Causes, impacts and patterns of disastrous river floods

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Abstract | Disastrous floods have caused millions of fatalities in the twentieth century, tens of billions of dollars of direct economic loss each year and serious disruption to global trade. In this Review, we provide a synthesis of the atmospheric, land surface and socio-economic processes that produce river floods with disastrous consequences. Disastrous floods have often been caused by processes fundamentally different from those of non-disastrous floods, such as unusual but recurring atmospheric circulation patterns or failures of flood defences, which lead to high levels of damage because they are unexpected both by citizens and by flood managers. Past trends in economic flood impacts show widespread increases, mostly driven by economic and population growth. However, the number of fatalities and people affected has decreased since the mid-1990s because of risk reduction measures, such as improved risk awareness and structural flood defences. Disastrous flooding is projected to increase in many regions, particularly in Asia and Africa, owing to climate and socio-economic changes, although substantial uncertainties remain. Assessing the risk of disastrous river floods requires a deeper understanding of their distinct causes. Transdisciplinary research is needed to understand the potential for surprise in flood risk systems better and to operationalize risk management concepts that account for limited knowledge and unexpected developments.

Annual average loss
(AAL). A widespread indicator for risk, it is the estimated average loss per year considering the full range of scenarios from frequent events (zero or small loss) to extreme events (large loss or worst-case scenario).

River floods caused about 7 million fatalities in the twentieth century[1], and their direct global average annual loss (AAL) is estimated at US$ 104 billion (2015) (REF.[2]). Exposure to floods is expected to grow by a factor of three by 2050 owing to increases in population and economic assets in flood-prone areas[3]. Depending on the socio-economic scenario, human losses from flooding are projected to rise by 70–83% and direct flood damage by 160–240% relative to 1976–2005, with a temperature increase of 1.5 °C (REF.[4]). Understanding river flooding and its associated impacts are critical to effective risk reduction.

River floods occur when a river overtops its banks and inundates adjacent areas. The expected impact floods have on society and the environment, often termed flood risk, results from the superposition of three components and the associated processes, which tend to be interlinked[5–7], including over large distances[8]. These components are: hazards — the processes leading to high river flood levels; exposure — the elements at risk, such as population or infrastructure; and vulnerability — the susceptibility of the elements at risk when they are affected by a flood[2]. These components are, in turn, the compound effects of multiple processes (FIG. 1).

Flood hazard is a consequence of flood-triggering processes in the atmosphere, runoff generation in the catchment, and flood waves travelling through the river network. Exposure depends on the use of the floodplains and the economic and population development. Vulnerability is shaped by human adaptive influences, such as private precautions, early warning or crisis management.

Human activities affect flood processes broadly[9–11]. Alteration of river basin land use affects runoff generation, and climate change can enhance heavy precipitation and affect snowmelt or catchment wetness, thus influencing flood risk[12,13]. Levées, flood retention by dams, and early warning systems reduce flood risk, but can fail unexpectedly, thereby surprising affected communities and amplifying the flood damage[14–16]. The confluence of these processes can lead to disastrous floods, defined here as those events with devasting consequences. Disastrous floods are prevalent — more than 2,500 disastrous floods were identified globally in the period 1985–2019 (FIG. 2a). However, the impacts of high river flood levels are strongly determined by the exposure and vulnerability of the affected society. High levels of flood protection (FIG. 2b), preparedness and coping capacity can prevent disastrous consequences even for extreme river flood levels.

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Key points

- The causative mechanisms of floods with disastrous consequences tend to be different from those of non-disastrous floods, and show anomalies in one or several flood- and loss-generating processes.
- Past trends in flood hazard show both upward and downward changes. In some regions, anthropogenic warming is already strong enough to override other drivers of change.
- Flood hazards and impacts are projected to increase for many regions around the globe. Future flooding hotspots are expected in Asia and Africa, owing to climate and socio-economic changes.
- Reducing vulnerability is a particularly effective way of reducing flood impacts. Global decreases in flood-affected people and fatalities since the mid-1990s (despite a growing population) are signs of effective risk reduction.
- Disastrous floods often come as a surprise. Effective risk reduction requires an understanding of the causative processes that make these events distinct and to address the sources of surprise, including cognitive biases.

Rain-on-snow events
Fall of rain onto existing snow, leading to flood runoff composed of snowmelt and rainfall.

Atmospheric rivers
Long, narrow and transient corridors of strong horizontal water vapour, transporting on average more than double the flow of the Amazon river and delivering moisture as heavy precipitation.

Therefore, we differentiate between small floods and extreme floods (those larger than a flood that occurs only once in a hundred years, termed the 100-year flood) when only hazards are considered and we differentiate between disastrous and non-disastrous floods when impacts are also included (BOX 1).

In this Review, we discuss the causes and impacts of disastrous river floods, and summarize current knowledge about their past and future changes. Whereas previous reviews (for instance, see REFS[12,17,18]) have examined river flooding in general, disastrous floods often show specific characteristics or mechanisms that set them apart from non-disastrous floods[19]. Therefore, we focus explicitly on disastrous floods and how they differ from non-disastrous floods in atmospheric, catchment and river network processes. We also describe the socio-economic factors that determine whether high river flood levels have disastrous consequences. Finally, we provide recommendations of how to estimate the associated risks better and how to develop adequate risk reduction measures.

Causes of extreme river floods

River floods can be generated by a variety of atmospheric processes, including extratropical frontal systems, monsoonal rainfall, landfalling hurricanes and strong temperature increases leading to snowmelt. Precipitation or snowmelt is then modified by the catchment state, in particular soil moisture, and catchment characteristics, such as soils, topography, land cover or river network, to produce floods of various magnitudes[20]. The interaction of all of these processes over time leads to typical flood regimes with distinct times of the year when floods occur, flood process types and flood peak distributions[18,21–24]. For example, in Austria the relative occurrence of flood process types, such as long-rain floods, short-rain floods, rain-on-snow floods and snowmelt floods, varies between regions and during the year[25]. Most importantly, the process types change with flood magnitude. Extreme floods in Austria are frequently caused by short-rain or long-rain events, but rarely by rain-on-snow events and almost never by snowmelt events.

Atmosphere and climate mechanisms. Extreme floods are linked to atmospheric mechanisms that differ from those mechanisms that cause small floods in many instances[26,27]. Extreme river floods are typically caused by heavy and/or prolonged rainfall, and above 40 °N, by snowmelt and ice-jam-related processes[28]. Rainfall-driven floods are conditioned on storm tracks delivering atmospheric moisture to the catchment, usually from the ocean[29]. Atmospheric moisture can also originate from evaporation from wet landscapes far from the flood. For example, the extreme and disastrous 2002 flood in central Europe was caused by record rainfall, related to the Mediterranean Sea and to strong evaporation from land owing to a wet spell in which soils were saturated in large parts of Europe[30].

Extreme river floods are often associated with unusual, but recurrent, atmospheric circulation patterns and storm tracks[26]. For example, the widespread flooding in 2011 in Thailand was marked by five very similar typhoon tracks over a period of 90 days[31]. The disastrous floods of the Mississippi river in the USA in 1993, in Pakistan in 2010 and in central Europe in 2013 have been linked to atmospheric blocking situations that can persist for weeks and guide repeated cyclones to the same region[32–34]. Relations between climatic anomalies and extreme flood occurrence have also been found for other regions, for instance, in central Europe[35] and the eastern USA[21]. Atmospheric rivers[29,36–38] can also generate extreme river floods, as observed in California[39], regional-scale flooding across the western USA[40], the United Kingdom and Ireland[41], northwest Spain[42], France[43], Chennai in India[44] and the southern Alps in New Zealand[45]. The hypothetical winter storm scenario ARkStorm (AR for atmospheric river, k for 1,000, because the storm was considered to be a 1,000-year event), which is based on the winter storm of 1861/62, would widely overwhelm California's flood-protection system and could cause damage of the order of $US 725 billion (2010)[46,47].

The long-term behaviour of these atmospheric processes is modulated by atmosphere–ocean interactions. Hence, the likelihood of the occurrence of extreme rainstorms, and of floods, tends to vary over decades[48]. One example is the El Niño/Southern Oscillation, which results in more frequent occurrence of extreme floods in northern Peru during strong El Niño phases[49,50], but also in many other regions around the world[51,52]. Similarly, more frequent flooding occurs in northwestern Europe during positive phases of the North Atlantic Oscillation[53].

