, one could mention a scenario analysis of damage due to river and coastal flooding in England and Wales in the 2080s (Hall et al. 2005), combining four emissions scenarios with four scenarios of socio-economic change in an SRES-like framework. In all scenarios, flood damages were predicted to increase unless current flood management policies, practices and infrastructure are changed. For a 2°C temperature increase in a B1-type world, by the 2080s annual damage was estimated to be £5 billion as compared to £1 billion today, while with approximately the same climate change, damage is only £1.5 billion in a B2-type world. In an A1-type world, with a temperature increase of 2°C, the annual damage would amount to £15 billion by the 2050s and £21 billion by the 2080s (Hall et al. 2005; Evans et al. 2004). These numbers strongly support the need for a considerable investment in adaptation to climate change with respect to flood risk management (cf. Kundzewicz et al. 2007).

[1] Projections on the country level has also been performed, too, but are here omitted due to space limitation.

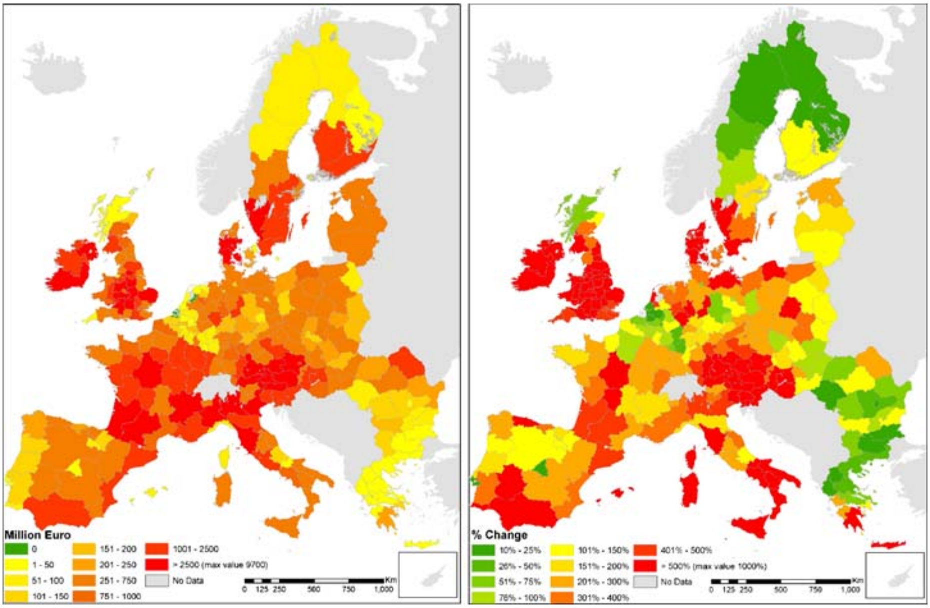

Fig. 5 Projected flood damages in 2071–2100. *Left*: absolute values. *Right*: % change with respect to 1961–1990

4 Uncertainty

There are many sources of uncertainty in future projections related to river flooding, starting from impossibility to foresee future human behavior (population change; social and economic development; climate mitigation policy: control of intensity of greenhouse effect via the curbing greenhouse gas emission and enhancing carbon sequestration; and adaptation to climate change impacts). Uncertainties are also introduced by several coupled transfer functions in the cause–effect suite of processes from greenhouse-gas emissions/ sequestration to atmospheric concentration of greenhouse gases, and then further to climate change (including feedbacks) and to climate change impacts. Every transfer function in the above system bears large uncertainty, so that amplification of uncertainty can be observed, throughout the logical chain from greenhouse gas emissions to climate change impacts. Already the climate model uncertainty (related to numerical converting of greenhouse gas concentrations into climatic variables, such as temperature and precipitation) is large. For a selected future time horizon, uncertainties of climate change projections increase with the remoteness of the future time horizon. In the near-term (e.g. 2020s), climate model uncertainties play the dominant role, while over longer time horizons, uncertainties due to the selection of emission scenarios become increasingly significant.

