15 Floods: lessons about early warning systems

Zbigniew W. Kundzewicz ([1]) ([2])

Floods are an increasingly acute problem. Intense precipitation has become more frequent and more intense, growing manmade pressure has increased the magnitude of floods that result from any level of precipitation, and flawed decisions about the location of human infrastructure have increased the flood loss potential.

Unlike most other case studies presented in this report, this chapter focuses on flooding as a phenomenon and the requirements for effective early warning systems, rather than addressing a particular event and the lessons that can be learned.

Flooding cannot be wholly prevented. The occurrence of a flood need not be considered a 'failure' and, conversely, minimisation of losses may constitute a 'success'. There are lessons to be learned from every flood and it is important to use them in preparing for the next flood. Once we accept that no flood protection measures can guarantee complete safety, a general change of paradigm is needed to reduce human vulnerability to floods. The attitude of 'living with floods' and accommodating them in planning seems more sustainable than hopelessly striving to eradicate them.

Flood forecasting and warning systems fail because links in the chain perform poorly or fail completely. A single weak point in a system that otherwise contains excellent components may render the overall system performance unsatisfactory. A successful system requires sufficient integration of components and collaboration and coordination between multiple institutions.

The chapter deals primarily with the challenges of fluvial (river) floods. It is complemented by three short supplementary texts. The first highlights the complex, dynamic and diverse ecosystems of river floodplains, which are often degraded during construction of flood defences. Despite their huge economic value, near-natural floodplains are among the most threatened ecosystems globally.

The second discusses uncertainties in anticipating rainfall patterns and intensity, and their relationship to flood levels during extreme flows. Such uncertainties present challenges for scientists and decision-makers alike.

The third addresses the increasing risks of coastal flooding due to factors such as climate change and sea-level rise, and reviews European experience with precautionary action.

([1]) The author gratefully acknowledges valuable comments from five reviewers, Keith Beven, Jim Hall, Irina Krasovskaia, Edmund Penning-Rowsell, and Bellie Sivakumar. They helped the author to improve and enrich the chapter.
([2]) The work on this chapter was carried out within the WATCH (Water and Global Change) Integrated Project of the European Union's 6th Framework Programme.

'And the rain was upon the earth forty days and forty nights … And the waters prevailed exceedingly upon the earth; and all the high hills that were under the whole heaven were covered' (Genesis 7:12, 19).

'We have first raised the dust and then complain we cannot see' (George Berkeley).

15.1 River floods and early warnings

The term 'flooding' denotes a potentially destructive abundance of water in a normally dry location. Various categories of flood exist. They include, for example, situations where intense precipitation overwhelms urban sewer and drainage systems. In contrast, groundwater flooding occurs when the water table reaches the ground surface in a location where it does not normally do so. And coastal and estuary flooding occurs when high sea levels (due to high tides, storm surges or tsunamis) cause the coastal line to recede.

This chapter addresses river (fluvial) floods, although Panel 15.3 contains information on coastal flooding. River floods occur when water inundates areas outside the river channel, where there is potential to cause damage. They can be caused by several mechanisms, such as rain (intense or long-lasting), snowmelt (possibly with rain), glacier melt, glacial lake outbursts, dam breaks (breach) and tidal surges. Unexpected flow obstructions such as landslides, ice jams, beaver dams or debris can also cause flooding upstream.

Floods differ considerably from some of the other hazards addressed in this report. Floods are intermittent events. They usually recur rarely in a given location, although they can be commonplace at some sites, for example occurring every spring when snow cover melts. This contrasts with hazards that affect the environment continuously and can impose cumulative 'pressures'.

River floods are natural phenomena, manifesting the natural spatial and temporal variability of the river water level and discharge, which can take on extremely high values from time to time. River floods, jeopardising settlements located in floodplains, have been a continued hazard for humanity and can be identified in old myths and narratives. For millennia, people have settled in river valleys to till fertile soils, benefit from flat terrain, access water supplies easily and use water for transport. Riparian people have historically lived in harmony with nature, benefiting from benign floods and the valuable services they provide to fisheries, wetlands, wildlife and agriculture.

The notion of 'early warning of floods' can be interpreted in at least two ways that are relevant to this chapter. The first refers to a short-term flood preparedness system, where a 'flood warning' is a technical term, denoting a means of reducing flood damage to people and property. In this sense, a flood warning contains specific timely information, based on a reliable forecast, that a high water level is expected at a particular location and time. It aims to ensure that emergency actions, such as strengthening dikes or evacuation, can be undertaken.

A 'flood alert', usually issued before a 'flood warning', is less specific and has the broader aim of raising vigilance. A warning should be issued sufficiently early prior to the potential inundation to allow adequate preparation. The appropriate timeframe is affected by the catchment size relative to the vulnerable zones. The warning should also be expressed in a way that persuades people to take appropriate action to reduce damage and costs of the flood.

The other interpretation of 'early warning' in the context of floods is a statement that a high water level or discharge is likely to occur more frequently in the future. Technically, this constitutes a 'prediction' of a change in flood frequency compared to a reference period, such as the 30-year climate normals 1961–1990. An early warning of this type could, for example, predict that at a site of concern the current 100-year flood (river flow exceeded once in 100 years on average) may become a 50-year flood within some defined future time horizon. Such an early warning, over a longer time scale, is (or should be) an important signal for decision-makers that the required level of protection is unlikely to be maintained in the future unless flood preparedness is improved.

Floods continue to be a problem and we clearly do not cope with them satisfactorily. In fact, they are an increasingly serious problem. Flood risk has been greatly intensified by humans, who — to use the language of mechanics — have increased the load and decreased the resistance of the system. In many places, humans have increased the flood magnitude for any level of precipitation and have amplified the flood damage potential. Severe floods cause rising material damage worldwide and continue to cause a considerable death toll. Annual global economic losses from extreme weather events, including floods, increased ten-fold between the 1950s and

Panel 15.1 Managing river flood plains as ecosystems of global strategic importance

Klement Tockner

River floodplains (including deltas) extend from the edge of permanent water bodies to the edge of uplands. Because of their unique position at the deepest location in the landscape, floodplains integrate and accumulate upstream and catchment processes.

In their natural state, floodplains are disturbance-dominated ecosystems tightly linked to fluvial and geomorphic processes, thereby creating some of the most complex, dynamic and diverse ecosystems globally — landscapes that were once comparable in diversity with tropical rain forests or coral reefs (Junk et al., 1989; Naiman et al., 2005; Tockner et al., 2002 and 2008). This diversity has, and continues to be, deeply degraded, a fact that has so far captured remarkably little attention at the policy level. Paradoxically, a good deal of this damage is done by hydrological engineering for flood defences that reduces the ecological integrity of floodplains, while other actions (in the floodplains and elsewhere in the catchments) simultaneously remove natural flood-mitigation features.

Worldwide, floodplains cover only about 2 % of the land surface (although an accurate estimation of their extent remains difficult). Nevertheless, they are calculated to provide about 25 % of all continental ecosystem services, which is more than any other continental ecosystem type (Costanza et al., 1997; Oppermann et al., 2008; Tockner et al., 2008). Major services include flood regulation, drinking water supply (including recharging groundwater) and waste treatment. Daily nitrogen removal ranges from 0.5 to 2.6 kg N per ha (although wasting nutrients is undesirable, current systems would otherwise require considerable expenditure to remove them, e.g. from drinking water). Floodplains also provide opportunities for recreation and, in areas such as the Danube Delta Biosphere Reserve, fishing. In Europe and elsewhere, benefits also include natural fertilisation, providing grazing land and firewood.

The multiple services provided by floodplains have favoured the development of civilisations along the Nile, Euphrates, Indus, Amazon, Yangtze, and Mississippi Rivers; and many indigenous human societies are well adapted to the conditions of flooding. Floodplains continue to be preferred sites for human occupation. For example, about half of the human population in Europe and Japan lives on (former) floodplains (Nakamura et al., 2006, Tockner et al., 2009). Bangladesh, the most densely populated country worldwide, is almost entirely covered by a vast deltaic floodplain (accounting for about 80 % of the country's area).

As described in the present chapter, floods are among the most costly natural disasters worldwide (see also Tockner et al., 2008). To reduce these costs, Switzerland has declared the remarkable intention (probably unique in Europe) to restore the ecological integrity of its river floodplains and their natural flood mitigation properties. This commitment was made because flood-related costs in Switzerland have been increasing since 1970, resulting in an accumulated cost of more than CHF 15 billion over the past 35 years (BUWAL and BWG, 2003). At the same time, Switzerland had the highest global expenditure per capita on traditional hydraulic engineered flood control measures (CHF 45 billion between 1970 and 2005). This was unaffordable.

In response, the Swiss government fundamentally altered its river management strategy. Future flood control measures are now required by law to be linked to a concurrent improvement of the integrity of river floodplain ecosystems. It has been estimated that about 22 000 ha of cultivated land need to be converted back to dynamic floodplains; about 11 000 km of streams and rivers need to be restored. The current restoration rate ranges between 15 and 28 km per year; and 50 000 barriers must be removed (Armin Peter, personal communication; EAWAG, 2006). At present, more than 95 % of former floodplains have been converted to industrial, agricultural, and urban areas.