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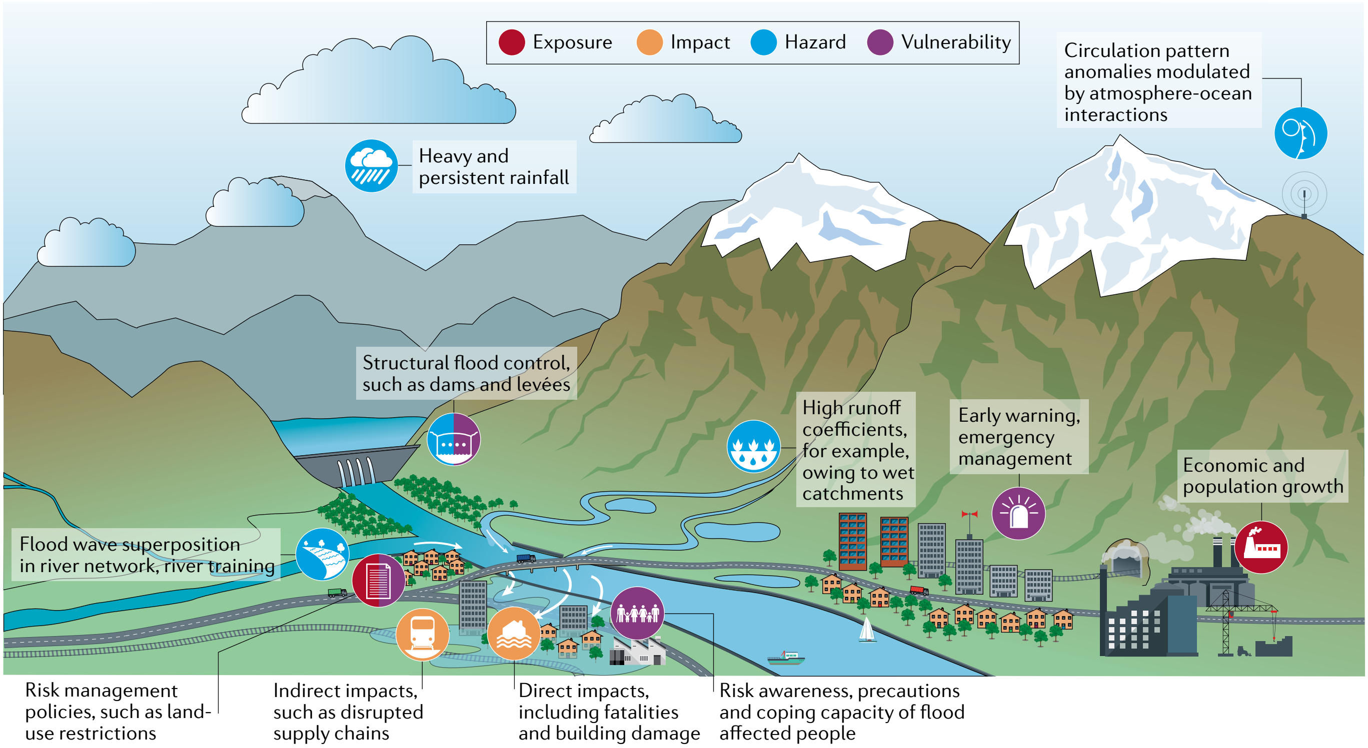


Fig. 1 | **Key processes that can cause or prevent disastrous river floods.** Atmospheric, catchment and river network processes interact to cause high river flood levels (hazards shown as blue symbols). The impacts (shown as orange symbols) of flood events depend on the exposed population and assets in flood-prone areas (exposure shown as red symbols), and on their susceptibility when they are hit by a flood (vulnerability shown as purple symbols). Indirect impacts can occur in regions far away from the inundated areas, for instance, owing to global supply chain disruptions.

Monsoon characteristics[54] and cyclone types[55] also tend to vary over decades. Such climate–flood links lead to flood-rich and flood-poor periods[56–60], which have been related to periods with above or below average flood damage[61–63]. For flood risk management, such variations can lead to predictability of regional floods as much as a season ahead[64,65].

Catchment and river network processes. Although heavy and/or prolonged rain is often the driver of extreme floods, the antecedent catchment state also exerts a strong influence. When the catchment is wet, and soil moisture and groundwater levels are high, most of the rainwater runs off the surface and directly contributes to the flood, whereas most of the rainwater infiltrates into the soil during dry conditions, usually with less effect on the flood. Persistent rainfall events that result from atmospheric circulation anomalies enhance antecedent catchment wetness and therefore the likelihood of extreme events[27]. Indeed, extreme and disastrous floods have been caused by extreme event rainfall and modest catchment wetness, for instance the 2002 central Europe flood, or extreme catchment wetness and modest rainfall, as in the 2013 central Europe flood[66].

Extreme floods often differ from small floods in the way rainwater moves on the hillslopes, infiltrates into the soil or enters a stream. The runoff coefficient often increases in a nonlinear way with catchment wetness and event precipitation[67–69], so that doubling precipitation results in more-than-doubled flood runoff. Strong and sometimes threshold-like increases in the runoff coefficient can be triggered by the activation of additional areas within the catchment, contributing to flood runoff when the water storage capacity of the subsurface is exceeded[70–72]. During the 2002 central Europe flood disaster, the runoff coefficient of the river Kamp in Austria was twice as high as for smaller floods, which, in combination with extreme rainfall, led to a flood peak that was three times as large as the second-largest flood in the past 100 years[73]. Because of averaging effects within the catchment, these types of thresholds are most important in small catchments and their relevance tends to decrease with catchment area[74].

The flood runoff generated in different parts of the catchment travels in the form of flood waves through the river network. If flood waves from different tributaries come together at river confluences at the same time, the downstream flood can be substantially bigger than the individual floods themselves[75]. Although this mechanism has not produced extreme floods in some regions[76], it might be highly relevant for other regions, such as river deltas with flat topography. The floods in 1988 and 1998 in Bangladesh, for instance, were characterized by the superposition of the peaks of the Brahmaputra and Ganges rivers, producing devastating inundation in the central region of Bangladesh near the confluence[77].

Land-use changes, such as urbanization and soil compaction through heavy agricultural machinery, can enhance runoff generation and hence flood peaks[78,79].

Runoff coefficient
The fraction of the event water input (precipitation or snowmelt within the catchment) that is not retained in the catchment and that directly contributes to discharge during the event.

These effects are most important in small catchments where the fraction of land-use change can be large relative to the catchment area, and because land-use change matters most for high-intensity storms that are most relevant in small catchments[12]. For larger river basins, land use tends to be less relevant. For the Rhine river basin, for example, realistic modifications of land use in terms of increasing urbanization and increasing forest cover change flood water levels by a few centimetres only[80,81]. Simulation studies suggest that the effect of land-use change decreases with flood magnitude, given that in an extreme scenario, when the catchment is close to saturation, the surface conditions have a minor role in runoff generation[80,82,83]. However, the link between land use and catchment-scale flood hazard is highly uncertain[84].

Floods can also be intensified by human alterations to the river systems, such as straightening and deepening of channels, the removal of floodplain retention area by levées, and the construction of weirs[6,85,86]. The construction of high levées in the Mekong delta in Vietnam increased downstream inundation duration by 15 days and inundation depth by up to 13 cm for the 2011 flood, contributing to the disastrous damage in the economic centre of the delta, including Can Tho[87]. Levée expansion along the Mississippi has increased flood stages up to 1 m owing to loss of floodplain retention[88]. In contrast, breaching of river levées can decrease downstream flood peaks when large water volumes are retained in the levée hinterland, as demonstrated for the lower Rhine river[89] and the Rhine–Meuse delta[90].

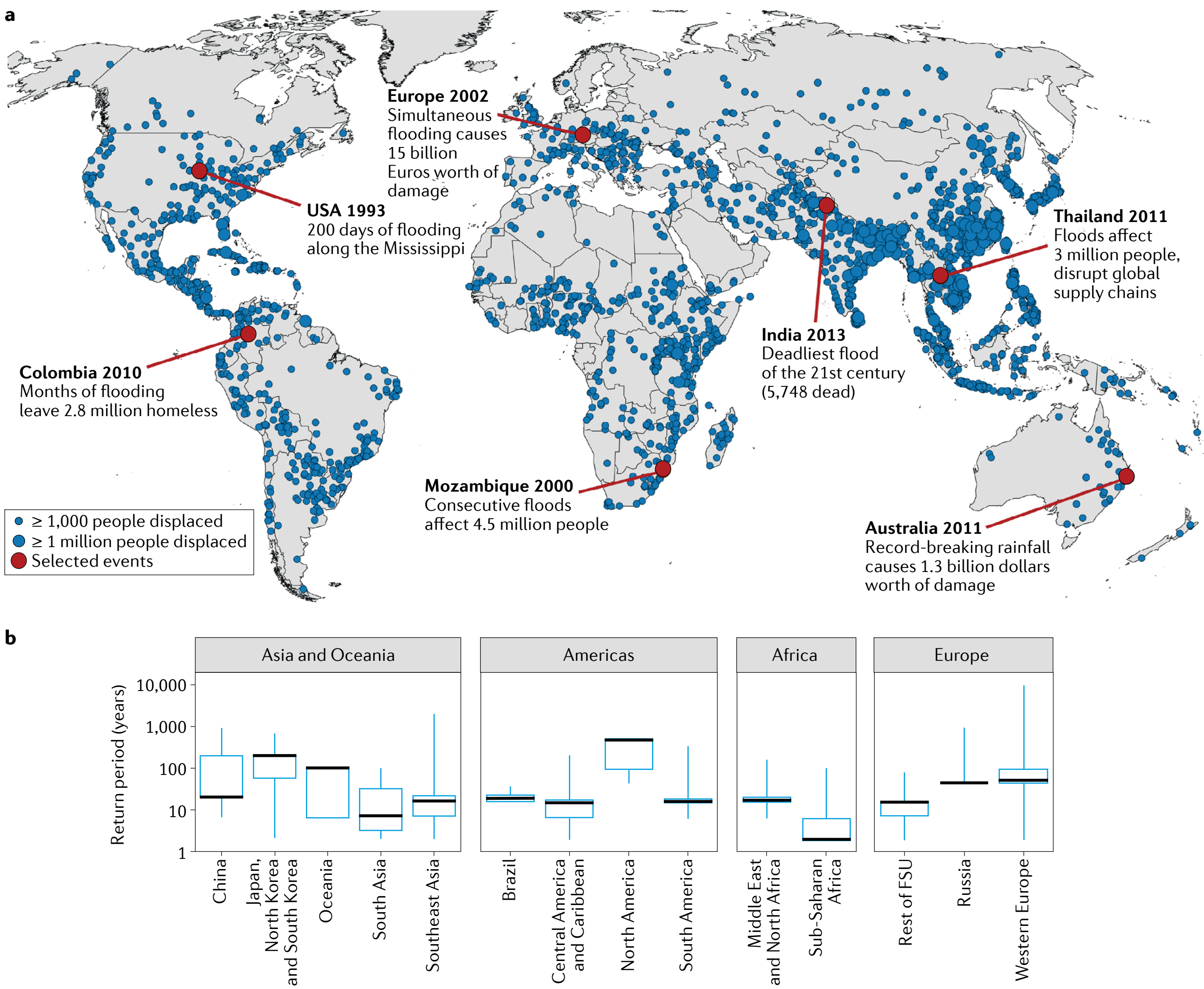
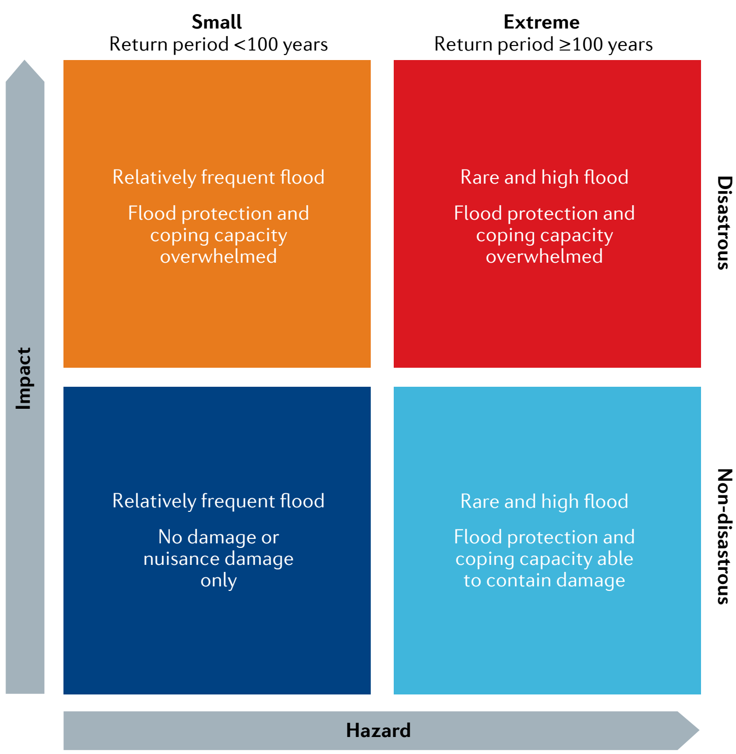


