

Extreme precipitation and floods in the changing world

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Abstract In recent decades, flood losses have shown a rapid growth tendency worldwide, which can be linked to socio-economic, hydrological and climatic factors. An increase in the flood risk is also foreseen for the future. Several land-use changes, such as deforestation and urbanization, reduce the available water storage capacity and exacerbate the flood hazard. Demographic pressure causes encroachment of informal settlements into hazardous locations in flood plains, e.g. around mega-cities in developing countries. Over-reliance on the safety provided by flood control works enhances accumulation of wealth in endangered areas. Climate impacts contribute considerably to the increase of flood exposure. As the atmosphere's water holding capacity grows with temperature, the possibility of intensive precipitation also increases. Higher and more intense precipitation has been observed already in many areas of the globe and this trend is expected to be even more pronounced in the future, warmer world. In a number of studies, floods have been found to become more frequent and intense. Yet, it would be a gross oversimplification to state that floods have uniformly exhibited growing trends everywhere. Adverse effects on floods have already been observed due to changing climatic variability (e.g. related to ENSO), and they are also projected to amplify. Despite the considerable investments into flood protection, in many countries there is a rising vulnerability to floods, as the increase of exposure to floods is faster than the growth of the adaptive capacity.

Key words climate change; climate impacts; climate variability; floods; global change; hydrological extremes; precipitation

FLOOD RISK ON THE RISE

It is ubiquitously felt that the media have been informing us more and more frequently about disastrous floods. Some people interpret this as a CNN-effect. In the past, before the globalization era, timely information on far-away floods was absent. Now, no matter where a destructive flood occurs, it is regarded as a spectacular event, and news of recent inundations are promptly shown on the TV worldwide.

Notwithstanding the observation that the availability of information grows in the global village, it is also clear that indeed the flood risk (understood as the probability of an extreme event multiplied by a measure of adverse consequences) is on the rise. The costs of extreme weather events have exhibited a rapid upward trend in recent decades and yearly economic losses from large events increased ten-fold between the 1950s and the 1990s, in inflation-adjusted dollars (IPCC, 2001b). The flood losses have soared globally to tens of billions of US\$ in material damage and there have been thousands of flood fatalities a year. According to data from the Red Cross, floods in

1971–1995 killed, on average, over 12 700 humans per year. The number of great flood disasters in the 1990s was higher than for three-and-half decades, 1950–1984 (Berz, 2001). In the 1990s, there have been over 20 floods worldwide, in each of which either the material losses exceeded one billion US\$, or the number of fatalities was greater than 1000, or both. In the most disastrous storm surge flood in Bangladesh, during two days in April 1991, 140 000 people were killed, while the highest material losses, of the order of 30 and 26.5 billion US\$, were recorded in China in the 1998 and 1996 floods, respectively.

In recent years, destructive deluges have occurred in many places, such as Mozambique, the Mekong drainage basin, Algeria, China, and several countries in Europe: Germany, Austria, Czech Republic and France, among others. The flood damage recorded in the European continent during summer 2002 was higher than in any single year previously.

The immediate question emerges as to the reasons for growth in the flood risk. One can identify three groups of factors: changes in climate, changes in hydrological systems, and changes in socio-economic systems.

IN SEARCH OF A CLIMATIC TRACK

The links between a sensible rise in flood risk and climate variability and change have been examined in the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC, 2001a,b), where floods are ubiquitously identified on short lists of key regional concerns.

It is well established that the atmosphere's capacity to absorb moisture, and thus potential for intensive precipitation, increases with temperature. This is a sufficient condition, *caeteris paribus*, for an increase in flood hazard.

Instrumental records of land surface precipitation show an increase of 0.5 to 1% per decade over much of the mid and high latitudes of the northern Hemisphere (IPCC, 2001a), particularly pronounced in autumn and winter (IPCC, 2001b), i.e. seasons when catchments' capacity to store precipitated water are limited. Even stronger increases have been observed in heavy and extreme precipitation events (Table 1).

Adverse impacts on flood hazard related to climatic variability have also been observed. The frequency and intensity of El Niño–Southern Oscillation (ENSO) have

Table 1 Sample of observed changes in intense precipitation (after IPCC, 2001a).

Location	Time period	Observation
Globally	1961–1990	A 4% increase in the annual maximum five-day precipitation total.
Mid- and high latitudes of the Northern Hemisphere	Latter half of the twentieth century	A 2 to 4% increase in the frequency of heavy precipitation
Many regions of Australia	1910–1995	A 10 to 45% increase in heavy rainfall, as defined by the 99th percentile of daily precipitation totals
Siberia	Summer season, 1936–1994	Increase in the frequency of heavy rainfall (>25 mm) of 1.9% per decade (despite a statistically significant decrease in total precipitation of 1.3% per decade)

been unusual since the mid 1970s, when compared with those of the previous 100 years. The warm phase of ENSO (i.e. El Niño) has become relatively more frequent, persistent and intense than the cool phase (La Niña) and this has been linked with the likelihood of intensive precipitation and floods in some areas, such as the Atlantic side of Central America, northwest Peru, and the central-western and Pampas regions of Argentina (IPCC, 2001b).