Despite their huge economic value for flood mitigation and other services and benefits, near-natural floodplains are among the most threatened ecosystems globally. In Europe, North America, and Japan, more than 90 % of former floodplains are functionally extinct or have been converted into cropland and urban areas. Conserving the remaining unimpaired floodplains as strategic global resources and restoring degraded floodplains are of the highest priority for future ecosystem management. There are major limitations, however, in implementing successful conservation and restoration strategies. Today, many river floodplains have been altered to such an extent that they must be considered as novel or emerging ecosystems where a mixture of native and non-native species, assemblages lacking a joint evolutionary

Panel 15.1 Managing river flood plains as ecosystems of global strategic importance (cont.)

history, dominate. For example, up to 80 % of the benthic invertebrates collected along the Upper Danube, the Rhine or the Elbe Rivers are already of non-native origin (Sommerwerk et al., 2010).

The rapid biotic turnover observed along regulated river corridors results from a combination of species decrease, species spread, and climate-induced species distribution shifts, although the relative contribution of these three components to the total turnover rate remains largely unknown. In central Europe, 28 000 km of navigation canals and navigable rivers connect 24 countries, creating a biological 'super-catchment' covering an area of 2.45 million km^2. This dense navigation network artificially facilitates the exchange of organisms across biogeographic barriers, thereby contributing to the increasing homogenisation of the European freshwater fauna and flora.

There is an urgent need to develop a comprehensive overview of river floodplains, their environmental state and anticipated pressures. Such an overview is a prerequisite for prioritising conservation and management. Further research should focus on:

- understanding the formation and dynamics of novel, emerging ecosystems and associated biotic communities;
- quantifying the ecological and evolutionary consequences of novel communities;
- quantifying the ecosystem services provided by novel ecosystems;
- measuring and predicting the resilience of ecosystems and species assemblages along human impact gradients;
- assessing the evolutionary potential of an ecosystem, i.e. its genetic diversity and genetic connectivity, as a complementary tool in biodiversity conservation planning;
- developing and testing new indicators of biodiversity change and impacts.

One of the best documented examples of a long-term and fundamental modification of a river floodplain is the Upper Rhine valley between Basel (Switzerland) and Worms (Germany). More than 150 years ago, Tulla's regulation of the Upper Rhine was a technical masterpiece and one of the largest construction projects worldwide during the nineteenth century. The river was shortened from 345 to 273 km, 2 200 islands were removed — an area of more than 100 000 ha between Basel and Strasbourg alone — and 240 km major dikes were constructed (Blackbourn, 2006). As a consequence, the Rhine floodplain has been converted from a fishery and waterfowl paradise to a productive agricultural area. Reconstruction of the native biodiversity is difficult because a first systematic inventory of the benthic invertebrate community was compiled at the beginning of the twentieth century, decades after the end of the 'rectification' of the Upper Rhine valley (Lauterborn, 1905). The rich biodiversity that still exists in the remnant floodplain channels and riparian forests along the Upper Rhine is most likely a legacy of past hydrogeomorphic processes. At the same time, however, the reduction in natural retention areas has led to an increase in flood peaks in the downstream sections of the Rhine valley.

A lack of adequate reference conditions restricts the development of guiding images for conservation and restoration, and limits implementation of the Water Framework Directive (EU, 2000), which strongly depends on defined reference standards for assessing alterations. Even the best protected floodplains in Europe such as the Alluvial Zone National Park (Danube, A), the Odra National Park (Odra, D) or the Danube Delta Biosphere Reserve, have been irreversibly modified. Traditional conservation and restoration strategies will simply not maintain their rich biodiversity and ecosystem processes and services in a sustainable way. Adaptive management strategies must manage these floodplains actively as coupled ecological-social-technological systems for the benefit of humans and nature. Active manipulation to deliver multiple ecosystem services is also needed to create the environmental conditions for rich (albeit largely non-native) floodplain communities (Dufour and Piegay, 2009).

At the European level, it is crucial to establish synergies among the partly contradictory requirements of the Water Framework Directive, the Habitats Directive (EU, 1992) and the Floods Directive (EU, 2007). Furthermore, we urgently need a European competence network that focuses on large rivers, including their role as long-distance migration and dispersal corridors linking various biomes; as key storage and transformation areas for carbon and nutrients; as centres for evolutionary processes; and as coupled social-ecological ecosystems.

1990s in constant prices (IPCC, 2001b). Data compiled by Munich Re (Kron, 2005) indicate that the number of great flood disasters (requiring international or interregional assistance) has grown significantly in recent decades, as have the economic impacts and the insured damage.

Several recent river flood events have caused material losses exceeding USD 10 billion. The death toll has been considerable, with individual events in less developed countries causing more than 1 000 fatalities (Kundzewicz et al., 2010a). The highest material losses, in the order of USD 30 billion, were recorded in China in the 1998 floods. Destructive floods are commonplace in many developing countries, in particular in the Asian continent (especially Bangladesh, China and India) and South America, yet numerous deluges have hit virtually all parts of the world, including Europe. As reported by Barredo (2007), a rising number of flood disasters have been observed in Europe in recent years and high-impact floods are occurring more frequently. The material flood damage recorded in Europe in 2002 (above EUR 20 billion) was higher than in any previous year.

Recognising that flood damage has increased worldwide, it is interesting to understand the reasons for this growth. Several factors may be responsible, including changes in socio-economic, terrestrial and climate systems:

- **Socio-economic changes** include increasing exposure and potential damage due to population growth and economic development in flood-prone areas; land-use change (such as urbanisation and deforestation) and changing perceptions of risk.

- **Changes in terrestrial systems** include changes in hydrological systems and ecosystems, driven by land-cover change, the regulation of river flow through such measures as channel straightening and shortening, and the construction of embankments. Conditions that determine the transformation of precipitation into runoff in the river basin also change. Draining wetlands and eliminating natural vegetation, alongside expanding impermeable areas, lead to reduced water storage capacity and consequently a higher flood peak and a shorter time to peak.

- Finally, **climate changes** are important, even if they may not always be detectable in the historical record. They include increased water-holding capacity and water content of the atmosphere in a warmer climate, increases in the frequency of heavy precipitation, changes in snow cover, and changes in seasonality and in atmospheric circulation patterns.

Human encroachment into floodplains has increased exposure to floods. Encroachment may increase as people become wealthier and technology or economic imperatives help populate more flood-prone areas. Many flawed decisions have increased the flood loss potential. The assets at risk from flooding can be enormous. For instance more than 10 million people live in areas at risk of extreme floods along the Rhine and the potential damage from floods there has been estimated at EUR 165 billion (EU, 2007). In some less developed countries, the portion of the population living in flood-prone areas is very much higher. The hope of overcoming poverty drives poor people to migrate to informal settlements in endangered, flood-prone zones around mega-cities in developing countries, which have previously been left uninhabited on purpose because effective flood protection cannot be assured.

Future changes in flood risks may be complex. In many places, flood risk is likely to grow due to a combination of anthropogenic and climatic factors. Quantifying flood statistics is difficult, however, and subject to high uncertainty. As stated in IPCC (2001a), 'the analysis of extreme events in both observations and coupled models is underdeveloped'. Recent modelling studies show that plausible climate change scenarios project future increases of both amplitude and frequency of rain-caused flooding events. Yet no conclusive and ubiquitous climate change trend in the flood behaviour has been found, based on the global data on high river flows observed so far (Kundzewicz et al., 2005; Svensson et al., 2005).

Detecting climate change at global or regional scales (let alone within catchments) is inherently difficult because of the low signal-to-noise ratio. The relatively weak climate change signal (if any) is superimposed on a strong natural variability of rainfall and river discharge, which is further confounded by land-use change. Hence, Wilby et al. (2008) speculate that statistically robust trends are unlikely to be apparent for several decades.

Although land use management and land cover change have an important effect on flood risk, it is less significant in the case of very high-intensity rainfall, which causes high flood runoff in both urban and forested basins.

There is always potential for floods that are higher than those recorded in the past, even under stationary conditions — i.e. without climate change. This is simply a sampling effect and its significance depends on the length of the historic record; as records get longer, the probability of record high precipitation occurring in an area with high damage potential increases. Flood defences are typically designed to withstand an event with a return period of 100 years, perhaps with some additional safety margin. However, the discharge for this return period is generally estimated from records gathered over an inadequately short interval and is therefore uncertain.

The highest point precipitation amounts ever recorded for different time intervals are 1 340 mm in 12 hours, 1 825 mm in one day and 3 847 mm in eight days (WMO, 1986). If precipitation of a similar scale occurred over (or directly upstream from) a large city, the result could be expected to be utter destruction.

It is important not to forget that, in addition to negative effects, floods can generate benefits. For example, the fertile Nile floods were crucial to the development of ancient Egypt. In some areas, floods are an important means of recharging groundwater aquifers. Floods may strengthen community solidarity and can enhance economic activity (related to flood preparedness and recovery). Any benefits that could be lost also need to be taken into account when considering flood prevention measures and options.

15.2 Flood forecasting and warning

Flood alerts, forecasts, warnings and responses are very important components of modern flood preparedness systems. They fall into the category of non-structural flood protection measures, which can save lives and reduce material losses and human suffering. An effective system should embrace detection of the risk of a flood-triggering situation, quantitative flood forecasting (with adequate lead time), development of a reliable warning message, issuing and disseminating the warning to communities at risk, adequate actions by communities to reduce losses and, finally, post-hoc audits to learn lessons and improve the system for the future.

Flood warning has existed for thousands of years. The Old Testament mentions the oldest 'early warning', received by Noah from God; archaeologists have revealed other, even earlier, accounts of a similar story. For centuries, floods were believed to be a divine punishment for the sins of mankind. In 1523, a forecast anticipating a flood in February 1524 was published in Augsburg, based on a quasi-scientific speculation: a peculiar conjunction of planets in the constellation Pisces. The forecast turned out to be false (Brázdil et al., 2005).