Fig. 2 | **Global distribution of disastrous river floods in 1985–2019 and flood protection standards. a** | Global extent of disastrous river floods during 1985–2019. Each dot represents an event in the Dartmouth Flood Observatory[171] (DFO) database, with at least 1,000 people displaced and with "significant damage to structures or agriculture, long (decades) reported intervals since the last similar event, and/or fatalities". The map contains 2,548 flood events during 1985–2019, including 105 events with more than a million people displaced. Monetary values represent reported, not inflation-corrected, values. Some particularly severe floods are noted. **b** | Flood protection standards contained in the global database FLOPROS[197], grouped according to regions. These values give a rough estimate of the return periods of river floods, which can lead to disastrous losses in different regions. Boxes and black lines indicate 25–75% and 50% percentiles, respectively, and whiskers show the range. FSU, the former Soviet Union.

Box 1 | **Flood typology**

Here, disastrous river floods are defined as events with disastrous consequences, often associated with fatalities and disruption to societies. This understanding of disastrous floods adheres to thresholds of global disaster databases. Given the biases in recording event consequences[230] and the different approaches of global disaster databases[231], the boundary between disastrous flooding and non-disastrous flooding is fuzzy. However, flood events are considered to be disastrous here when they are included in EmDAT[172] and/or are classified as "large floods" in the Dartmouth Flood Observatory (DFO)[171]. EmDAT records an event when there are either at least ten fatalities, there are at least 100 people affected, a declaration of state of emergency is made, or a call for international assistance is made. The DFO defines large floods as events with at least 1,000 people displaced and with significant damage to structures or agriculture, long (decades) reported intervals since the last similar event, and/or fatalities.

This definition relates to the event impact and thus includes the exposure and vulnerability of the affected society. When discussing only the hazard aspects of floods, the terms "small floods" and "extreme floods" are used, where the latter refers to rare events with return periods of 100 years or larger. Extreme events that are rare (>100-year return period) and of high magnitude often cause disastrous floods (Extreme and Disastrous; upper-right quadrant of the box figure). The threshold when a flood causes disastrous consequences varies between regions, and an extreme flood is not necessarily classified as a disastrous flood. For instance, a flood with a 200-year return period would not be classified as disastrous in areas with a high coping capacity, such as the Netherlands, that are protected against a 1,250-year event (Extreme and Non-disastrous; lower-right quadrant of the box figure). In contrast, many cities in Africa are almost wholly unprotected and their citizens rarely benefit from timely flood forecasts and external assistance when flooding occurs[201,232]. In such cases, even an event with a 20-year return period can have disastrous consequences (Small and Disastrous; upper-left quadrant of the box figure).



Direct impacts
Consequences occurring in the inundated region during a flooding event.

Indirect impacts
Consequences occurring far away from the flooded region and/or after a flooding event.

Dams also affect flood characteristics. Very large dams (each storing at least 1.2 km^3 of water) in the USA reduce annual flood peaks by 67% on average[91]. The aggregated effect of many small dams can also be considerable, with 20–70% flood peak reduction[92], depending on their relative size, position in the basin and operation rules[93–95]. For very extreme floods, the reservoirs associated with dams tend to fill up and thus reservoirs lose their efficacy as flood control structures. If dams breach or are overtopped, extraordinary flood waves can occur, as in the 1963 Vajont disaster in Italy. There, a massive landslide into the reservoir caused a wave of 50 million m^3, overtopping the dam and resulting in more than 1,900 fatalities[96]. Given that many dams around the world are now beyond their original design lifespan, potential failure during flooding is a substantial concern[14].

In low-lying coastal areas, the impacts of river floods can be aggravated by their co-occurrence with storm surges and high tides. Examples of such compound floods[97] with disastrous impacts are cyclone Idai in 2019 in southeast Africa, hurricane Harvey in Texas, storm Xaver in northwestern Europe in 2013, or typhoon Haiyan in southeast Asia in 2013[98–100]. Climate-change-related sea level rise in combination with land subsidence in coastal areas, due to sediment compaction from extraction of groundwater, oil or gas, and trapping of sediments in upstream dams, are expected to substantially increase the frequency of compound flooding in river deltas around the world[101,102].

In summary, the catchment and river network processes of extreme floods often differ from those of small floods. Flood types differ in relevance and nonlinearities in the runoff generation play an important part. Human interventions also tend to influence small and extreme floods in different ways. Land-use changes, for example, can substantially affect small floods but their influence vanishes for extreme events.

Impacts of disastrous river floods

Disastrous river floods directly affect, on average, 125 million people annually, by evacuation, homelessness, injury or death[103], and have a wide range of direct impacts and indirect impacts, monetary and intangible impacts[104] on societies and the environment. Although indirect and intangible impacts are rarely assessed, they are not less important for society[105].

Socio-economic impacts. The flood-affected population and the number of fatalities vary very much globally[106,107] (FIG. 2a). More than 90% of the people affected by disastrous river floods live in Asia, owing to the large spatial extent of floodplains and the high number of people living in flood-prone areas[103,106]. Global flood mortality is estimated to be 0.007% for the period 1977–2019 (Supplementary Information), although estimates vary (from 0.004% (REF.[108]) to 0.5% (REF.[109])). High-mortality situations occur when dams or levées break, substantially contributing to the years with anomalously high numbers of flood fatalities in the USA[110]. Disastrous floods are also associated with a wide range of indirect health impacts, caused, for instance, by flood-induced psychological stress, loss of health infrastructure or contamination[111]. There are even higher-order indirect effects on society: for instance, a national analysis for the USA concludes that natural hazards increase residential mobility; disaster-affected communities tend to experience both outward and inward migration, which is particularly noticeable among racial and ethnic minorities[112].

Globally, river floods (including both disastrous and low-impact events) are estimated to cause direct

Intangible impacts
Consequences of a flooding event that are difficult or impossible to monetarize, such as loss of life or loss of memorabilia.

Mortality
The ratio of the number of people who lose their lives in a flood to the number of people affected by the flooding event.

economic losses of $US 104 billion (2015) per year on average[2]. Notably, low-impact events are much more frequent and typically contribute a large share to the annual average loss[113,114]. This estimate does not include the damage to agriculture and to infrastructure, such as roads, energy facilities and dams; however, losses to agriculture and infrastructure have been estimated for single disastrous floods. For instance, the 2000 Limpopo flood in Mozambique inundated large areas for several weeks[115]. More than 20,000 cattle were lost and over 140,000 ha of cultivated and grazing land were destroyed. The country's infrastructure was badly affected, and 90% of its functioning irrigation was damaged[115].

Disastrous river floods can have wide-ranging indirect economic consequences, extending far beyond the flooded region and long after the event. Indirect economic losses from 1996–2015 have been estimated to be of the same order of magnitude as direct economic losses[116]. For example, the Thailand flood disaster in 2011 substantially disrupted the supply chains of the global automobile industry[117]. In today's hyper-connected world[118], highly efficient networks of trade, communication and mobility can generate systemic risks with interdependent, so-called 'cascading' failures[119,120]. A local failure, such as a flood-induced power blackout or inundation of a critical infrastructure element, might propagate to other networks with disastrous consequences totally unrelated to the characteristics of the initiating flood[121].