Uncertainty in practical flood-related projections is also due to a spatial and temporal scale mismatch between coarse-resolution climate models and the smaller-grid scale of a drainage basin, for which the much finer information is necessary and for a "point" scale of a locality (e.g. a small riparian town) where (costly) adaptation is undertaken. Further, time scales of interest may differ from the available climate model results (typically given at monthly/daily intervals), since for heavy precipitation resulting in flash flood, the dynamics of flood routing is at the scale of minutes to hours. As noted by Wilby et al. (2008), subgrid parameterization in critically important, because a Regional Climate Model scale is much larger than the scale of an individual storm cell. Scale mismatch renders downscaling (disaggregation) necessary and this is another source of uncertainty. Uncertainty in findings about future climate change impacts refers particularly to extreme events. Part of uncertainty is due to deficiencies of hydrological models and available observation records for model validation. There is an overwhelming scarcity of available homogeneous long-term observation records. The inherent uncertainty in analysis of any set of flood flows stems also from the fact that direct measurements in the range of extreme flows are problematic (rating curves not available for the high flow range, gauges destroyed by the flood wave, observers evacuated), and recourse to indirect determination is necessary.

According to Wilby et al. (2008), detection of climate change at global or regional (let alone catchment) scales is inherently difficult, because of the low signal-to-noise ratio. The relatively weak climate change signal is superimposed on a large natural, inter-annual variability of rainfall and river flow (under a confounding effect of land-use change). Hence, Wilby et al. (2008) speculate that statistically robust trends are unlikely to be found for several decades more. They state that for flood risk assessment, "treatment of uncertainty is still very much in its infancy".

5 Adaptation

There have been three basic adaptation strategies of coping with floods (cf. Kundzewicz and Schellnhuber 2004):

(i) protection (as far as technically possible and financially feasible, bearing in mind that the absolute protection cannot be achieved);
(ii) accommodation (living with floods); and
(iii) retreat (relocation from flood-risky to flood-safe areas). This latter option aims to rectify maladaptation (inappropriate adaptation of flood-prone areas) and floodplain development.

Strategies for flood protection and management may modify flood waters and/or susceptibility to flood damage and impact of flooding. Site-specific adaptation may include some of the following components of holistic flood management (cf. Kundzewicz, Takeuchi 1999).

The pre-flood preparedness may comprise:

- flood risk management under consideration of all possible causes of flooding;
- construction of physical flood defense infrastructure;
- legislation;
- investment on research and development on floods;
- development control within the flood plains;
- increasing source control, infiltration and storage/retardation facilities in urban basins;
- land-use planning and management;
- building codes, flood proofing; implementation of flood forecasting and warning arrangements;
- public communication and education of the extent of flood risk and actions to take in a flood emergency;
- disaster contingency planning; maintenance of preparedness of community self-protection activities; and
- insurance schemes.

Operational flood management includes

- detection of the likelihood of flood formation;
- forecasting of future river flow conditions from hydrometeorological observations;
- warning issued to the appropriate authorities and the public on the extent, severity and timing of the flood;
- emergency protection of levees from breach and overtopping;
- strengthening of defenses; decision to operate reservoirs and retardation ponds;
- issuing prior warning on emergency spill to the people to be affected;
- emergency rescue of lives and property from the flooded areas.

Finally, the post-flood response comprises such activity area as

- relief for the immediate needs of those affected by the disaster;
- reconstruction of damaged buildings, infrastructure and flood defenses;
- recovery and regeneration of the environment and the economic activities in the flooded area;
- review of the flood management activities to improve the process and planning for future events.

Adaptation measures can be perceived in the context of the flood risk management cycle. The phases of the cycle can be seen as prevention, protection and preparedness. Prevention can be understood as preventing flood damage by avoiding construction of infrastructure in present and future flood-prone areas (e.g. restriction of settlement in risk areas); or by adapting future developments to the risk of flooding. Legal regulations can be implemented, related to use of flood-plain areas, such as restrictions on new infrastructure and on handling substances dangerous to water (e.g. non-use of oil-fired heating systems). The need for costly defense and relocation measures, e.g., relocating industry and settlements from flood plains may be envisaged. Flood prevention may also include modification of construction standards. A small-scale structural action is flood-proofing on the site, i.e. adapting existing building codes to ensure that long-term infrastructure will withstand future climate risks.

Protection means taking measures to reduce the likelihood of floods and/or the impact of floods in a specific location, e.g. via dike strengthening or heightening, or creating storage room. Flood preparedness includes forecasting and information, insurance schemes, and providing instructions to the public on what specific actions to undertake in the event of flooding.