15.2.1 Flood forecasts

A flood forecast should ideally deliver reliable and accurate information on the future development of an event, enabling an alert and warning to be issued. A forecast expresses when a flood is expected to occur (ranging from minutes to days or even weeks ahead), its location and its intensity. Flood magnitude is determined by the stage, discharge, inundated area and duration of flooding. A forecast also conveys how a flood will travel downstream and evolve and what secondary effects it may cause.

In order to detect the risk of a flood-triggering situation occurring, a meteorological and hydrological monitoring system should be in place. Forecasting, based on mathematical modelling, allows experts to convert the information on rainfall, hydrological status of soil moisture and snow cover into a forecast of river discharge, water level and inundated area for a future time horizon.

For small or urban catchments and for flash floods in steep and rapid mountain streams, the time lag between an intense precipitation and the resulting river flood peak is very short (minutes to hours). In these circumstances, observations of rising river water levels may come too late for a useful flood forecast. Weather radar data (which brings its own issues) or quantitative precipitation forecasts are therefore required to estimate future river flows with sufficient lead time to provide a useful warning.

At the other extreme, the formation of a flood wave in a large river may take several weeks, allowing ample time for response to a flood forecast. A hydrodynamic flood-routing model can be used, allowing visualisation (via GIS) of the forthcoming inundation in downstream cross-sections of the river. Many activities are under way to improve forecast accuracy and to extend the forecast lead time. In this context, two important factors are data assimilation and adaptive forecasting, which makes use of current measurements to reduce forecast errors (Young, 2002).

15.2.2 Flood warnings

Flood warnings should contain more information than flood forecasts. This includes recommendations or orders for affected populations to take actions, such as evacuation or emergency flood-proofing, specifically designed to safeguard life and property (Smith and Ward, 1998). According to Nigg (1995), warning systems must fulfil two basic functions:

- assessment (from the moment that a specific hazard is detected to the point when a risk message is developed for the threatened locality);
- dissemination (issuing and transmitting the warning message to a target audience).

A warning, converting scientific forecasts into lay language, is a communication that a hazard will produce specific risks for a specific population (Nigg, 1995). Affected communities should not just be told about the hazard but also informed in such a way that they are persuaded to take specific remedial action in time. Such warnings should be 'populist' in tone and communication but their design is actually a skilled task requiring careful forethought and design.

There is an important difference between flood alerts and flood warnings. The latter have much shorter lead times that must be accurate to maintain public confidence. In Vaison-la-Romaine in 1992, Meteo-France issued two (accurate) flood alerts based on heavy rainfall predictions 12 and 24 hours ahead but because the local authorities did not know which catchment would be affected no warning was issued and many people died. The European Flood Alert System (EFAS) at the European Commission's Joint Research Centre (JRC) now produces flood alerts for the whole of Europe (JRC, 2011).

It is often noted that forecasts have advanced markedly, while progress in warnings has lagged behind despite recent advances in some countries, such as automatic telephone and text-messaging services and the provision of detailed forecasting services on the internet.

Nigg (1995) argues that to formulate warning messages:

- the basis of the warning must be credible;
- the warning message must explain the degree to which a specific area is at risk;
- people must be told what they can do to reduce their exposure to danger.

Speed of reaction to warnings is essential because there may be a short time to implement emergency pre-flood actions, such as strengthening or deploying

Photo: © istockphoto/Mitja Mladkovic defences and evacuation, before the risk becomes high. Other useful criteria or indicators of warning quality are the penetration of the warning (the proportion of those who need information that receive it) and degree of satisfaction.

15.2.3 Flood warning errors

Two types of warning errors occur:

- first, when a warning is issued but the risk does not materialise;
- second, when no warning is issued but a risk and the ensuing disaster occur.

The first does not include situations where the risk has materialised but the disaster has not. For instance, flood warning in the Netherlands in January 1995 resulted in massive evacuation. A disaster did not arrive, as the levees withstood the high water load but the warning and the evacuation were justified and perceived by the population as the right decision. The risk of dike failure was high. Similarly, during the summer 1997 flood on the Odra (see Box 15.1), the Polish town Słubice was evacuated due to high risk of inundation. As a result of major dike-strengthening action, however, and dike breaches upstream in Germany, which reduced the load, Słubice was not inundated.

As noted by Nigg (1995), officials often hesitate to issue warnings due to fear of error, especially when warning systems are just developing or when there is still a great deal of uncertainty about the occurrence of the future event.

15.2.4 Credibility and efficiency of flood warnings

The more personal the manner in which a message is delivered, the greater its credibility. In principle, person-specific warnings may trigger more urgent responses than communication directed at the general public. There can be challenges, however, in establishing more focused communication mechanisms. In the United Kingdom people in flood risk zones can sign up to receive warnings by telephone, text message or email but the take-up has not been high. This is partly because many people do not want to recognise that they are in a flood risk zone because of a fear of reduced house prices or the inability to acquire insurance.

Factors influencing the efficiency of message dissemination include the credibility of the source (which may vary according to the recipient of the message); the accessibility of the chosen communication channel; the usefulness or redundancy of the information; and the communication of a system's resistance to floods. Essentially, the information should be conveyed in wording that the public can understand and empathise with and via channels that the public finds credible.

15.2.5 Long-term early warnings

In addition to short-term (real-time) warnings related to a specific, forthcoming flood event, recent work has also emphasised the need to issue another type of early warning if the projections (predictions) of flood hazards in the more distant future indicate considerable changes in the anticipated risk (Hall et al., 2003, 2005; Hirabayashi et al., 2008; Dankers and Feyen, 2008; Kundzewicz et al., 2010a, 2010b). Early warnings of increasing flood risk in the decades ahead are necessary to upgrade defence strategies, for example by undertaking the time-consuming and resource-intensive task of strengthening levees.

Climatic and non-climatic factors affect future flood risk and adaptation needs. For example, land-cover changes and urbanisation can increase flood risk regardless of any change in climate. Observations and climate projections show widespread increases in the contribution of very wet days to total annual precipitation in the warming atmosphere (Trenberth et al., 2007). Increasing flood magnitudes are projected in areas where floods result from heavy rainfall; decreasing flood magnitudes are anticipated where they result from spring snowmelt. Winter (rain-caused) flood hazard is likely to rise for many catchments under several climate scenarios. However, global warming may not necessarily reduce snowmelt flooding everywhere. Since an increase in winter precipitation is expected, snow cover may actually increase in cold areas where the temperature remains below 0 °C.

Floods corresponding to a 100-year return in the control period may become more or less frequent in the future climate. Where they increase, upgraded flood prevention measures will be needed to ensure the required protection level. Projections by Hirabayashi et al. (2008) and by Dankers and Feyen (2008) indicate that in much of Poland, France, the United Kingdom, southern Sweden and northern Italy, today's 100-year floods will occur more frequently in 2071–2100. They are projected to occur less frequently over most of Finland and the European part of the Russian Federation. These two studies show that, in aggregate terms, the control 100-year flood is projected to become more frequent over more than 40 % of Europe, and that over 30 % of Europe the mean recurrence interval of such floods is projected to decrease from 100 years to below 50 years by 2071–2100 (Kundzewicz et al., 2010b).

Systems continue to be designed and operated assuming stationarity (the past is the key to the future). Since this assumption is clearly incorrect due to both non-climatic and climatic changes (Milly et al., 2008), existing design procedures need to be revised, accounting for land-cover change, climate change and other changes of relevance. Otherwise, systems will be under- or over-designed and either not serve their purpose adequately or be overly costly (with excessive safety margins).

Difficulties in isolating the greenhouse signal in river flow observation records, coupled with the large uncertainty in projections of future precipitation and related variables, mean that no precise quantitative information can be delivered for long-term flood preparedness planning. Nevertheless, water managers in some countries, including Germany, the Netherlands and the United Kingdom, have begun to take account of these early climate change warnings explicitly in flood protection design codes.

In Bavaria, for example, flood design values now take into account projections of a 40–50 % increase in small and medium flood discharges by 2050, and an increase of around 15 % in 100-year floods. In the United Kingdom, the precautionary allowance of the Department for Environment, Food and Rural Affairs (Defra, 2006) includes projections of increased peak river flow volumes (10 % up to 2025 and 20 % after 2085), to reflect the possible effects of climate change, based on early impact assessments. A 'climate change factor' is to be reflected in any new plans for flood control measures in the Netherlands. Measures are planned to manage the Rhine's increased discharge in the Netherlands resulting from climate change. By 2015, the measures implemented should increase the design discharge from 15 000 to 16 000 m^3/s and this should increase further to 18 000 m^3/s in the longer term (Kundzewicz et al., 2007).

15.3 Flood preparedness systems — the science and its use

Complete flood safety is impossible in low-lying areas adjacent to rivers. Flood risk can be considerably restricted, however, if an adequate preparedness system is built, consisting of a site-specific mix of measures. Flood-related research, financed by regional, national and international funding institutions, administrative authorities, water agencies, and the insurance and reinsurance industry, is indispensable to optimise preparedness systems.

In Europe, important research initiatives have been undertaken at the international and national levels. A prominent example of integrated international action is the interdisciplinary FLOODsite project (Klijn, 2009) within the Sixth Framework Programme of the European Union. FLOODsite developed integrated flood risk analysis and management methods, covering the physical, environmental and socio-economic aspects of floods from rivers, estuaries and the sea. It integrated different scientific disciplines, spatial planning and management and considered flood risk as a combination of hazard sources, pathways and consequences for people, property and the environment.