Where data are available, changes in annual streamflow usually relate well to changes in total precipitation (IPCC, 2001a). However, this does not directly translate to general changes in flood flows, even if there are a number of studies reporting that high flows have become more frequent (Table 2).

Table 2 Sample of observed changes in high flows as reported in the literature.

Location	Time period	Observation	Reference
Rhine at Cologne	1890–2000	Positive trend in annual maxima	Engel (1997)
Rivers in southwest Germany	Last several decades	Increased frequency of occurrence of wet Wz (West cyclonic) atmospheric circulation in winter, resulting in high flows	Bárdossy & Caspary (1990)
Four rivers in Germany	Long time series	Marked recent increase in the amplitude of floods. The 100-year-flood determined from the older data corresponds to much lower return periods (between 5- and 30-year flood) for the more recent data.	Caspary (2000)
Rivers in Austria	1952–1991	Analysis of the full 40-year period results in detection of a positive trend in 66.3% of the cases with significant trend.	Nobilis & Lorenz (1997)
River Tay in Scotland	1978–1997	Number of flood-induced embankment failures in the time period 1988/99 to 1996/97 was nearly five times higher than in 1978/79–1987/88.	Gilvear & Black (1999)
Four rivers in Scotland	Last 30 years	General increase in river flow (including the maximum), being significantly stronger than the increase in rainfall over the same period.	Mansell (1997)
UK, ~600 stream gauges	Long time series (from 15 to over 100 years)	Significant non-stationarity in annual maxima and peak-over-threshold (POT) variables. More incidences of increased flooding than decreasing flooding, particularly in Scotland and in southeast England.	Robson & Reed (1996)
Upper Mississippi, Lower Missouri and Illinois rivers	Long series (up to nearly 120 years)	Past-to-present and present-to-past analysis of subsets of data (between 10 and 100 years of length) showed several significant, typically growing, trends.	Olsen <i>et al.</i> (1999)
Conterminous USA, 395 climate-sensitive stream gauges	Long time series	For all, but the highest quantiles, streamflow has increased across broad areas. As far as 70th percentiles are concerned, all statistically significant trends detected in series of 60 and 70 years (all ending in 1993) correspond to growth of flow. Yet this percentage is lower for higher percentiles. These results were summarized as “getting wetter, but less extreme”.	Lins & Slack (1999)
USA	1932–1997	Increase in total annual flood damage, adjusted for inflation, with the rate of 2.92% per year, that is more strongly than population (+1.26%) and tangible wealth per capita, in inflation-adjusted dollars (+1.85%).	Pielke & Downton (2000)
Australia	Long time series	No clear evidence to suggest that the greenhouse signal is impacting on Australian streamflow	Chiew & McMahon (1993)

Globally, no uniform increasing trend in flood flow has been detected. Climate-related changes in flood frequency are complex, depending on the flood-generating mechanism. Flood magnitudes typically increase with warming if high flows result from heavy rainfall, and decrease where they are generated by spring snowmelt (IPCC; 2001a). In some places, rapid snowmelt from rain-on-snow events or warm periods in the middle of winter, cause a potential flood threat in a warmer world (IPCC, 2001b).

The prediction of extreme events for future climate is highly uncertain. There are large quantitative differences between scenarios and models. Yet, based on global model simulations and for a wide range of scenarios, global average water vapour concentration and precipitation are expected to increase further during the twenty-first century, while precipitation extremes are projected to increase more than the mean (Table 3), with consequences for the flood risk.

In articles on floods recently published in *Nature*, Palmer & Räissänen (2002), Milly *et al.* (2002), and Schnur (2002) strengthened our confidence in observed and projected changes in extreme rainfall and flooding.

Milly *et al.* (2002) demonstrated that the frequency of large floods has increased substantially during the twentieth century. For all (but one) large basin (>200 000 km²) analysed, the control 100-year flood is exceeded more frequently as a result of CO₂ quadrupling. In some areas, what is given as a 100-year flood in the control run, is projected to become much more frequent, even occurring as often as every two to five years (i.e. 20- to 50-fold increase in frequency). Particularly strong increases are projected in Northern Asia. According to Milly *et al.* (2002), the likelihood that these changes are due to natural climate variability is small.