Post-disaster dynamics in the economic system depends on the connectedness, dependencies and flexibility of the economic actors within and outside the flood-affected area[105,117]. Areas outside the flood footprint can amplify or partially compensate the losses[116]. Most flood impact assessments neglect indirect economic impacts or apply very simple models, such as estimating the indirect losses as a ratio of direct losses[116,122]. However, this ratio seems to vary strongly between economic sectors, for instance, ranging from 0.2 for 'human health and social work' to values above 2.0 for 'manufacturing' for the disastrous flood in 2013 in Germany[122]. Clearly, a better understanding of how flood impacts propagate through economies and how to mitigate indirect consequences is much needed[116].

Controls of disastrous flood impacts. Hazard characteristics, such as river flood peaks or inundation depths, have traditionally been considered as the dominant loss-influencing factors[123–125]. However, risk perception and human behaviour also influence flood impacts; for instance, mortality can increase, because unnecessary risk-taking behaviour contributes significantly to flood deaths[126], or decrease, as a result of the effectiveness of early warning and evacuation[108]. Indeed, the relationship between river flood characteristics and losses is highly nonlinear and dynamic: the Rhine floods in January 1995 caused monetary damage in Cologne 67% lower compared to the Rhine flood in December 1993, although the former had a higher water level[127]. The Mekong flood disaster in 2000 caused 481 fatalities and damage worth US$ 500 million (2011), whereas a similar flood in 2011 had 89 fatalities and damage worth US$ 209 million (2011) (REF.[15]).

Across case studies where two similar floods occurred in the same region, with the second flood causing substantially lower damage[15], the damage reduction is mainly attributed to substantial reductions in vulnerability, via raised risk awareness, better preparedness and improvements of organizational emergency management. Compared with measures that reduce the hazard (such as construction of upstream reservoirs), or the exposure (such as reducing the assets in river floodplains), measures to reduce vulnerability can be readily implemented and unfold their effects rapidly[15]. For instance, in the year after the 1993 Rhine flood, the number of precautionary measures taken by private households, such as securing oil tanks or deploying mobile flood barriers, more than doubled[127]. However, the potential of local-scale vulnerability changes to reduce flood risk should be assessed holistically, with longer-term policies addressing risk reduction via changes in hazard and exposure[128]. For example, land use and urban planning have an essential role in flood risk management[129], and neglecting the link between spatial planning and risk management has amplified urban exposure to flooding[130,131].

There is now widespread evidence that disastrous floods can trigger adaptation, such a changing risk management policies or implementing private precautionary measures[15,132,133]. Whether disastrous floods are perceived as a signal to adapt depends to a large degree on risk perception[133–135]. According to the so-called focusing-event theory[136], a problem might be hovering under the radar of decision makers, but a disaster can provide a push in calling attention to it, and consequently trigger change. This change can extend far beyond the flood footprint. The UK floods in 2000[137] and the central Europe floods in 2002[15] were perceived as signal to society and policy, and triggered wide-ranging changes in flood risk management, including the EU Flood Directive[138]. This directive, in turn, has consequences for risk management throughout the EU. The focusing-event theory also suggests that people tend to forget about the issue over time[139]. Insurance take-up in the USA peaks in the year after flood disasters, but declines steadily to the historic baseline thereafter[140]. Similar short-lived effects have been found elsewhere[133], such as significant drops in property prices after flood disasters and a disappearance of this flood risk discount within a few years[141].

Income and wealth are important determinants for risk, adaptation and recovery. Higher income and wealth tend to increase exposure to floods, but allow investment in risk reduction, implementation of adaption measures and faster recovery from disastrous floods[105,108,142,143]. Countries with higher incomes and stronger institutions tend to suffer fewer losses from natural disasters[144,145]. Many low-income and middle-income countries are faced with very high AALs relative to their wealth, because they are not able to invest in flood risk reduction measures as well as high-income countries can[2]. For instance, the AAL for river flooding represents over 20% of the country's capital investment for Myanmar and Somalia[2]. Furthermore, flood-induced death rates (fatalities per million people) and flood-affected rates decreased with the growth of

Annual maximum flows
The highest streamflow peak in each year.

Flood timing
The dates of the year when floods occur.

Flood extent
The distance over which flooding occurs simultaneously.

GDP per capita[107]. However, the relation between wealth and impacts is fuzzy, because further factors come into play, such as education[135,144,146,147].

In summary, many factors influence whether a flood event is disastrous. Structural failures of dams and levées contribute to disastrous flooding owing to their high potential for fatalities. Strong regional and global connectivity, and trade, communication and mobility dependencies are not well understood but might turn even small events into disasters. Risk perception and resources available for risk reduction and adaptation are the main controls of the link between flood events and disastrous consequences.

Observed trends

All of the processes discussed here change with time. Understanding how flood risk and the associated processes have changed in the past and how they might change in the future is fundamental to risk management, presenting the opportunity for mitigation and risk reduction. We discuss trends in flood hazard and impacts to understand their agreement (FIG. 3a,b), and to probe whether the latter are a consequence of changes in flood peaks or changes in socio-economic factors.

Observed changes in flood hazard. A significant increase in the occurrence of 100-year floods in the twentieth century was detected across 29 very large river basins (>200,000 km^2) from all continents[148]. Indeed, 16 of 21 extreme floods occurred after 1953. According to more than 1,200 gauges from North America and Europe, however, changes in the occurrence of 100-year floods were dominated by climate variability, not long-term trends[59]. A global analysis using time series of at least 70 years found mainly decreasing trends for the 100-year flood in arid regions (236 gauges, median trend: –26.4%) and temperate regions (401 gauges, median trend: –16.5%) for the period 1970 to the present day[149]. Cold regions showed mixed results (610 gauges, median trend: –0.4%) and tropical regions showed mostly upward trends (27 gauges, median trend: 35.3%). However, coverage across the globe is highly uneven, and available studies do not allow a comprehensive assessment of past changes in extreme floods. Therefore, we summarize the extensive knowledge on changes in annual maximum flows here, and the relationship between changes in small floods and extreme floods is discussed.

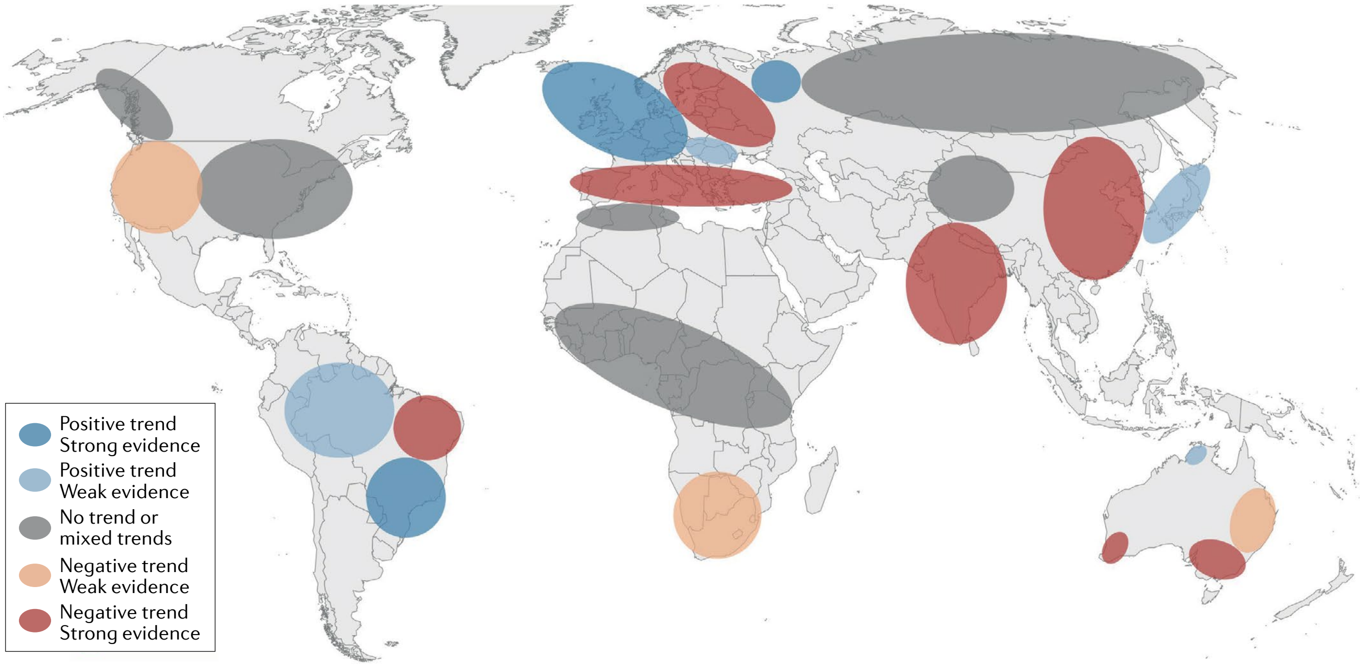
Large-scale coherent patterns of changes in annual maximum flows were identified in Europe, with increases in northwestern Europe and decreases in eastern Europe and in medium and large catchments of southern Europe[150] (FIG. 3a). In the USA, mixed changes have been found for central and eastern regions; clearer patterns of decreasing floods have been detected in the western USA, particularly in California, in line with decreases in precipitation and catchment wetness[151–156]. In other regions of the world, decreasing trends in annual maximum flows have been found in northeast Brazil[157] and southeast Australia[158] as well as in China[159] and India[156]. There are also a number of regions with increasing trends such as the south of Brazil[157] and the north of Australia[158].