The EU Floods Directive (EU, 2007; Box 15.2) explicitly refers to FLOODsite as the largest ever EU flood research project. The FLOODsite project dealt with detection and forecasting of hydro-meteorological conditions and timely warning of the relevant authorities and the public. The research aimed to enhance the performance and shorten the lead time of flash-flood forecasting by linking rainfall-runoff models to real-time remotely sensed (radar and satellite) data. A system for detecting and estimating extreme storm rainfall was developed and tested and the uncertainty of the radar rainfall estimates was assessed.

15.3.1 Protect, adapt, retreat

An example of national flood-related research initiatives is the UK's Foresight Project (Evans et al., 2004; Hall et al., 2005), dealing with flood and coastal defence. The project's aim was to forecast changes in flood risks in the United Kingdom over the next 100 years and to identify the best options for responding to future challenges. The key finding was that if existing policies are continued the flood risks in 2080 could increase substantially. Projected changes range from little increases above current expected annual damage in an optimistic scenario to a 20-fold increase under another scenario. The projections suggest that it will be necessary to choose between investing more in sustainable approaches to flood management or learning to live with increased flooding. An integrated portfolio of responses can reduce future risk by an order of magnitude, although the relative effectiveness of response measures depends very much on the scenario considered.

The current strategy for flood preparedness in Europe can be summarised as 'protect as far as technically possible and affordable' and otherwise 'adapt and accommodate'. This has also been expressed as 'living with floods' (Germany, Netherlands) and 'making space for water' (Netherlands, the United Kingdom). If a necessary level of protection cannot be achieved and accommodation (living with floods) is not possible, then another option is retreat.

Decisions have to be made about how to design protection systems and how to control the damage potential, for example by enforcing zoning, banning floodplain development and moving out of the harm's way. Flood protection measures may either modify flood waters or modify the system susceptibility. They depend on the rate of recurrence of floods: natural measures (such as enhancing wetlands and floodplains) are appropriate for frequent floods; engineering measures are suitable for rare floods; residual risk management is essential for very rare floods (Kron, 2005). This latter category contains extreme but possible floods, and those beyond the limits of past experience.

15.3.2 *Structural and non-structural flood protection measures*

A range of flood protection and management measures exist, falling into structural ('hard') or non-structural ('soft') approaches. The former refer to large-scale defences, such as dikes, dams and flood control reservoirs, diversions and floodways, and improving drainage channel capacity. Structural defences have a very long tradition, with dams and dikes having been built for millennia. Constructing reservoirs where excess water can be stored allows a regulated temporal distribution of streamflow, reducing the natural peak flow.

The physical dimensions of structural flood protection measures, such as levees, are based on probability theory to withstand a predicted 'design flood' of a certain magnitude, e.g. a 100-year flood (although this is difficult to determine in practice), in a given location. The longer the assumed return period of the design flood, the better the level of protection and the greater the costs. This raises various value judgements, such as whether to design dikes to withstand a 100-year flood or perhaps a 1 000-year flood. The latter solution would give better protection but be far more costly. Moreover, it is misleading to expect complete flood protection or total certainty of outcomes.

Dikes protect well against small- and medium-size floods but when a deluge is of disastrous size and dikes break, losses in a levee-protected landscape can be higher than in the absence of a levee due to the false feeling of security that levees can generate among the riparian population and the high damage potential in apparently (but not completely) safe areas. No matter how high a design flood is, there is always a possibility of a greater flood occurring, inducing losses. A dike designed for a 100-year flood is likely to fail if a 1 000-year flood occurs.

In the United Kingdom, the 2005 Carlisle flood occurred when the plans for the new Carlisle flood defences were out for public consultation. The planned defences would have met the UK standard of the 100-year return period and if built they would have been breached because the 2005 event had a return period in excess of 150 years. After the event, the defences were therefore redesigned to address a 200-year return period.

Several developed countries have costly structural protection facilities to withstand a high, rare flood. Reinforced dikes or super-dikes of 300–500 meters width play an important part in flood protection of major cities in Japan, where a very high level of safety must be assured (Kundzewicz and Takeuchi, 1999). Even higher protection levels are achieved in the low-lying Netherlands. The Flood Defence Act of 1996 set high safety standards with the return period of design flood set at 1 250 years for middle to upper rivers in the Netherlands and 2 000 years for lower river reaches (Pilarczyk, 2007).

'Soft' non-structural flood protection measures include source control (watershed management), laws and regulations, zoning, economic instruments, efficient flood forecast warning systems, flood risk assessment systems, awareness-raising information and flood-related databases. Source control modifies the formation of floodwater by catching water where it falls, enhancing infiltration, reducing impermeable areas and increasing storage in the watershed. These measures counteract the adverse effects of urbanisation, such as reduced storage potential, growth in the runoff coefficient and flood peak, and acceleration of a flood wave. Restoring, retaining or enhancing water storage capacity in the river system (floodplains, polders and washlands) is also important.

Appropriate schemes of insurance, which distribute risks and losses over many people and over a longer time, coupled with aid that can compensate

Panel 15.2 Uncertainty in predicting floods (and other environmental variables)

Keith Beven

In its report on the causes of the Mississippi floods in 1993, the US Interagency Floodplain Management Review Committee's major conclusion was that the rainfalls were 'without precedent' (Galloway, 1995). Similarly, in the United Kingdom the Pitt Report described the summer 2007 rainfalls and floods as 'exceptional' and noted widespread demand for better warnings to provide the public more time to prepare and protect their property (Pitt, 2007).

The demand for better warnings appears to pose a relatively simple problem for hydrological science. With some knowledge of the pattern of heavy rainfalls, it should be possible to predict river flows and, during extremes, the likely extent of flooding. Of course, there are also organisational and social problems in conveying flood warnings to the public but here we will concentrate on the scientific problem. It is an example of the type of predictions about environmental variables that are increasingly demanded and extend all the way up to predictions about the future climate based on global atmosphere and ocean circulation models.

In fact, many of these apparently simple science problems turn out to be complex and fraught with uncertainties that are difficult to evaluate. In the case of floods, measurement technique limitations mean that there is uncertainty about the pattern and intensity of rainfall and the relationship between discharge and flood levels during extreme flows. There is uncertainty about how much rainfall will reach a river and when — in part because there is a highly non-linear relationship between the wetness of a catchment before an event and runoff generation processes. Many major floods (examples from the United Kingdom include the summer 2007 floods, the Lynmouth flood in 1952, the Boscastle flood in 2004, the Carlisle flood in 2005 and the Cumbria floods in 2009) were preceded by prior wetting, which increased subsequent runoff. Hydrological models can simulate and predict runoff generation but they can only approximate, thereby introducing further uncertainty.

There are also important modelling uncertainties in predicting the frequency with which a flood of a given magnitude will occur, how that might change in the future as a result of climate variability or change, and the impacts of land management changes on runoff generation. It is therefore unsurprising that uncertainty estimation has been an important research topic in hydrological modelling in the last two decades. This has included analysis of how the nature and magnitude of predictive uncertainties should be communicated to decision-makers and stakeholders (e.g. Faulkner et al., 2007; Beven, 2009).

This research has determined that there is still significant debate about how the effects of relevant uncertainties should be estimated, with the literature revealing a range of strongly held opinions and some interesting debates. The failure to reach more general consensus over this period may appear surprising but there are some fundamental issues involved, which apply much more generally in environmental modelling (see Beven, 2002, 2006a and 2006b).

Disagreement centres on the types of uncertainties involved. Aleatory uncertainties, arising from natural variability, can be distinguished from epistemic uncertainties, which result from the limitations of our knowledge about the system under study. Inherent unpredictability of nature and unrecognised uncertainties ('unknown unknowns') may also influence the errors in model predictions but cannot be treated explicitly because, by definition, they are not accessible for analysis (Sivakumar, 2008).

It is commonly assumed that most sources of uncertainty can be treated as aleatory, which is advantageous because such uncertainties can be treated in terms of probabilities and the full panoply of statistical theory can be used in analysis and prediction. Beven (2006b) argues, however, that this only applies in 'ideal cases'. Most of the uncertainties involved in hydrological and other environmental models have an epistemic as well as an aleatory component. Treating the sources of uncertainty as if they were aleatory in non-ideal cases will produce over-confidence in the model predictions because of the time-variable nature of epistemic uncertainties.

There is no general theory of how to handle epistemic uncertainties and some debate has focused on whether it is always appropriate to estimate uncertainties based on probabilities. Other frameworks, such as the possibilities of fuzzy set theory, allow more flexibility but introduce more subjectivity into the

Panel 15.2 Uncertainty in predicting floods (and other environmental variables) (cont.)

associated assumptions. Probability theory has the attraction of being logically consistent and objective — but if and only if the assumptions about the nature of the errors can be shown to be consistently valid and this is rarely the case. Even in models it can be shown that small departures from the ideal can lead to overconfidence in predictions (e.g. Beven et al., 2008).

In real applications, most sources of uncertainty have both aleatory and epistemic components, but it will often be the epistemic component that dominates. In predicting floods, rain gauges, radar and numerical weather prediction can be used to measure or forecast rainfall over a catchment area and provide inputs to hydrological models of runoff generation. All will be subject to epistemic errors. Numerical weather prediction is useful for identifying potential flood events but does not (yet) give generally reliable rainfall forecasts. Such forecasts are essential for flood warning, especially for flash floods in small basins with short response times, since there is no other way to provide warnings to the public with sufficient lead time. They will, however, be uncertain and not just in aleatory ways.