The principal flood protection measures in Europe include: technical flood protection (e.g. dikes, floodwalls, relief channels) and natural storage of flood water, e.g. by restoring flood plains and wetlands. In several countries of Europe (e.g. Sweden, Finland, Czech Republic), activities are underway to improve dam safety (e.g. via spillway re-dimensioning) and to re-design major dam discharges. Assessment of the technical and safety conditions of individual water structures and of the potential for further development is being done. Upgrade of structural defenses (e.g. expanding enclosure within embankments and improving the existing embankments around low-lying areas, increasing the height and strengthening of levees, enlarging reservoirs etc.) and revision of the management regulations for water structures are being envisaged. Upgrade of drainage systems (in particular of urban drainage) for a future wetter climate is also found necessary.

However, countries of Europe have been increasingly acknowledging the importance of not relying only on technical flood protection. Land-use planning measures are regarded as efficient and allow to combine flood management and nature protection. One of the options is watershed management ("to keep water where it falls" and to reduce surface runoff and erosion). Restoration of wetlands and floodplain forests and re-connection of old river arms are being considered. There is a call (e.g. in Germany and The Netherlands) to "give more space to the rivers", to designate flood areas, and to devise flood plain protection measures.

Nevertheless, non-technical measures based on land-use planning face difficulties in implementation. They may bring results in a longer term and they involve complex changes in the socio-economic system. A study by Daniel et al. (2007) shows that in the Netherlands, the announcement of an area designation for emergency inundation, resulted in decrease of the prices in the local housing estate market. Despite compensation schemes and low probabilities of a critical event, the social reaction was cautious. Public understanding and public reactions, beside the technical aspect, are of high importance for adaptation (Borowski et al. 2008; Pahl-Wostl and Hare 2004).

Detection of changes in long time series of flood data is an important scientific issue, fundamental for planning of future water resources and disaster protection. If studies come to predict in a reliable way a significant increase in the severity of hydrological extremes in the warmer world, then the consequences for the existing procedures for designing dikes, spillways, dams and reservoirs, by-pass channels, etc., traditionally based on the assumption of stationarity of river flow, would be severe. For instance, in some areas, one would have to design and build bigger storage volumes, at higher costs, to accommodate larger flood waves. Existing infrastructure, e.g. dikes, storm sewers, may not guarantee the adequate level of protection and may need to be re-adjusted (Milly et al. 2008). Without this, systems will be over- or under-designed and will either not serve their purpose adequately, or will be overly costly. However, there are considerable technical difficulties of detecting and attributing a climate change signal in flood records and vast uncertainty in future flood projections. Hence, a question arises: adapting to what?

In general, adaptation to increasing flood risk poses a difficult challenge to integrated flood preparedness and flood management systems, which should include an optimal, site-specific, mix of structural and non-structural measures.

Flood defenses are typically designed to withstand an N-year flood, i.e. a flood discharge whose probability of exceedance in any 1 year is 1/N, where N may differ between countries and land-use classes within the range from 10 to 4,000 years. In the Netherlands, the protection level of flood defenses is probably higher than in any other country (even up to 4,000-year flood for major dikes). In most countries the principal design standard for river dikes is a 100-year flood. The return period of 50–100 years provides a plausible and acceptable measure of the flood-affected population (Hirabayashi and Kanae 2009).

The notion of 100-year floods has to be revisited in the light of ongoing, and projected, climate change. The 100-year flood for a past control period is unlikely to be of the same amplitude as the 100-year flood in a future time horizon, and this is of importance for design and operation of large water infrastructure (e.g. dikes, dams and spillways). It clearly results from Figs. 3 and 4, that, over much of Europe, what used to be a 100-year flood under current climate conditions will occur more frequently in the future. Hence, in order to maintain the same standard of protection against a 100-year flood, a need for a costly overhauling comes about.

However, due to the difficulty in isolating the greenhouse signal in the observation records and the large uncertainty of projections for the future, no precise quantitative information can be delivered. In parts of Germany (e.g. the State of Bavaria), flood design values have been increased by a safety margin, based on climate change impact scenarios. The projections for 2050 include an increase of 40–50% in small and medium flood discharges and of around 15% in 100-year floods. In the UK, the Defra's precautionary allowance includes projection of increase in peak rainfall intensity (up to 20% by 2085 and 30% by 2115) and in peak river flow volume (up to 10% by 2025 and 20% by 2085), cf. Defra (2006), to reflect the possible effects of climate change, based on early impact assessments. Measures to cope with the increase of the design discharge for the Rhine in the Netherlands from 15,000 to 16,000 m^3/s must be implemented by 2015 and it is planned to increase the design discharge to 18,000 m^3/s in the longer term due to climate change. A 'climate change factor' was introduced, which is to be taken into account in any new plans for flood control measures in The Netherlands (EEA 2007). One can expect that in those areas where 100-year floods become lower and the adequate, and properly maintained, protection systems are in place, the existing defenses will provide higher-than-standard protection level.