It is not easy to attribute the observed flood trends to their drivers because of data scarcity and the interaction of multiple drivers[160,161]. In some studies, patterns of flood changes are coherent across large areas, suggesting that these regional patterns are driven by climatic changes. This suggestion is supported by parallel changes in flood-related variables, such as precipitation, soil moisture, catchment wetness or snowmelt[150,151,153]. Moreover, other potential drivers, such as dams or land-cover changes, could not be related to observed river flood changes at the regional scale[155]. For instance, floods in northwestern Europe predominantly result from winter rainfall associated with high soil moisture, and the observed upward flood trends follow increases in winter rainfall and soil moisture[150].

Further evidence for a clear climate signal in flood observations is found for Europe when analysing trends in flood timing[24]. For instance, earlier snowmelt has led to earlier flood occurrence in northeastern Europe, whereas later winter storms caused later flood occurrences in the North Sea region. The regional trends in flood timing range from –65 days towards earlier floods to +45 days towards later floods across the past five decades[24]. To what extent these climate-related flood trends are caused by human-induced warming or natural climate variability is not investigated in these flood trend studies, but an association between flood trends in Europe and anthropogenic warming has been suggested[24,150]. Climatic changes have also affected the flood extent[162]. At the Atlantic coast, the United Kingdom and Ireland and in central Europe, flood extent has increased by 9% per decade. In contrast, it has decreased by –11% per decade in eastern Europe. There is a close correlation between trends in flood extent and magnitude[162]. For regions with upward trends, this alignment might challenge flood management more than expected, as floods tend to be higher and to affect larger areas simultaneously than in the past.

One interpretation of the increase in floods in northwestern Europe is the northward shift of the subpolar jet and corresponding storm tracks since the 1970s related to more prevalent positive phases of the North Atlantic Oscillation and polar warming[150,163]. More generally, the amplification of mid-latitude, quasi-stationary atmospheric planetary waves has been suggested as one mechanism for an increased frequency of extreme precipitation and thus more extreme flooding[32,164,165]. The larger amplitude results from the stronger warming in the northern polar region compared with mid-latitudes, weakening the north–south temperature gradient[166]. Such quasi-stationary planetary waves can lead to highly persistent and anomalous weather patterns, and possibly to extreme rainfall and disastrous flooding[167].

The behaviour of extreme floods can be quite different to that of small floods. For example, in a flood time series of the Mekong river, the magnitude of extreme floods has increased, while the magnitude of small floods has decreased[168]. In a large dataset of 2,370 catchments in Europe, a strong correlation of 0.79 between the trends in small and extreme floods was found (FIG. 4a,b)[169]. The overall alignment between trends in small and extreme floods varied between regions as consequence of different flood-generation processes. For instance, the 100-year floods of Mediterranean catchments decreased less than the 2-year floods, owing to the smaller effect of changes in soil moisture on extreme flooding relative to small floods[69,169]. However, this smaller sensitivity of extreme floods to changes in soil moisture does not mean



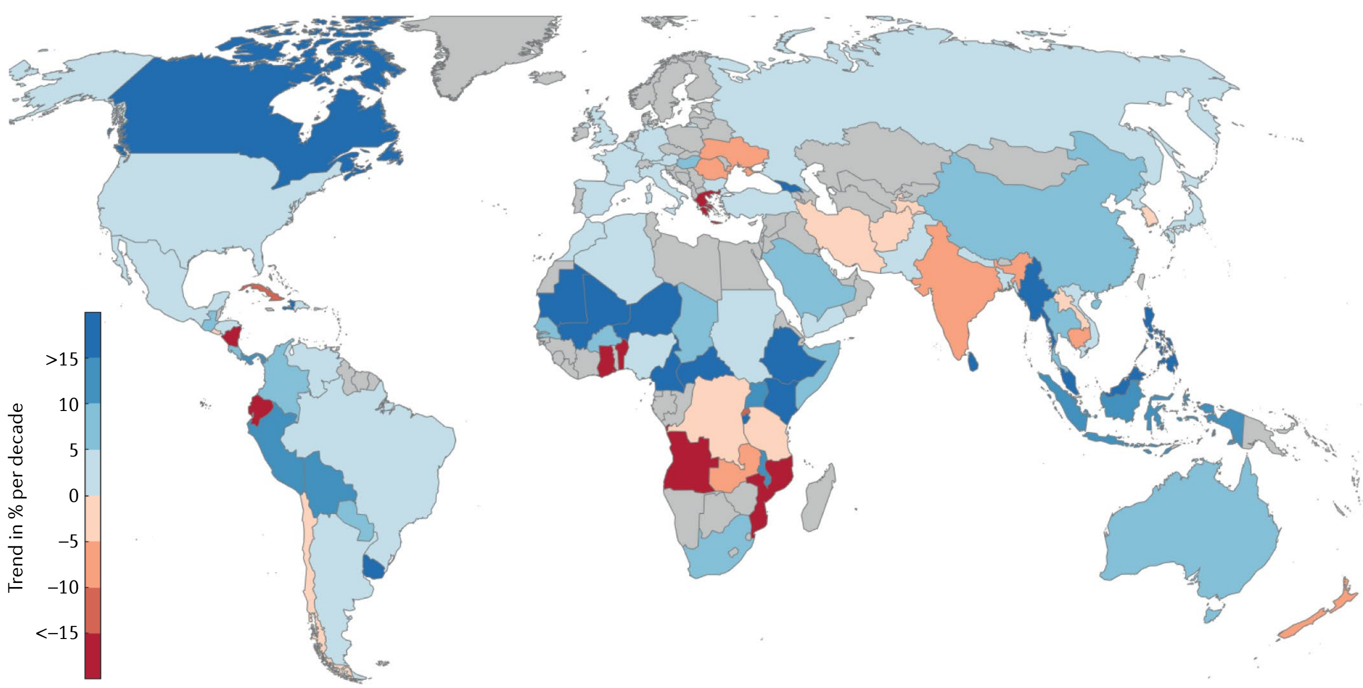


Fig. 3 | **Observed flooding-related trends. a** | Observed trends in annual maximum flow in the past decades based on large-scale trend studies. These trends mostly relate to small floods and might not always be representative of extreme floods. The circles and ellipses represent regions where large-scale trend studies are available and do not necessarily correspond to river basins or administrative units. The trend classification (colours in key) is based on a qualitative assessment, including the availability of large-scale trend studies, the strength and significance of detected trends and the regional coherence of trends. For each region, the specific references and their main findings are given in the Supplementary Information. **b** | Trends in number of people affected by disastrous floods during 1977–2019. Data, based on EmDAT (2020)[172], are not normalized by population growth. Trends (% change per decade) are given as Sen's slope[228] on a country basis. Countries with little data are plotted in grey. The criterion for a country to be plotted is that at least 15 events occurred in at least 5 different years, with a minimum interval of 20 years between the first and last event. The mismatch between trend patterns in hazard and impact suggests that population growth in river floodplains has been a major driver for the increasing number of flood-affected people over the past four decades.