In larger basins, measurements of rainfall will be sufficient as an input to warning models. However, a rain gauge network may not always provide a good estimate of that input, particularly for localised convective cells or orographic effects, because the spatial pattern of the gauges may not properly represent the spatial pattern of the rainfall. Radar gives relatively good spatial coverage but does not measure rainfall directly and there may be epistemic uncertainties in the corrections and reflectivity-rainfall intensity relationship used, which will vary from event to event.

Similar arguments apply to other types of uncertainties in flood forecasting and frequency estimation.

There is no question that it is better to estimate some form of uncertainty for these predictions than to ignore the uncertainties. But this creates certain challenges. For the scientist, the problem is how best to deal with epistemic uncertainties. For the decision-maker, who depends on model predictions, the problem is how to understand and interpret the uncertainty estimates associated with a prediction — and under what circumstances not to rely on model predictions when making a decision.

Flood forecasting poses additional difficulties. One is the issue of conveying the meaning of flood warnings when the uncertainties in the forecasting process might result in one or a succession of false alarms. Furthermore, as Kundzewicz notes in the present chapter, there is also a need to explain to the public (and even to some decision-makers) that there is a finite possibility that even a new flood defence scheme may be breached by the next flood event (or, as in Carlisle in January 2005, before the new design has been built).

Estimating uncertainty associated with these types of predictions can have important consequences if it alters the resulting decision. Understanding such estimates is easier for users with a clear theoretical foundation in probability (Hall et al., 2007; Todini and Mantovan, 2007; Montanari, 2007) but, as already noted, estimates can be misleading if they lead to overconfidence in the outcomes.

Essentially, science lacks a theory of the true information content of data that is subject to epistemic uncertainties (Beven, 2008). That will take time to develop but in the meantime there are some practical ways of proceeding. One is to involve potential users of model predictions earlier in the prediction process so that decisions can be taken about how to evaluate model performance and handle different sources of uncertainty. The Environment Agency of England and Wales is starting to implement this approach within the framework of 'guidelines for good practice' for incorporating risk and uncertainty into different areas of flood risk management.

This type of stakeholder involvement in the prediction process has been advocated for some time (e.g. Stirling, 1999; EEA, 2001). The guidelines concept provides a framework for agreeing on reasonable assumptions about both aleatory and epistemic uncertainties. It should provide a good basis for assessing the value of different types of model prediction in the decision-making process.

for uninsurable losses, are additional important components of flood preparedness. Flood-risk maps developed for the insurance industry are used to help estimate insurance premiums for properties in the United Kingdom. Post-flood disaster aid, based on voluntary solidarity contributions, national assistance and international help, is essential to restore the livelihoods of survivors.

Despite some encouraging examples, such as in the US after the 1993 flood, the permanent evacuation of floodplains is virtually unthinkable in most countries. This is definitely true for Bangladesh, a densely populated and low-lying country, which ranks as the most flood-prone country on earth. The people of Bangladesh, growing rapidly in number, have to live with regular floods. Most of the country is made up of floodplains and soil fertility depends on regular flood inundation. In 1998, more than two thirds of the country were inundated. New flood embankments, even if affordable, would occupy scarce and highly demanded land. Thus, the options include reinforcing the existing structural defences and enhancing and optimising non-structural measures, including the forecast-warning system. As this example makes clear, optimum strategies for flood protection must be site-specific.

15.3.3 Uncertainty in flood risk assessment

Notwithstanding major research efforts, there is much uncertainty in the hydrological studies that underpin flood risk assessment and management (e.g. in determining a 100-year flood). Various studies (e.g. Beven, 2006a; Hall et al., 2007; Sivakumar, 2008) have judged the uncertainty analysis in hydrological studies to be highly unsatisfactory. Although disagreeing in significant respects, all called for the promotion of uncertainty analysis of measurements and modelled results in hydrological studies; uncertainty analysis should not be an add-on element — an afterthought of little importance. This is easier said than done, however, as there is considerable uncertainty regarding uncertainty estimation.

A good start would be greater rigour and consistency in analysing and reporting uncertainties. One weakness arises from the deficiencies of hydrological models and available observation records for model validation. There is an overwhelming scarcity of homogeneous long-term observation records. The inherent uncertainty in analysing any set of flood flows also stems from the fact that directly measuring the range of extreme flows can be challenging because, for example, rating curves are not available for the high flow range, gauges are destroyed by flood waves or observers are evacuated. Recourse to indirect determination is therefore necessary (Kundzewicz et al., 2010b).

Uncertainty in future projections of river flooding is very high (see Kundzewicz et al., 2010b), and grows the further we look into the future. In the near-term (e.g. the 2020s), climate model uncertainties play the dominant role, while over longer time horizons uncertainties due to greenhouse gas 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 finer scale of a drainage basin. Scale mismatch renders downscaling (disaggregation) necessary. In fact, much more refined data are necessary for the 'point' scale of a locality (e.g. a small riparian town), which is the level at which costly adaptation is undertaken.

15.4 Lessons from floods

Flooding cannot be totally prevented. The occurrence of a flood need not be considered a 'failure' and, conversely, minimisation of losses may constitute a 'success'. The first lesson is that there are always lessons to be learned, from every flood. An example of lessons learned from a single, destructive, flood on the Odra in 1997 is presented in Box 15.1.

Learning a lesson means building awareness and understanding of the reasons for a system's failure or inadequate performance, and identifying weak points using an holistic perspective. Flood forecasting and warning systems fail because links in the chain perform poorly or not at all. The observation system may fail, the forecast may be grossly in error, the warning message may be wrong, the communication of a warning may be deficient and the response may be inadequate. A single weak point in a system, which otherwise contains many excellent components, may render the overall system performance unsatisfactory.

The components in flood forecasting and warning systems must be adequately integrated but responsibility for them may reside with different agencies. This necessitates adequate collaboration and coordination between multiple institutions, which can be challenging. In emergency situations, it may become evident that distribution of roles of

Box 15.1 Lessons learned from the 1997 Odra flood

The dramatic Odra flood in July 1997 occurred after a long flood-free period and revealed the weaknesses of the existing flood preparedness system in Poland, in particular the deficiencies of relevant legislation (Kundzewicz et al., 1999).

The flood occurred during a period of legal transition, as the previous regime's laws were essentially abandoned and many new acts were passed during a short time. The distribution of responsibilities was ambiguous and conflictual, with complicated links between different participants in flood defence activities. The law at the time provided that low-level authorities were not entitled to announce a flood alert or the alarm status. Such decisions had to be issued by the provincial anti-flood committees and were delayed as a result. Local authorities typically resorted to common-sense decisions, without waiting for instructions from above.

The information flow was similarly deficient. Hydrometeorological stations reported to the regional branches of the hydrometeorological service, although also making information available, on request, to local authorities. Some forecasts proved to be of low accuracy.

Responsibilities and cost coverage for the army, police and fire brigades were also not clearly defined. Polish civil defence was geared to act in the event of a war, rather than to deal with a peacetime emergency. In addition, telecommunication support proved vulnerable as some 189 000 telecommunication links were disconnected. Mobile phones provided more reliable communication, but network limitations were also revealed.

Advance warning on the Odra was available for the medium and lower course when the flood occurred in headwaters in Czech Republic and Poland. In principle, the State of Brandenburg in Germany had ten days before the arrival of the floodwater. Even so, detailed forecasts were difficult to obtain due to problems such as the interruption of observations in several gauges and flooding of the flood information office in Wrocław.

Consequently, the need for numerous improvements was recognised, such as building the network of weather radars; automating observations and data transmission; technical upgrading of flood warning centres, including telecommunication facilities (enabling phone, radio and fax to work without mains electricity supply); upgrading and modernising the warning system; enhanced regional, interregional and international flows of flood-related information; and building more suitable forecast models.

Considerable investments were made to improve many of these systems. The nation and the relevant services learned a lesson. When a second flood wave occurred in July 1997 the preparedness and flood management were far better than during the first crest when the nation had largely been taken by surprise.

agencies is unclear and possibly redundant. The institutional framework is a key socio-economic determinant of a nation's vulnerability against natural disasters (Raschky, 2008).

People's experience of flooding may reduce damage in the next flood. Where large floods occur in the same location twice in a short time period (e.g. on the Rhine in Cologne in December 1993 and January 1995), losses during the second flood are typically far lower than those during the first (Munich Re, 1997; Kundzewicz and Takeuchi, 1999). The first flood will provide lessons for diverse groups: riparian homeowners; farmers with fields on the floodplain; professionals in the affected water district; legislators; spatial planning (zoning) officers; and public administrators at the country, province, town and community levels.

Although flood events and human failures provide valuable lessons, memories can fade quickly after a flood. Typically, a destructive flood generates enthusiasm for strengthening flood preparedness systems and heavy expenditure follows. Following a deluge, the relevant authorities elaborate ambitious plans and launch works but lessons are soon forgotten. After some time without flooding, willingness to pay for flood preparedness decreases sharply and projects are downscaled or suspended. When the next deluge comes, it acts as a reminder and starts a new cycle. This vicious turn of events, known as the 'hydro-illogical cycle' (a concept introduced in the drought context by Donald Wilhite in the mid-1980s) is a general principle, valid across different political and economic systems. The return period of a destructive flood is usually much greater than the political horizon of decision-makers and the electorate, which is determined by terms of office and electoral cycles. Of course, the hydro-illogical cycle is also at odds with the precautionary principle.