Palmer & Räissänen (2002) analysed the modelled differences between the control run with twentieth century levels of carbon dioxide, and an ensemble with transient increase in CO₂ and calculated for around the time of CO₂ doubling (61–80 years from present). They found a considerable increase of the risk of a very wet winter in Europe and a very wet monsoon season in the Asian monsoon region. The modelling results indicate that the probability of total boreal winter precipitation exceeding two standard deviations above normal will increase by a factor of five to seven, or more, over large

Table 3 Sample of projected future changes in intense precipitation and flood risk. Source: IPCC (2001a, b).

Location	Observation
Europe	Wetter winters are predicted throughout the continent. In summer, northern Europe is likely to get wetter, while the southern Europe is likely to become drier. Flood risk generally would increase across much of Europe.
North America	For CO ₂ doubling, 20-year return period for heavy precipitation would be reduced by a factor of two.
Parts of India, Nepal and Bangladesh	Possibility of more frequent flash floods is foreseen.
Tropical Indian Ocean region	Future seasonal precipitation extremes associated with an ENSO event are likely to be more intense. The anomalously wet areas could become even wetter.
Australia	Although drier conditions are anticipated for most of Australia over the 21st century, an increase in heavy rainfall is also projected, even in regions with small decreases in mean rainfall. This is due to a shift in the frequency distribution of daily rainfall toward fewer light and moderate events and more heavy events.

areas of Europe. For example, an over five-fold increase is projected over Scotland and Ireland and much of the Baltic Sea basin, and even over seven-fold increase for parts of Russia.

Neither a single simulation nor an ensemble (consensus) average of model results is appropriate in extreme event studies. As stated by Schnur (2002), the ensemble (consensus) average of several models would lead to an underestimation of extreme precipitation and flooding. Studying frequency distributions of extreme events among large multi-model ensembles is likely to produce more trustworthy results (Palmer & Räissänen, 2002).

CHANGES IN HYDROLOGICAL AND SOCIO-ECONOMIC SYSTEMS

There exist important non-climatic factors that exacerbate flood hazard. Flood risk growth may be due to a range of land-use changes, which induce changes of hydrological systems. Deforestation, urbanization, and reduction of wetlands impoverish the available water storage capacity and increase the runoff coefficient. That is, growth in amplitude and reduction in time-to-peak of a flood triggered by a “typical” intense precipitation have been observed. As indicated earlier, the nature of a “typical” intense precipitation event may also have changed due to climatic reasons, becoming more intense. Abundant and destructive flood waters run off faster to the sea. The timing of river conveyance may have been considerably altered by river regulation (channel straightening and shortening, construction of embankments). Yet, the impact of urbanization on flood risk depends on the type of flood-provoking precipitation. The land-use change may play a more prominent role for convective precipitation, and a less prominent role for advective precipitation (Niehoff, 2001).

There are several factors influencing the process of river flow, so it is difficult to attribute the causes quantitatively. The longest existing Polish flow record of the river Warta, in Poznań, where daily values are available since 1822, has been subject to analyses of variability and change (e.g. Graczyk *et al.*, 2002). Figure 1 shows the annual maximum flow; a statistically significant decrease can be detected, the origin of which is not likely to be attributed to climate.

Studying the complete time series does not provide persuasive evidence as to the existence of a significant long-term trend in annual flow records. Therefore the search for a change can be performed on sub-sets of the complete record. Figure 2 presents fitting of linear regression to 15 different 30-year intervals whose origins are shifted by

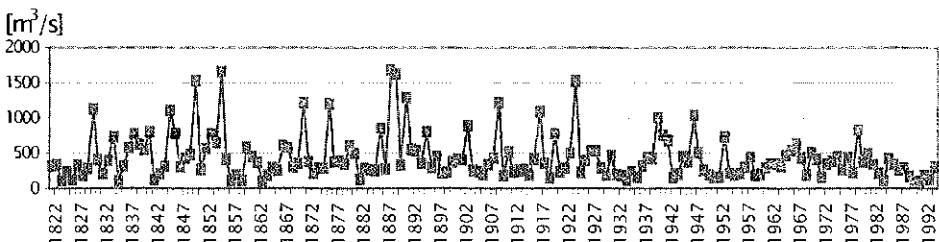


Fig. 1 Time series of annual maxima of flows of the River Warta in Poznan, 1822–1994.