In response to destructive recent floods in Europe and projections of growing risk, the Floods Directive (CEC 2007) was adopted on the European Union (27 countries) level, embracing river floods, flash floods, urban floods, sewer floods and coastal floods. The Directive states that EU Member States shall, for each river basin district or the portion of an international river basin district lying within their territory, undertake:

- a preliminary flood risk assessment (a map of the river basin; description of past floods; description of flooding processes and their sensitivity to change; description of development plans; assessment of the likelihood of future floods based on hydrological data, types of floods and the projected impact of climate change and land use trends; forecast of estimated consequences of future floods);
- preparation of flood hazard maps and flood risk maps (i.e. damage maps), for areas which could be flooded with a high probability (such as 10-year flood); with a medium probability (return period of 100 years), and with a low probability (extreme events);
- preparation and implementation of flood risk management plans, aimed at achieving the required levels of protection, by 2015.

It is expected that implementation of the Directive, probably the most advanced legislation worldwide in the area of flood protection and flood preparedness, will considerably reduce the flood risk throughout the 27 EU Member States.

Preparedness for floods varies with the wealth (cf. Kundzewicz, Takeuchi 1999). In wealthy countries, when an extreme flood arrives, it is not possible to avoid high material damage, but it is possible to save lives, thanks to a well-functioning forecast-warning system. Considerable progress in reducing the number of flood fatalities can be achieved in flood risk awareness and management is improved. Many fatalities are avoidable (e.g. car drivers entering water of unknown depth).

6 Conclusions

Observations to-date provide no conclusive and general proof as to how climate change affects flood risk. Increasing trends in heavy rains (Trenberth et al. 2007) have been documented in some regions, but ubiquitous increase in flood maxima is not evident (e.g. Kundzewicz et al. 2005).

Flooding is a complex phenomenon and several generating mechanisms can be involved, such as intense and/or long-lasting precipitation, snowmelt, dike or dam break, ice jam/landslide, outburst of glacial lake. Climate-driven changes in future flood frequency are projected to be complex, depending on the generating mechanism, e.g., increasing flood magnitudes where floods result of heavy rainfall and decreasing magnitudes where floods are generated by spring snowmelt. However, global warming may not necessarily reduce snowmelt flooding everywhere, as an increase in winter precipitation is expected, and snow cover may increase in areas where the temperature is still below 0^0C. Climate change is likely to cause an increase of the risk of riverine flooding across much of Europe. In some areas, where snowmelt is the principal flood-generating mechanism, the time of greatest flood risk would shift from spring to winter. Winter (rain-caused) flood hazard is likely to rise for many catchments under many scenarios.

Flood risk and vulnerability tend to increase over many areas, due to a range of climatic and non-climatic impacts whose relative importance is site-specific. Deforestation, urbanization, and reduction of wetlands diminish the available water storage capacity and increase the runoff coefficient, leading to growth in the flow amplitude and reduction of the time-to-peak of a flood triggered by 'typical' intense precipitation (e.g. design precipitation). However, almost ubiquitously, what used to be 'typical' intense precipitation in the past is very likely to become more intense in the future, due to anthropogenic climate change. Furthermore, human encroachment into unsafe areas has increased the potential for damage. Societies become more exposed, developing flood-prone areas (maladaptation).

Due to the large uncertainty of climate projections, it is currently not possible to devise a scientifically-sound procedure for redefining design floods (e.g. 100-year flood) under strong non-stationarity of the changing climate and land use. For the time being, we recommend to adjust design floods using a "climate change factor" approach. This factor can be greater than 1 in areas with likely increase of flood hazard and less than 1 in areas with likely decrease of flood hazard. In the former case, strengthening and heightening of dikes would be needed in order to maintain the protection level. In the latter case, a fine dike, dimensioned after the old design flood would offer over-protection, without any need for strenghening and heightening effort. Due to uncertainty, flood risk reduction strategies should be reviewed on regular basis, in the light of new data and information, and—if necessary—updated.

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