In some countries, codifying preparedness in legislation helps overcome the hydro-illogical cycle. A prominent example is the European Union's Floods Directive (Box 15.2).

Interestingly, an important turning point in the development of flood protection strategy can be traced back to the mid-19th century in the US (Williams, 1994) when Congress looked into the problem of the Mississippi floods. The two options considered were:

- using large areas of the Mississippi floodplains as flood storage and overflow areas;
- attempting to control floods by embanking the River Mississippi in a single channel isolated from its floodplain.

Congress selected the latter option and the decision has remained influential on flood protection policy in the US and elsewhere, leading to the transformation of rivers and reduction of wetlands worldwide. In 1936, the US Federal Government assumed primary responsibility for flood damage reduction across the nation and, over the next half a century, embarked on a multibillion dollar programme of structural defences (Galloway, 1999).

Another paradigm shift resulted from the great 1993 US mid-west flood, which proved that structural 'hard' defences cannot guarantee absolute protection. As a result, the US Interagency Floodplain Management Review Committee recommended that the administration should fund acquisition of land and structures at risk from willing sellers in the floodplains, and many vulnerable families have been relocated from risky areas (Galloway, 1999). However, this response is not universal. In most countries, people who suffer in a

Box 15.2 EU Floods Directive

Between 1998 and 2004, Europe suffered over 100 major destructive floods, including the record-breaking August 2002 flood on the Danube, the Elbe and their tributaries. In response to these floods and projections of growing flood risks in Europe, in April 2007 the European Union adopted Directive 2007/60/EC on the assessment and management of flood risks (EU, 2007), commonly known as the Floods Directive. The directive embraces river floods, flash floods, urban floods, sewer floods and coastal floods; its objective is to reduce and manage the risks of floods to human health, the environment, infrastructure and property. It provides that EU Member States shall undertake, for each river basin or other management unit:

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

Noting the diversity across the EU, the Floods Directive affords Member States flexibility to determine the level of protection required, the measures needed to achieve that level of protection (taking into account the work already done at national and local levels) and the timetables for implementing flood risk management plans.

The directive is probably the most advanced flood protection and preparedness legislation worldwide and implementation should considerably reduce flood risk throughout the 27 EU Member States. Mandatory activities, including assessing, mapping and managing flood risk in the river districts are expected to result in an unprecedented multinational upgrading of preparedness systems. The directive foresees that 'the potential future damage to be expected if no action is taken distinctly outweighs the costs' of implementation.

flood rebuild their houses (possibly more robustly) and their livelihoods in the place devastated by the flood, rather than moving elsewhere. The hazard may not have decreased, however, and floods could recur in that location.

People also take lessons from the failures of past policies. For example, some flood protection infrastructure has been criticised from a sustainable development perspective because it limits options for future generations and introduces disturbances in ecosystems. According to the Environment Agency of England and Wales (1998), sustainable flood defence schemes should protect the present generation from destructive floods but also 'avoid as far as possible committing future generations to inappropriate options for defence'. Renaturalising rivers and flood plains and reconstructing wetlands have been discussed for many years and is now actually likely to come about. Similarly, some large reservoirs, whose construction required the inundation of large areas or the displacement of many people, certainly did not match the principles of sustainable development (Kundzewicz, 1999). Studies on decommissioning reservoirs are now under way and in some cases decommissioning has already taken place, for example in France (Kernansquillec, Maisons-Rouges and St Etienne du Vigan).

Looking back at past developments often reveals that major decisions, such as regarding the construction of a large dam, are based on one-sided arguments with important aspects neglected. This bias can result from a lack of knowledge and understanding at the time that the decision was taken, as well as the evolution of value judgements over time.

15.5 Conclusions: living with floods

Floods are natural events that cannot be avoided. We should protect ourselves against floods up to an agreed safety level, this being a compromise between the desired level of safety and the accepted willingness to pay for protection. Once we accept that no flood protection measures can guarantee complete safety, a general change of paradigm is needed to reduce human vulnerability to floods. The attitude of 'living with floods' and accommodating them in planning seems more sustainable than hopelessly striving to eradicate them (Kundzewicz and Takeuchi, 1999). There must be action plans for events exceeding the design flood (i.e. when defences are bound to fail) and in this context early warning can save lives.

Misconceptions and myths about floods and flood protection are deeply rooted in society — among the general public, politicians and decision-makers. Some people naively believe that floods occur at large and regular time intervals — that terms such as 'return period' and 'recurrence interval' can be taken literally (rather than understood as averages) — and that embankments offer perfect safety.

Each tick of the clock marks the passage of time since the last flood and the countdown to the next. It is therefore important to prepare using a variety of different means, notably:

- rigorous implementation of zoning — using regulations to develop flood hazard areas and leaving floodplains with low-value infrastructure;
- strengthening existing defences;
- building or enhancing flood mitigation monitoring systems;
- forecasting;
- issuing and disseminating warnings;
- evacuation;
- relief and post-flood recovery;
- flood insurance;
- capacity-building (improving flood awareness, understanding and preparedness);
- enhancing a participatory approach, including consultation on the preparedness strategy and the level of flood protection, and household-level flood-proofing and mitigation measurements for both newly built and existing properties.

Only informed stakeholders can make rational decisions and agree on an acceptable flood protection strategy, being aware of both costs and benefits. There may be conflicting interests between those living in floodplains and demanding efficient and very costly protection, and the rest of the nation.

Efficient actions aimed at awareness-raising can reduce flood losses. Many past fatalities could have been avoided with greater awareness. In some developed countries such as the US, most flood fatalities involve vehicles whose drivers underestimate the danger.

Panel 15.3 Dealing with the risk of coastal flooding — experiences from European countries

Pier Vellinga and Jeroen Aerts

Coastal storm surges and floods are the most frequent and costly extreme weather events occurring in Europe, representing 69 % of the overall natural catastrophic losses (CEA, 2007). In 2010, for example, France was the European country hit hardest by the winter storm Xynthia, with 51 casualties and damages of more than EUR 1.5 billion. Many of the country's sea walls, including those around the Isle de Re off the country's west coast, were damaged or washed away (AIR, 2010).

Other low-lying coastal regions in Europe have endured similar experiences. In 1953 the winter storm that hit coastal stretches around the North Sea, especially in the United Kingdom and the Netherlands, killed more than 2 000 people. Areas around Hamburg and Bremen and parts of the Baltic coast are frequently hit by coastal storm surges. And although the shores of the Mediterranean and the Black Sea are generally steep, the river deltas of the Rhone, the Po, the Danube and many other smaller deltas experience floods from time to time. The 'Aqua Alta' in Venice Lagoon is a well known phenomenon.

The risk from coastal flooding is expected to increase in the future. First, climate change and sea-level rise is expected to increase the frequency and severity of flood events. Sea levels on average have already risen by about 10 cm per century over the last two to three centuries and are expected to rise at even higher rates in coming centuries (IPCC, 2007). This trend is exacerbated by land subsidence, which is determined by soil quality and the degree of water extraction in some low-lying coastal areas in Europe. The economic impact of natural catastrophes is also increasing due to the growing number of people living in areas with high risk levels, and increased economic activity in these regions (Bouwer et al., 2007).

History suggests that the human population is usually taken by surprise by coastal floods due to their 'low probability and high impact' character. Vulnerability to such events increases very gradually through slow sea-level rise and socio-economic developments. There is never an acute reason for strengthening the coastal protection system or for elevating settlements until the area and its population are hit by a major flood with significant loss of lives and economic damage.

The records of major coastal flooding episodes in the Netherlands, for example, illustrate that people have been taken by surprise about once every hundred years for the last 1 000 years. Apparently after some 50 years the flood disaster tends to disappear from the collective memory and flood protection measures are insufficiently maintained as a consequence. While the sea level keeps on rising and settlements keep expanding, a new high water event starts a new cycle of disaster and renovation of coastal protection works. The Netherlands and the United Kingdom only began investing in large-scale storm surge barriers after the devastating storm in 1953. The challenge for low-lying countries now is to anticipate climate change and accelerated sea-level rise.

The concept of measures to reduce the risk of flooding varies over time and by region. It ranges from local small-scale embankments to large-scale reclamation works and tidal barriers to lower the probability of coastal flooding. For example, London, large parts of the Netherlands, St. Petersburg in Russia and more recently Venice either have developed or are developing large-scale tidal storm surge barriers. These large engineering projects are expensive but protect population and capital investments up to a certain standard, usually in the order of withstanding the most extreme conditions statistically expected to occur once in a thousand or so years.

On the other hand, the closure of environmentally rich coastal areas such as estuaries through dams and barriers can harm biodiversity and water quality. Hence, flood protection through 'building with nature' has recently gained interest. Examples are periodic beach nourishment and coastal marshland development as ways to protect land and create buffer zones to lower wave impact (Day et al., 2007). Furthermore, coastal zone management strategies in, for example, the United Kingdom and France also aim to reduce the impact of coastal flooding by developing stringent building codes (flood proofing buildings) and zoning regulations (limiting urban expansion).

In France, a system of community-based prevention plans for natural risks addresses floodreducing measures. The possibility of gaining more favourable flood insurance terms provides an incentive for implementing such plans (Letermy, 2009). Innovative examples are found in the cities of Hamburg and

Panel 15.3 Dealing with the risk of coastal flooding — experiences from European countries (cont.)