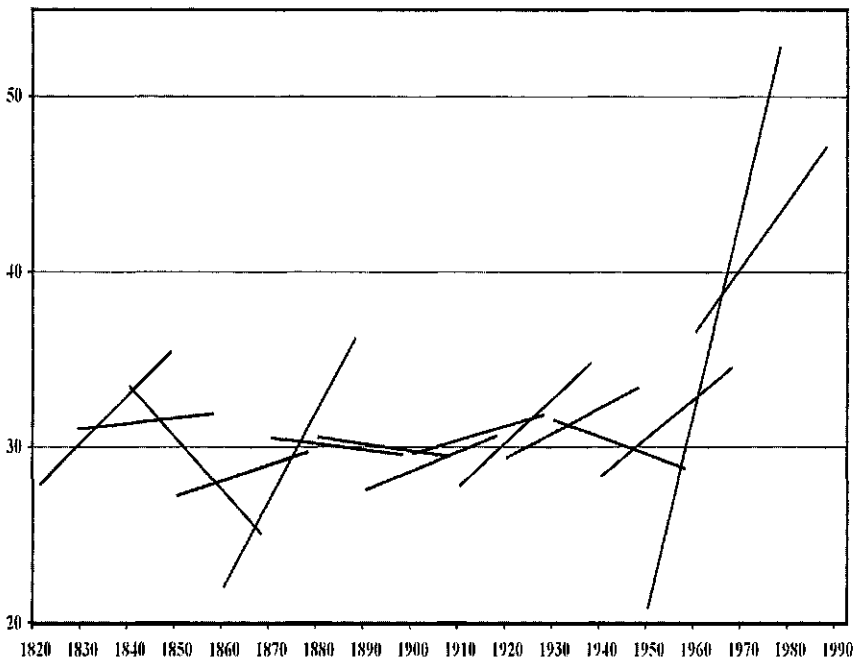


Fig. 2 Illustration of multi-decadal variability of flow of the River Warta at Poznan: linear regression for 15 different 30-year intervals.

one decade (1822–1851, 1832–1861, ,1962–1991). It can be seen that significant changes in both directions have been observed (growth in 11 cases and drop in 4 cases).

Flood risk has grown substantially due to changes in socio-economic systems, such as economic development of flood-prone areas, with a general increase in population and wealth, which led to increasing exposure and exacerbated flood losses.

Humans have been driven to occupy unsafe areas, thereby increasing the loss potential. Growing wealth has been accumulated in flood-endangered areas. For instance, about 7% of the area of the conterminous United States is located in the 100-year flood zone and about 10% of the population live there. In Japan, half the total population and about 70% of the total assets are located on flood plains, which cover only about 10% of the land surface. Yet, the percentage of the flood-prone area is much higher in Bangladesh. The 1998 flood inundated two thirds of the country's area.

Demographic growth and shortage of land cause human encroachment into flood plains. Hopes of overcoming poverty drives poor people to migrate to informal settlements in endangered, flood-prone zones around mega-cities in developing countries. Such places are left uninhabited on purpose, since effective flood protection is not assured.

An important factor influencing the flood hazard is an unjustified belief in the absolute safety of structural defences. Even an over-dimensioned and perfectly maintained dike does not guarantee complete protection, as it can be overtopped or broken by an extreme flood, and the losses may considerably exceed those which would have happened in a levee-free landscape.

Further, a short memory syndrome can be observed: societies and decision makers gradually keep forgetting about the investments necessary for flood-preparedness systems, so that the solidarity and dedication, plentiful during a deluge and immediately after it, may have faded away a few years after a disaster.

In many places flood risk is likely to grow, due to a combination of anthropogenic and climatic factors. Vulnerability to floods can be regarded as a function of exposure and adaptive capacity (cf. IPCC, 2001b), and all three entities have been increasing in many areas, where exposure grows faster than the adaptive capacity.

CONCLUSIONS

Recent studies show that the flood hazard is likely to rise in the future and that plausible climate change scenarios indicate the possibility of increases in both the amplitude and frequency of flooding events. Yet there has been no conclusive and general proof as to how climate change affects flood behaviour, in the light of data observed so far.

The strategy for flood preparedness can be based on the following attitude: protect as far as is technically possible and affordable, and accommodate, i.e. prepare for "living with floods". If a necessary level of protection cannot be provided and accommodation is not possible, a retreat could be a solution.

Regional changes in the timing of floods have been observed in many areas, with increasing late autumn and winter floods (caused by rain) and less ice-jam-related floods, e.g. in Europe. This has been a robust result. Yet intensive and long-lasting precipitation episodes happening in summer have also led to disastrous recent flooding in Europe, e.g. the Odra/Oder deluge in 1997 (cf. Kundzewicz *et al.*, 1999), and the 2002 floods, among others, on the Elbe and its tributaries, the Danube, and other rivers.

Quantification of flood statistics is subject to high uncertainty. It is difficult to disentangle the climatic component in flood data subject to strong natural variability and influenced by man-made environmental changes: urbanization, deforestation, humans occupying hazardous areas, reduction in storage capacity and increase in runoff coefficient.

All in all, the response of flood risk to climate forcing in the future will be complex. In many places flood risk is likely to grow, due to a combination of anthropogenic and climatic factors. Yet, as stated in the IPCC Technical Summary (2001a), "the analysis of extreme events in both observations and coupled models is underdeveloped" "the changes in frequency of extreme events cannot be generally attributed to the human influence on global climate".

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