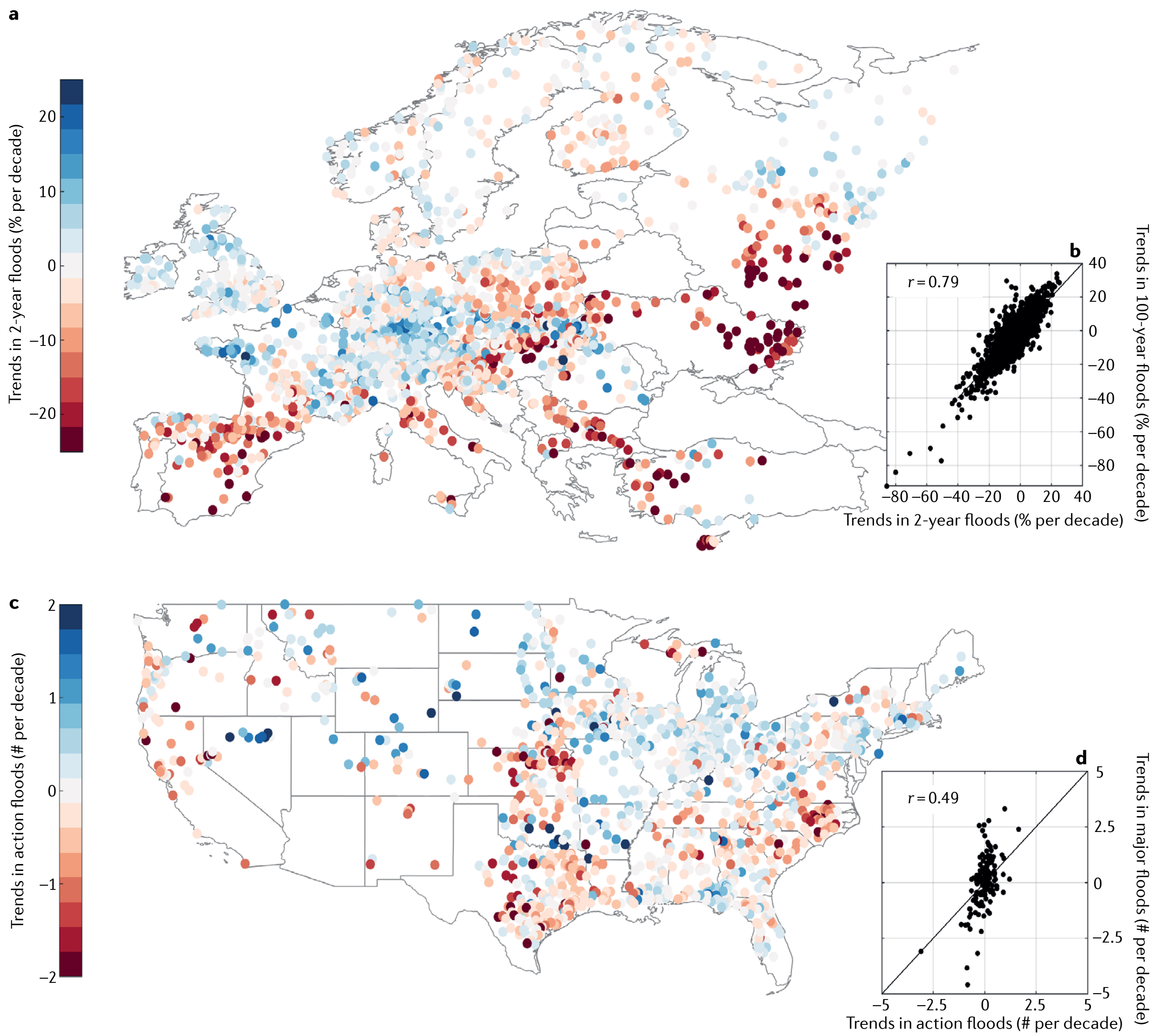


Fig. 4 | **Past changes in flood levels in Europe and the USA. a** | Trends in 2-year floods for Europe for 1960–2010 (based on REF.[169]). **b** | Relationship (Spearman correlation $r = 0.79$) between the trends in the 100-year flood and the 2-year flood. **c** | Trends in action flood levels for USA for 1985–2015 (based on REF.[151]). **d** | Relationship (Spearman correlation $r = 0.49$) between the trends in major flood levels and action flood levels. Major flood level is defined according to the US National Weather Service as having "extensive inundation, significant evacuations, or property transfer to higher ground", and action flood level is defined as "requiring mitigation action in preparation for more substantial flooding". The association between trends in small and extreme floods is disturbed, partly because atmospheric and land surface processes and human interventions have different relevance for small and extreme floods.

Major flood level
Level at which a flood causes extensive inundation, significant evacuations, or property transfer to higher ground.

Action flood level
Level at which a flood does not cause damage but requires mitigation action in preparation for more substantial flooding.

that soil moisture is of little importance for generating extreme floods.

For the USA, trends of major flood levels were significantly correlated to action flood levels based on data from 150 catchments (correlation coefficient of 0.49, FIG. 4c,d)[151]. However, the variation of trends in major flood levels is clearly stronger: the standard deviations of the trends in action and major flood levels are 0.5 and 1.2, respectively. The higher correlation between trends in small and extreme floods for the European dataset relative to the USA dataset might be, to some extent, a consequence of the different approaches used. Trends in the USA action and major floods were estimated based on independent sets of observations[151]. The European estimates were based on a non-stationary flood frequency approach[169], related to the widely used index flood methodology[170], estimating the 2-year flood and the 100-year growth curve. Although this model explicitly allows, and detects, different trends in small and extreme floods, these trends are estimated using the same observations.

In summary, annual maximum streamflow time series, representing mainly small floods, show upward and downward trends for the past decades. Spatially coherent trend patterns and parallel changes in climate variables suggest that, for some regions, anthropogenic warming is already strong enough to override other drivers. Trends in extreme floods are less clear owing to short time series, which only contain a few extreme events. Data for Europe and USA suggest statistically significant correlation between trends in small and extreme floods. However, this general association is disturbed, as atmospheric, catchment and river network processes and the effects of human interventions often differ between small and extreme floods.

Observed changes in flood impacts. Direct impacts on people and economy are documented in global or regional disasters databases[171–174]. Although these time series are uncertain and highly volatile, and great care needs to be taken when deriving trends[175], there are some notable general tendencies.

The number of fatalities and people affected by disastrous river floods increased from the mid-1970s to the mid-1990s, and has since decreased from around 150 million people affected per year to 40 million people, and from around 10,000 fatalities per year to 4,000 (see Supplementary Information). A plausible hypothesis for the recent decrease, despite population growth in many regions, is that risk reduction measures (such as structural flood defence and early warning systems) have been successfully implemented, as has been found for the decreasing mortality of coastal floods[176]. These global trends vary greatly between countries (FIG. 3b) and are dominated by development in Asia. For instance, 80% of the fatalities and 85% of the people displaced by disastrous floods in 1985–2019 occurred in Asia[171]. Flood fatalities in Africa increased by one order of magnitude over the period 1950–2009 (REF.[177]). This increase is particularly pronounced in the earlier decades; fatalities have slightly decreased since the mid-1990s. As annual maximum flows in Africa do not show significant changes, the increase observed over the period 1950–2009 is suggested to be dominated by intensive and unplanned human settlements in flood-prone areas[177].

From 1870 to 2016 in Europe, an increase of 2% per year in the number of flood-affected persons has been reported, in contrast to a decrease of 0.3% per year in flood fatalities[178]. Normalizing the number of affected people and fatalities using the population growth leads to an increase of 0.7% per year and a decrease of 1.2% per year, respectively. Hence, population growth has been an important, but not the only, driver of the increase in affected population. For 1970–2016, the trends of the normalized variables are 0.3% per year for affected people and −2.0% per year for fatalities. This strong decline suggests that risk management has been effective in reducing loss of life in the recent decades.

The trend patterns in annual maximum flow (FIG. 3a) and in flood-affected people (FIG. 3b) show some similarities, such as decreasing trends in both indicators for India. However, a close agreement should not be expected, because changes in flood impacts are not only affected by trends in flood hazard, but also by changes in exposure and vulnerability. There are several regions, such as in China, Australia and North America, with strong upward trends in number of affected people but downward or no regional trends in number of flood peaks. This mismatch suggests that population growth in river floodplains has been a major driver for increasing flood impacts over the past four decades[107].

Time series of economic damage from disastrous floods typically show substantial increases, even after adjusting for inflation, particularly for countries in eastern and southern Asia, Australia and North America[107]. At the global scale, and in contrast to trends in flood fatalities, economic loss per capita increased with growth of GDP per capita[107]. These different developments suggest that economic development has helped to reduce flood fatalities, but has also increased economic loss by increasing the exposure of property values. This conclusion is supported by normalization studies that condition the reported damage by population growth and economic development, which consistently find that upward trends in economic damage vanish after normalization[179]. For instance, normalization by GDP by region reduces the trend in reported economic damage in Europe from 3% to 0.2% per year for the period 1870–2016 and from 1.3% to −1.2% per year for the period 1970–2016[178]. These normalization studies conclude that the increasing exposure of people and economic assets is the major cause of increasing trends in economic damage from flood disasters, although the role played by climate change cannot be excluded[180].

Future changes in hazard and impacts

Future flood changes are typically explored with a scenario approach using simulation models. A typical model chain consists of general circulation models (GCMs) driven by emission scenarios, downscaling to disaggregate the GCM results to the higher resolution needed for flood studies including bias correction, hydrological models to simulate the rainfall-runoff processes, impact models to calculate inundation areas and damage, and statistical models to estimate probabilities of flood peaks and impacts. Early projections were mostly limited to changes in flood hazard[163]. More recent studies include exposure and vulnerability to consider socio-economic scenarios (for instance, using the Shared Socio-Economic Pathways (SSPs)[181]), to simulate the dynamic response of society to disastrous floods[182], and how present and future adaptation strategies might influence vulnerability[108,183–185]. These models estimate a range of impacts including population and property exposed[186], damage to urban areas and economic sectors[4,187–189], and mortality[4,108].

Global studies based on different subsets of CMIP5 GCMs and hydrological models that analysed future changes in medium to extreme floods (30- to 100-year floods[186,190,191]) show similar qualitative trends of flood hazard in most regions (FIG. 5a). Relevant increases in flood hazard are projected for most of sub-Saharan Africa, east and south Asia, northwestern Europe, northern Russia and specific regions in South and North America. Decreasing trends are projected in eastern Europe, southwestern Russia and northern Africa, whereas other areas exhibit less clear trends.

People displaced
According to the DFO, either the total number of people left homeless after the incident, or the number of people evacuated during the flood.

CMIP5
Coupled Model Intercomparison Project Phase 5; for coordinated climate change experiments for the Fifth Assessment Report AR5 of the Intergovernmental Panel on Climate Change and beyond.

These trends differ in part from the outcomes summarized in the earlier IPCC Special Report[163], where a more generalized increase in flood hazard was projected worldwide. Future flood trends have been explained with projected trends in precipitation and wetness conditions[163]. However, the links between projected extreme