Rotterdam. These cities have chosen to develop new residential areas on old port facilities located outside the main flood defences and hence prone to flooding but are elevating the buildings to safe levels. In Hamburg even public roads and bridges will be elevated to the height of 7.5 m above sea level to ensure unrestricted access for the fire and emergency services in the event of an extreme storm tide (Aerts et al., 2009).

Future projections of sea-level rise and human exposure to flood risk are inherently uncertain, necessitating new flood management methods and strategies. The 'climate proofing' concept has been developed to deal with sea-level rise and greater uncertainty about extreme weather events (Kabat et al., 2005). For example, levees and storm surge barriers are currently designed according to deterministic principles, using relatively short historic records and extrapolation methods to determine maximum surge heights. Extreme events are rare, however, and data on these events are sparse. Hence, new probabilistic methods are needed that provide engineers with a range of possible scenarios and may support a more robust protection designs.

Other 'climate proofing' measures include broadening levees to form 'superlevees', which can be used as ground for urban development (Vellinga et al., 2009). Such unbreachable dikes were developed in Japan near Tokyo, to protect against the potentially very high seas caused by tsunamis. They are now being considered by many water boards in the Netherlands as a way to deal with higher flood levels. For sandy beaches, the existing practice of beach nourishment (with sand) has become more sophisticated, such that the sand can be placed on the foreshore, creating a buffer against continuously rising seas. Finally, spatial planners, developers and insurers are actively engaged in reconsidering current regulations in order to ensure more flood- and climate-proof development of vulnerable coastal areas (Burby, 2001).

Despite their shortcomings, hard structural flood protection measures, such as dams and levees, will be needed to safeguard existing developments, in particular in urban areas. An effective flood protection system is generally a mix of structural and non-structural measures, with the latter approaches normally conforming better to the spirit of sustainable development.

Mitigating flood risks requires a change from reaction to anticipation. An immediate challenge is to improve flood forecasting at a range of time horizons of concern, from short-term weather forecasting and quantitative precipitation forecasts (useful for flash floods) to longer-term forecasting, useful for large basins. In this we should be encouraged that, thanks to improvements in the advance time and accuracy of forecasts, it has already been possible to reduce the number of flood fatalities in many countries.

Smith and Ward (1998) identify the development of infrastructure on floodplains as the major factor increasing flood risk (in terms of both hazard and vulnerability). Floods constitute a danger to life and property only when humans encroach into flood-prone areas and become vulnerable. This has already happened in many locations in Europe. If endangered locations have already been developed, a remedy is that humans, and infrastructure, move out of harm's way. In many countries the strategy of retreat is unpalatable, however, favoured by neither the broader population nor decision-makers. In some countries, such as Bangladesh, it is simply not an option.

Modern flood risk management comprises pre-flood prevention, risk mitigation measures and preparedness, followed by pre-planned flood management actions during and after an event. The risk-based approach to flood management is based on analysing the probability and consequences of flooding across the full range of severity, and implementing mechanisms to manage all possible events. Modern flood management also looks to the future and flood risk managers should continuously acquire and update evidence about long-term changes in flood risk.

Table 15.1 Early warnings and actions

C. 2000 BC	Levees and dams in China and the Middle-East provide flood protection
1854	Regular flood forecasting in France, following the advance of the telegraph. Italy developed such systems in 1866 and the US did so in 1871
1861	Adoption of a flood protection policy based on levee construction in the US, following a report by the US Army Corps of Engineers (Smith and Ward, 1998). This led to the transformation of seasonal wetlands to productive agricultural land
1931	Destructive summer floods in China cause a huge number of fatalities (although sources vary significantly on the numbers — ranging from 145 000 to 3 700 000)
1944	The Pick-Sloan Flood Control Act, enacted in the second session of the 78th US Congress, authorised a programme of structural defences, dams and levees across the US. It led to the establishment of the Pick-Sloan Missouri Basin Program
1970s	Early use of radar and satellite in flood forecasting
1994	After the 1993 mid-west flood in the US, the Interagency Floodplain Management Review Committee suggested relocating people off the floodplains and reclaiming wetlands (IFMRC, 1994)
1997	Large floods in central Europe affecting the basins of the Odra/Oder (Czech Republic, Poland, Germany) and the Vistula cause 110 fatalities and material damage in the range of billions of dollars — a substantial portion of the GDP of the countries in economic transition
1998	Floods in China cause material damage of USD 30 billion and over 3 600 fatalities
1998	Major flooding occurs in Bangladesh, inundating nearly 70 % of the country
2002	Dramatic floods in Europe (Austria, Bulgaria, Czech Republic, Germany, Hungary, Moldova, Romania, Slovakia, Ukraine) in August 2002 cause total damage in excess of EUR 20 billion
2007	Adoption of the EU Floods Directive

References

Aerts, J.C.J.H., Major, D., Bowman, M. and Dircke, P., 2009, *Connecting Delta Cities: Coastal Cities, Flood Risk Management and Adaptation to Climate Change*, VU University Press, Amsterdam p. 96.

AIR, 2010, *AIR Estimates Windstorm Xynthia Insured Losses at $2 to $4.1 Billion,* AIR Worldwide, Wells Publishing, Inc.

Andréassian, V., Lerat, J., Loumagne, C., Mathevet, T., Michel, C., Oudin, L. and Perrin, C., 2007, 'What is really undermining hydrologic science today?', *Hydrological Processes,* (21/20) 2 819–2 822.

Barredo, J.I., 2007, 'Major flood disasters in Europe: 1950–2005', *Nat. Hazards,* (42) 125–148.

Beven, K.J., 2002, 'Towards a coherent philosophy of environmental modelling' *Proceedings of the Royal Society of London Series, (A*458) 2 465–2 484.

Beven, K.J., 2006a, 'On undermining the science?', *Hydrological Processes,* (20) 3 141–3 146.

Beven, K.J., 2006b, 'A manifesto for the equifinality thesis', *Journal of Hydrology,* (320) 18–36.

Beven, K.J., 2008, 'On doing better hydrological Science', *Hydrol. Process.*, (22) 3 549–3 553.

Beven, K.J., 2009, *Environmental Modelling — An Uncertain Future?*, Routledge, London.

Beven, K.J., Smith, P. J. and Freer, J., 2008, 'So just why would a modeller choose to be incoherent?', *J. Hydrology*, (354) 15–32.

Blackbourn, D., 2006, *The conquest of nature — Water, landscape and the making of modern Germany*, Jonathan Cape (Random House), London.

Bouwer, L.M., Crompton, R.P., Faust, E., Höppe, P. and Pielke, Jr., R.A., 2007, 'Confronting Disaster Losses', *Science*, (318) 753.

Burby, R.J., 2001, 'Flood insurance and floodplain management: The US experience', *Environmental Hazards*, (3/3–4) 111–122.

Brázdil, R., Kundzewicz, Z.W. and Benito, G., 2005, 'Historical hydrology for studying flood risk in Europe', *Hydrol. Sci. J.,* (51/5) 739–764.

BUWAL and BWG, 2003, *Leitbild Fliessgewässer Schweiz*, Bundesamt für Umwelt, Wald und Landschaft und Bundesamt für Wasser und Geologie, Bern.

CEA, 2008, *Reducing the social and economic impact of climate change and natural catastrophes — insurance solutions and public-private partnership, Insurance* *solution and public-private partnership,* CEA, insurers for Europe.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P. and van der Belt, M., 1997, 'The value of the world's ecosystem services and natural capital' *Nature, (*387) 253–260.

Dufour, S. and Piegay, H., 2009, 'From the myth of a post paradise to targeted river restoration: forget natural references and focus on human benefits', *River Research and Applications, (*25) 568–581.

Dankers, R. and Feyen, L., 2008, 'Climate change impact on flood hazard in Europe: An assessment based on high resolution climate simulations', *Journal of Geophys. Res*., doi:10.1029/2007JD009719.

Day, J.W., Boesch D.F., Clairain, E.J., Kemp, G.P., Laska, S.B., Mitsch, W.J., Orth, K., Mashriqui, H., Reed, D.J., Shabman, L., Simenstad, C.A., Streever, B.J., Twilley, R.R., Watson, C.C., Wells J.T. and Whigham, D.F., 2007, 'Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita', *Science*, (315) 1 679–1 684.

Defra, 2006, *Flood and coastal defence appraisal guidance (FCDPAG3), Economic appraisal supplementary note to operating authorities — Climate change impacts*, Department for Environment, Food and Rural Affairs, London, the United Kingdom.

EAWAG, 2006, '*Flood Protection and Rehabilitation: New Directions for Our Rivers*', EAWAG News, 61, Duebendorf, Switzerland.

EEA, 2001, *Late lessons from early warnings: the precautionary principle 1896–2000*, Environmental Issues Report No 22, European Environment Agency.

Environment Agency (of England and Wales), 1998, 'An action plan for flood defence', London, the United Kingdom.

EU, 1992, Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, OJ L 206, 22.7.1992, p. 7.

EU, 2000, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, OJ L 327, 22.12.2000, p. 1–73.

EU, 2007, Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risk.

Evans, E.M., Ashley, R., Hall, J., Penning-Rowsell, E., Saul, A., Sayers, P., Thorne, C. and Watkinson, A., 2004, *Future Flooding. Scientific Summary*, vol. I: *Future Risks and their Drivers*, vol. II: *Managing Future Risks*. Foresight, Office of Science and Technology, London, UK.

Faulkner, H., Parker, D., Green, C. and Beven, K., 2007, 'Developing a translational discourse to communicate uncertainty in flood risk between science and the practitioner', *Ambio*, (16/7) 692–703.