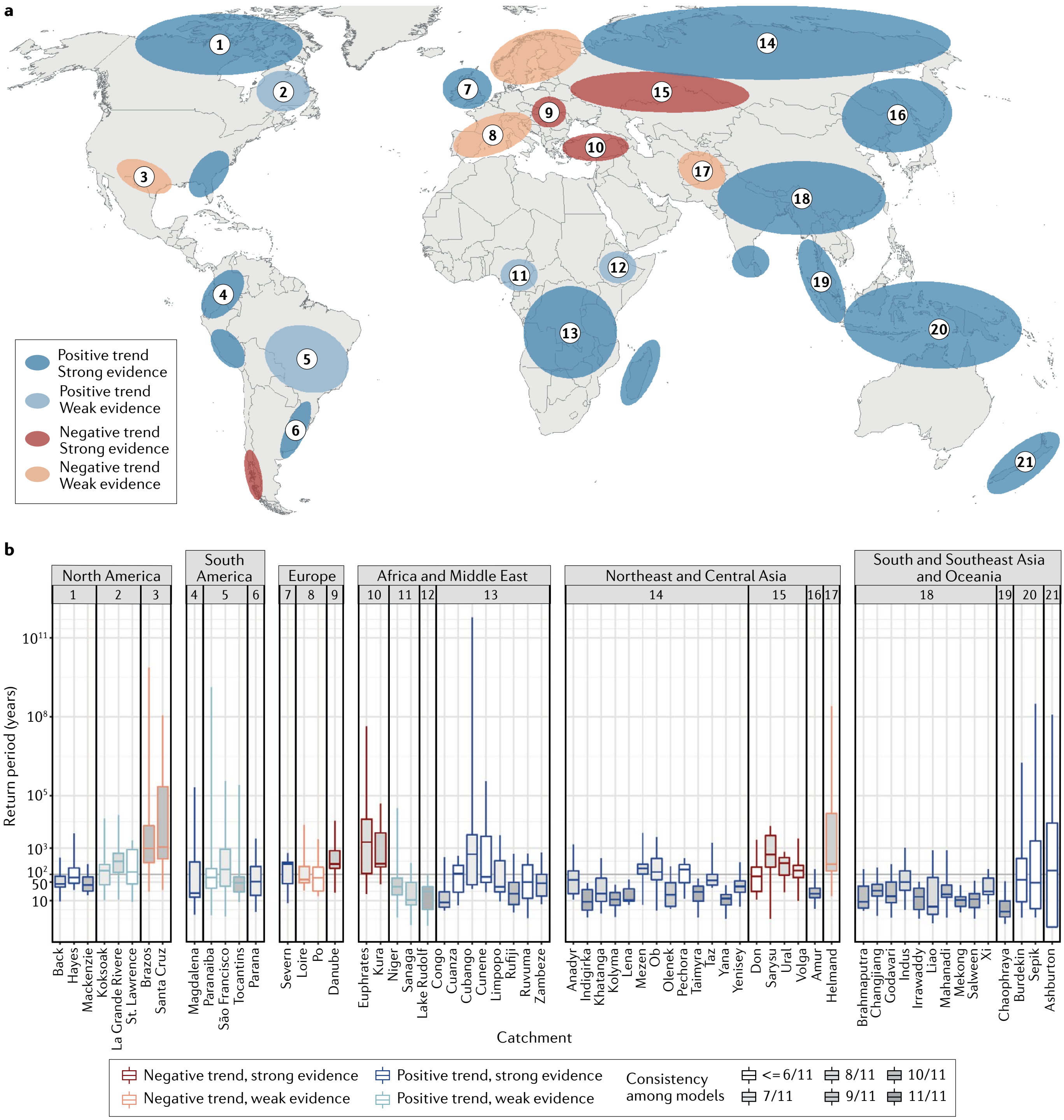


Fig. 5 | **Projections of extreme river floods. a** | Future changes in river flood hazard based on projections of regional changes in the 100-year flood peak of the twenty-first century[186,191]. Blue ellipses show increasing flood hazard, that is, the twentieth-century 100-year flood discharge will occur more often in the future. Red ellipses indicate the opposite (decreasing flood hazard, less frequent 100-year flood discharge). Changes are shown for regions where the two studies are consistent. **b** | Projected (2071–2100) return period of the baseline period (1971–2000) 100-year flood discharge at the outlets of 63 river basins[186]. Catchments are grouped according to subregions, indicated by the numbers in the ellipses. The boxplots show the return periods for 11 climate models. The box indicates the interquartile range and the solid line within each box indicates the median. The whiskers show the maximum and minimum return periods for all 11 models. Boxplot colours corresponds to the colours of the respective ellipses in the top panel. Grey shading shows the consistency between the 11 climate models in relation to the direction of change (upward or downward). These global studies mostly agree on the overall patterns of change, but large differences between model projections are found for river basins. For details see Supplementary Information.

Return period
An indicator expressing the exceedance probability or rarity of an event. For instance, a 100-year flood discharge has a probability of 1/100 of being exceeded in a given year.

Flood frequency curve
Relation between flood discharge and the associated return period.

floods and changes in atmospheric drivers (such as jet streams, monsoonal flows, tropical cyclones and storm tracks) have yet to be understood in detail.

The twenty-first-century return period of the twentieth-century 100-year flood discharge has been projected for selected rivers, based on the worst-case, business-as-usual emission scenario Representative Concentration Pathway RCP 8.5 (FIG. 5b)[186]. Large differences in the model results are obvious, although this rather limited multi-model ensemble probably does not sample the full uncertainty range. With the exception of some catchments in Asia, the 11 CMIP5 GCMs do not agree on the sign of change. Further, the range in projected return period can span over several orders of magnitude. The latter is partly the result of the sensitivity of the flood frequency curve, where a modest change in discharge can be associated with a large change in return period.

The patterns of observed flood trends (FIGS 3,4) do not agree well with those of projected changes in flood hazard (FIG. 5). The projections suggest mainly increases, in contrast with the past changes, which are mostly downward. This discrepancy, noted earlier[17,192], might be explained as follows. First, a past trend in flood characteristics does not necessarily need to continue into the future, even with a warming climate in both periods. One example is a change in flood-generation process, such as a switch from snowmelt floods to rainfall floods. In a warming climate, catchments at lower elevations will experience such a switch earlier than higher-altitude catchments in the same region. Once such a threshold has been passed, a temperature increase has different consequences for floods compared with a similar temperature increase below the threshold. Second, projections and observations consider different drivers of change. Projections represent only the effects of climate change, whereas streamflow observations are affected by a variety of non-climatic influences. Finally, projections of floods are plagued with large biases and uncertainties, and trend studies are often not robust owing to high variability and low-frequency variations in flood records.

Although global models strongly differ in flood impact estimates, there is a general qualitative agreement on future flood risk trends[4,187,188]. Future risk hotspots are expected in Asia and Africa, owing to the combined effect of climatic and socio-economic drivers[187,188]. Impacts in Asia have been estimated to represent more than two-thirds of the global future losses and more than half of the future population affected[4]. Assuming a global average temperature 2 °C above pre-industrial levels and a rapid and fossil-fuelled socio-economic development (SSP5), but time-constant flood protection and vulnerability (for details see Supplementary Information), there would be a widespread increase in the number of flood-affected people (FIG. 6a). A few countries would experience an increase of more than 200% relative to the period 1976–2005. Economic damage would also increase substantially in most countries, mainly because of economic growth, with a few exceptions in eastern Europe, Russia and the Middle East. All continents are expected to experience substantial increases in flood-affected people and direct damage for a future warmer world and the SSP5 scenario (FIG. 6b). Globally, the number of flood-affected people would rise from 57 million (1976–2005) to 101 million and 127 million for warming levels of 2 °C and 3 °C, respectively. The global direct economic damage would grow from 110 billion Euros (2010) to 687 and 1,237 billion Euros (2010), respectively.

Validation analyses show that GCMs and impact model ensembles have some skill in simulating extreme events, even though uncertainty bounds are very large[4,191]. There is disagreement in the sign of flood hazard projections in some regions[17], and even larger uncertainties are seen in impact projections compared to hazard projections[4,193]. These uncertainties result from differences and deficiencies in global and regional climate and impact models, and downscaling and bias-correction methods[17]. The specific selection of GCMs and hydrological models within an ensemble can result in substantial differences in flood hazard projections at the regional scale[192]. For instance, the response of mid-latitude precipitation extremes to global warming at the regional scale is strongly influenced by changes in circulation patterns, and these dynamic aspects of atmospheric response to climate change are not well understood and modelled[194,195]. Different assumptions, for example, regarding emission and socio-economic scenarios, additionally complicate the comparison between projections.

The true uncertainty of twenty-first-century projections might even be larger because their uncertainty has only been partially explored[194,196]. Most climate impact model chains contain hydrological models that were not originally designed to reproduce floods. Processes that are of particular importance for disastrous floods, such as failures of flood defence measures, are not included or are represented in a simplified way, owing to data scarcity and the complexity and uncertainty of simulating these mechanisms[197,198]. The models used to estimate flood impacts are even less advanced compared with flood hazard models. Simple approaches, such as depth-damage functions, are used where the damage per asset or land-use class depends only on the inundation depth, ignoring important adaptation aspects such as the effect of early warning or private precautions[199,200]. In addition to these challenges, projections of future changes need to make assumptions about the future states of the flood risk system under study. Most often, flood hazard and impact models are calibrated using past observations and are then driven by future climate forcing without considering other potential changes or societal adaptations. However, catchments, river systems and their related socio-economic systems have undergone tremendous changes in the past, and substantial but unknown variations that are not driven by climate change must be expected in the future as well. Given these uncertainties and biases, the projections of extreme floods and their impacts need to be treated with utmost care.