Galloway, G.E., 1995, 'Learning from the Mississippi flood of 1993: Impacts, Management Issues and areas for research', Proceedings of the US-Italy Research Workshop on the Hydrometeorology, Impacts and Management of Extreme Floods, Perugia, November 1995.

Galloway, G.E., 1999, 'Towards sustainable management of river basins: challenges for the 21st century', in: Balabanis, P., Bronstert, A., Casale, R. and Samuels, P. (eds), *Ribamod. River Basin Modelling, Management and Flood Mitigation. Concerted Action*, Proc. of the final workshop, Wallingford, 26–27 February 1998, 235–250, Office for Official Publications of the European Communities, Luxembourg.

Hall, J.W., Meadowcroft, I.C., Sayers, P.B. and Bramley, M.E., 2003, 'Integrated flood risk management in England and Wales', *Natural Hazards Review*, (4/3) 126–135.

Hall, J. W., Sayers, P. B. and Dawson, R. J., 2005, 'National-scale assessment of current and future flood risk in England and Wales', *Nat. Hazards,* (36) 147–164.

Hall, J.W., O'Connell, E. and Ewen J., 2007, 'On not undermining the science: discussion of invited commentary by Keith Beven', *Hydrological Processes,* (21/7) 985–988.

Hirabayashi, Y., Kanae, S., Emori, S., Oki, T. and Kimoto, M., 2008, 'Global projections of changing risks of floods and droughts in a changing climate', *Hydrol. Sci. J.,* (53/4) 754–773.

IFMRC, 1994, *Sharing the challenge: Floodplain management into the 21st century — A blueprint for change*, Interagency Floodplain Management Review Committee, Washington DC, USA.

IPCC, 2001a, *Climate Change 2001: The Scientific Basis.* Contribution of the Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

IPCC, 2001b, *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Contribution of the Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

IPCC, 2007, *The Physical Science Basis*, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

JRC, 2011, 'European Flood Alert System', European Commission Joint Research Centre.

Junk, W.J., Bayley, P.B. and Sparks, R.E., 1989, 'The flood pulse concept in river-floodplain systems', *Canadian Special Publication of Fisheries and Aquatic Sciences, (*106) 110–127.

Kabat, P., van Vierssen, W., Veraart, J., Vellinga, P. and Aerts, J., 2005, 'Climate Proofing the Netherlands', Commentary in *Nature*, (438) 238–284.

Klijn, F. (ed.), 2009, *Flood risk assessment and flood risk management; An introduction and guidance based on experiences and findings of FLOODsite (an EU-funded Integrated Project),* Deltares, Delft Hydraulics, Delft, the Netherlands.

Kron, W., 2005, 'Flood', in: Munich Re, *Weather Catastrophes and Climate Change. Is There Still Hope for Us?*, Munich Re., Munich, Germany, pp. 122–131.

Kundzewicz, Z.W., 1999, 'Flood protection — sustainability issues', *Hydrol. Sci. J.*, (44) 559–571.

Kundzewicz, Z.W., Graczyk, D., Maurer, T., Pińskwar, I., Radziejewski, M., Svensson, C. and Szwed, M., 2005, 'Trend detection in river flow series: 1. Annual maximum flow', *Hydrol. Sci. J.*, (50/5) 797–810.

Kundzewicz, Z.W., Hirabayashi, Y. and Kanae, S., 2010a, 'River floods in the changing climate — observations and projections', *Water Resour. Manage*, (24/11) 2 633–2 646, doi:10.1007/s11269-009-9571–6.

Kundzewicz, Z.W., Lugeri, N., Dankers, R., Hirabayashi, Y., Döll, P., Pińskwar, I., Dysarz, T., Hochrainer, S. and Matczak, P., 2010b, 'Assessing river flood risk and adaptation in Europe — review of projections for the future', *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-010-9213-615:641–656.

Kundzewicz, Z.W., Mata, L.J., Arnell, N., Döll, P., Kabat, P., Jiménez, B., Miller, K., Oki, T., Sen, Z. and Shiklomanov, I., 2007, 'Freshwater resources and their management', in: Parry M. L., Canziani O.F., Palutikof J.P., Hanson C.E. and van der Linden P.J. (eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, the United Kingdom.

Kundzewicz, Z.W., Szamałek, K. and Kowalczak, P., 1999, 'The Great Flood of 1997 in Poland', *Hydrol. Sci. J.*, (44) 855–870.

Kundzewicz, Z.W., Takeuchi, K., 1999, 'Flood protection and management: Quo vadimus?', *Hydrol. Sci. J.*, (44) 417–432.

Lauterborn, R., 2005, 'Die Ergebnisse einer biologischen Probeuntersuchung des Rheins', *Arbeiten aus dem Kaiserlichen Gesundheitsamt* Bd. XXII:630–652.

Letremy, C., 2009, 'Assurance des risques naturels en France : Sous quelles conditions les assureurs peuvent-ils inciter à la prévention des catastrophes naturelles ?', *Etudes et documents,* No 1. March 2009. Commissariat Général au Développement Durable.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P. and Stouffer, R.J., 2008, 'Stationarity is dead: whither water management?', *Science*, (319) 573–574.

Montanari, A, 2007, 'What do we mean by "uncertainty"? The need for a consistent wording about uncertainty assessment in hydrology', *Hydrological Processes*, (21) 841–845.

Munich Re, 1997, *Flooding and Insurance*. Munich Re, Munich, Germany.

Naiman R.J., Decamps, H. and McClain, M.E., 2005, *Riparia*, Elsevier/Academic Press, San Diego, USA.

Nakamura, K., Tockner, K. and Amano, K., 2006, 'River and wetland restoration: Lessons from Japan', *BioScience, (*56) 419–429.

Nigg, J., 1995, 'Risk communication and warning systems', in: Hotlick-Jones, T., Amendola, A. and Casale, R. (eds), *Natural Risk and Civil Protection*, E & FN Spon, pp. 369–382.

Pilarczyk, K.W., 2007, 'Flood protection and management in the Netherlands', in: (by Vasiliev, O.F., van Gelder, P.H.A.J.M., Plate, E.J. and Bolgov, M.V. (eds), *Extreme Hydrological Events: New Concepts for Security (NATO Science Series, IV: Earth and Environmental Sciences)*, (78), Springer, The Netherlands, pp. 385–407.

Pitt, M., 2007, *Learning lessons from the 2007 floods*, Cabinet Office, London.

Opperman, J.J., Galloway, G.E., Fargione, J. Mount, J.F., Richter, B.D. and Secchi, S., 2009, 'Sustainable floodplain through large-scale reconnection to rivers', *Science, (*326) 1 487–1 488.

Raschky, P.A., 2008, 'Institutions and the losses from natural disasters', *Nat.Hazards Earth Syst. Sci.*, (8) 627–634.

Sivakumar, B., 2008, 'Undermining the science or undermining Nature?', *Hydrological Processes,* (22) 893–897.

Smith, K. and Ward, R., 1998, *Floods. Physical Processes and Human Impacts*, Wiley, Chichester.

Sommerwerk, N., Bloesch, J., Paunović, M., Baumgartner, C., Venohr, M., Schneider-Jacoby, M., Hein, T. and Tockner, K., 2010, 'Managing the world's most international river basin: the Danube', *Marine and Freshwater Research, (*61) 736–748.

Stirling, A., 1999, *On Science and Precaution In the Management of Technological Risk*, European Commission — JRC Institute Prospective Technological Studies Seville, Report EU 19056 EN.

Svensson, C., Kundzewicz, Z.W. and Maurer, T., 2005, 'Trend detection in river flow series: 2. Flood and low-flow index series', *Hydrol. Sci. J.*, (50/5) 811–824.

Tockner, K., Uehlinger, U. and Robsinson, C. . (eds), 2009, *Rivers of Europe*, Academic Press.

Tockner, K., Bunn, S.E., Quinn, G., Naiman, R., Stanford, J.A. and Gordon, C., 2008, 'Floodplains: Critically threatened ecosystems', in: Polunin, N. C. (ed.) *Aquatic Ecosystems*, Cambridge University Press, pp. 45–61.

Todini, E. and Mantovan, P., 2007, 'Comment on: "On undermining the science?" by Keith Beven', *Hydrological Processes,* (21/12) 1 633–1 638.

Trenberth, K.E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J. A., Rusticucci, M., Soden, B. and Zhai, P., 2007, 'Observations: Surface and Atmospheric Climate Change' in: Solomon, S.D., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds), *Climate Change 2007: The Physical Science Basis,* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, the United Kingdom and New York, NY, USA.

Vellinga, P., Marinova, N.A. and van Loon-Steensma, J.M., 2009, 'Adaptation to Climate Change: A Framework for Analysis with Examples from the Netherlands', *Built Environment,* (35/4) 452–470.

Wilby, R.L., Beven, K.J. and Reynard, N.S., 2008, 'Climate change and fluvial risk in the UK: more of the same?', *Hydrol. Process.*, (22) 2 511–2 523.

Williams, P.B., 1994, 'Flood control vs. flood management', *Civil Engineering*, 51–54.

WMO, 1986, 'Manual for estimation of probable maximum precipitation', *Operational Hydrology Report* 1, WMO No 332, 2nd ed., World Meteorological Organization, Geneva, Switzerland.

Young, P.C., 2002, 'Advances in real time forecasting', *Phil. Trans. R. Soc. Lond.*, (A 2002 360) 1 433–1 450.