Future perspectives

This review provides a synthesis of the atmospheric, land surface and socio-economic processes that cause disastrous river floods. The reasons that an event

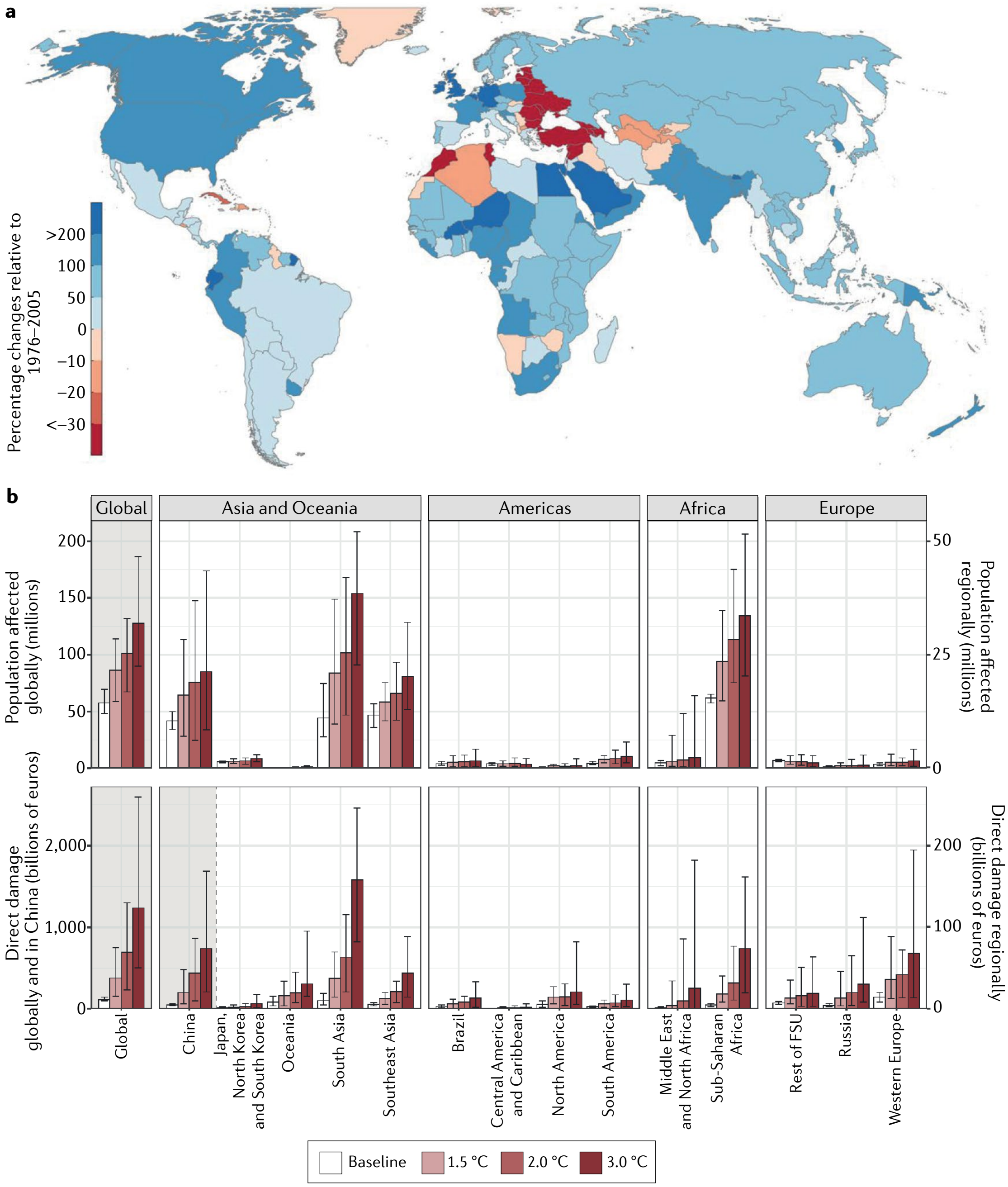


Fig. 6 | **Projections of river flood impacts.** Flood impacts based on REF.[4]. **a** | Future changes in number of people affected by river floods relative to 1976–2005 for the SSP5 (fossil-fueled development) scenario[229]. The future period is a 30-year period centred on the year with a global average temperature 2 °C above preindustrial levels (varying between 2030 and 2055, depending on the general circulation model). **b** | Number of people affected and direct flood damage per year for the baseline period 1976–2005 and for three levels of global warming (1.5–3.0 °C above preindustrial level) for the SSP5 scenario and aggregated to macro-regions. Bars indicate the ensemble average and the whiskers indicate the ensemble range. For all continents, substantial increases in flood-affected people and direct damage are expected for a future warmer world and rapid and fossil-fuelled socio-economic development. Bars with grey background shading refer to the left *y*-axis, bars without shading refer to the right *y*-axis. For details see Supplementary Information.

develops into a disaster are manifold. There is the lack of resources and income, translating into unprotected and vulnerable populations, which can turn even a small flood into a disaster[2,201]. Equally, disastrous floods are often associated with atmospheric, land surface and socio-economic mechanisms that differ from those of non-disastrous floods. They contain an element of surprise for affected people and decision makers, as in the case of rare climate anomalies leading to the superposition of extreme event rainfall and wet antecedent catchments, failures of major flood defence structures, and the unnoticed growth of exposure and vulnerability during an extended flood-poor period. Similarly, supply chain disruptions can extend across thousands of kilometres; such disruptions are specific to disastrous flooding and do not occur during non-disastrous floods.

Flood risk management is thus confronted with the challenge of understanding the mechanisms that might turn flood events into disasters, of estimating the associated risks, and of developing adequate risk reduction measures, some of which have lifetimes of several decades. Extrapolating historic observed behaviour is insufficient to address these challenges, because the past might be a poor guide to the future. Current projections of flood hazard and risk are also perceived as insufficient for guiding risk management decisions, given that important controls on flood risk are not considered and given the substantial biases when simulating extremes and their consequences[194]. It has been argued that disaster impact projections can only be given for one or two decades into the future, owing to unknown changes in vulnerability and dynamic relations between climate change, economic growth and violent conflicts[180]. For instance, a flood risk assessment for Europe found that future adaptive behaviour of households and governments, which influences flood vulnerability, can largely offset climate-driven increases in risk[128].

One key to improving disastrous flood prediction is improving the understanding of mechanisms that can lead to disastrous floods, and of how these mechanisms differ between disastrous and non-disastrous floods. Knowledge about small floods is often extrapolated to estimate extreme floods and their impacts. For example, the standard assumption in flood frequency analysis considers floods to be independent, identically distributed realizations, neglecting the possibility that extreme floods might be generated by mechanisms that differ from those generating most flood events. Hence, we recommend dedicated efforts to investigate the events at the upper tail of flood frequency and flood loss distributions. Historical events can be a rich source from which to infer details and storylines: how the triggering event evolved or could have evolved into a disaster[194,202]. Therefore, historical disastrous flood events and their root causes must be explored in detail, following the forensic disaster investigations concept[203]. Historical near misses, which could have developed into disastrous events but did not, should be investigated to supplement this dataset. Attempts should additionally be made to identify possible disastrous flood scenarios or possible future developments that are preparing the ground for disastrous floods, by simulation or expert inference[204,205]. For instance, in the flood risk assessment for the city of Rotterdam in The Netherlands, the scenario space has been widened by exploring imaginable surprises, termed wildcards[206].

Another key in disastrous flood prediction is to understand better the potential for surprise and the consequences of limited knowledge. Understanding whether a given flood risk system is 'surprise-prone'[207] will support reasonable judgements about whether surprise is negligible, non-negligible but small, or substantial[208]. For instance, many regions experience multi-scale (inter-annual to century-scale) quasi-periodic variations in climate that can translate into dramatic shifts in the occurrence probability of floods. Given limited records, a regime transition then comes as a surprise even for long record lengths[209]. Other sources of surprise are threshold processes, such as failures of defence systems, or cascading effects and compound events[119,210].

Human behaviour during floods, between flood events and in flood-poor periods can also lead to surprise-prone situations[5,6,135]. Cognitive biases in human perception and decision making[211] contribute to surprises by distorting risk perception and flood risk assessments[207,208]. A widespread problem is availability bias; one assigns a higher probability to events that are more readily available, such as events that one can recall from memory or imagine easily, but downgrades the probability of events that are difficult to imagine. There is also an inherent human bias when reflecting about counterfactuals, that is, how a past event might have developed in another way. Upward counterfactuals, which are alternative realizations of the past with a better outcome than in reality, are favoured[212].

Natural scientists, engineers and social scientists must cooperate to develop methods and protocols for understanding, reporting and reducing the potential for surprise in flood risk systems, and to understand how cognitive biases affect the implementation of flood adaptation. Cognitive biases should be reduced by debiasing approaches[207,213,214]. For instance, when exploring the possibility space of future floods, biases of wishful thinking should be avoided by purposefully constructing downward counterfactuals. These scenarios can be constructed by starting from historical floods and exploring alternative realizations in which things turn out worse[212]. Admittedly, it might not be possible to assign probabilities to such scenarios. Yet, scientifically constructed storylines are important contributions to the characterization of risk, complementary to the probability-based risk assessment approach, and to risk communication[194].

Finally, risk assessments should evaluate whether surprises and uncertainty could lead to disastrous consequences[207]. Besides the traditional way of assessing the plausibility of our models, it is necessary to know whether there could be disastrous consequences should our assumption and models be wrong, or if the future evolves outside the range of our scenarios[215,216].

To mitigate disastrous river floods, risk management must be attuned to their risk characteristics in terms of uncertainty, and the potential for surprise and catastrophic consequences[217]. In most cases, routine-based risk management strategies, such as introducing laws or regulation, and risk-based decision-making will not suffice given the large uncertainty about flood risk systems and their future evolution. Risk management should attempt to account for limited knowledge and unexpected developments. In the last decades, strategies with this ambition have emerged in water resources management and disaster risk reduction, which can loosely be clustered under the term 'decision-making under deep uncertainty'[218,219]. They include robust decision-making[220,221], adaptive flood risk management[222], dynamic adaptive policy pathways[223], info-gap decision theory[224], decision scaling[225], resilience-focused strategies[226,227] and the

Risk-based decision-making
Optimizing risk reduction measures based on the best available knowledge.

'building back better' strategy, which has been officially described in the United Nations' Sendai Framework for Disaster Risk Reduction[130]. We call for transdisciplinary research to operationalize these concepts and translate them to the (often local) practice of flood risk management to fully harness their benefits for mitigating disastrous river floods.

Data availability

The authors declare that the data supporting the findings of this study are available within the article and its supplementary information files. Other data can be provided by the authors on request.

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