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Three hypotheses on changing river flood hazards

Günter Blöschl[1],*

[1] Institute of Hydraulic Engineering and Water Resources Management, Vienna University of Technology, Karlsplatz 13/223, 1040 Vienna, Austria

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Correspondence: Günter Blöschl (bloeschl@hydro.tuwien.ac.at)

Abstract. There is serious concern that the hazard, or probability, of river floods is increasing over time. Starting from narratives that are sometimes discussed in public, the article addresses three hypotheses. The first suggests that land use changes, such as deforestation, urbanisation and soil compaction by agriculture, increase flood hazard. This review finds that land use effects on floods are particularly pronounced in small catchments as soil permeability plays an important role in infiltration at this scale. For regional floods, and the most extreme events, land use is usually not the most important control, as areas of soil saturation play a greater role in runoff generation, which are less dependent on soil permeability. The second hypothesis suggests that hydraulic interventions and structures, such as river training, levees and dams, increase flood hazard. This review finds that hydraulic structures have the greatest impact on events of medium magnitude, associated with return periods of tens to hundreds of years, and that their effects are usually local. Long-term interactions between humans and floods must be taken into account when predicting future flood hazards. The third hypothesis suggests that climate change increases flood hazard. This review finds that, in small catchments of a few hectares, flood hazard may increase due to convective storms. In large catchments, where regional floods occur, changes are not necessarily directly related to precipitation, nor are they directly related to rising air temperatures, but are determined by the seasonal interplay of soil moisture, snow and extreme precipitation via runoff generation. Increases and decreases in flood hazard have been observed worldwide. It is concluded that significant progress has been made in recent years in understanding the role of land use, hydraulic structures and climate in changing river flood hazards. It is crucial to consider all three factors of change in flood risk management and communicate them to the general public in a nuanced way.

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1 Introduction

Floods are a threat to humans. Floods involve unusually high water levels that inundate the landscape in diverse settings, be it in urban areas, in mountains, at the coast or along rivers. Inundations along rivers in particular, can cause major damage to infrastructure and surprise citizens when water levels rise rapidly. The action of flowing water, sometimes combined with sediment and debris, adds to the damage. River floods are therefore one of the most costly natural hazard, both in financial terms and in loss of life (World Economic Forum, 2022). In the twentieth century, river floods have caused a direct global average annual loss of US$ 104 billion (UNDRR, 2015) and claimed about seven million lives (Doocy et al., 2013). It is therefore understandable that societies, have always strived to reduce the likelihood of being flooded through flood management instruments.

The instruments fall into two categories (Blöschl, 2017). The first are non-engineering (or non-structural) instruments such as evacuation (to minimise loss of life), regional planning (to ensure flood prone areas are not developed or existing buildings are relocated to less risky areas) and flood insurance (to offset the negative economic impact of flooding). The second are engineering (or structural) instruments such as land use change (e.g. afforestation to increase infiltration), flood storage (to hold back some of the flood water upstream of the point of interest), levees and mobile walls (to prevent flood plain flooding), local flood proofing (to reduce damage to buildings) and dredging (i.e. deepening the channel to increase its flood conveyance).

Both types of instruments require accurate estimates of the flood hazard, i.e. the probability that a location will be flooded in a year, or the probability that the peak runoff of a given magnitude will be exceeded in a year. (The peak runoff represents the maximum volume per unit time flowing through a cross section of a stream during a flood event, measured in m^3/s). There is a very good reason why accurate estimates of the flood hazard are so important. All the instruments can be implemented to different extents. Levees can be higher or lower, flood storage reservoirs can be bigger or smaller, and insurance coverage can be higher or lower. In general, the instruments are most cost effective (i.e., the reduction in the expected damage is much greater than the cost of the instruments) if the protection level matches the magnitude of the hazard, i.e., the higher the hazard, the higher the protection level. In order to minimise the resource use (e.g. financial resources, land) with the greatest possible benefit, the flood hazard must therefore be precisely known.

Hydrologists have developed a plethora of methods for estimating the flood hazard that can be grouped into two types, empirical approaches based on flood observations, and process based approaches based on the drivers that control the flood magnitudes and their probabilities (Rosbjerg et al., 2013; François et al., 2019; Blöschl, 2022). In both instances, a stationarity assumption has traditionally been made, i.e. the assumption that the future will be “in some ways” similar to the

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past (Montanari and Koutsoyiannis, 2014). Alas, what else can we do but base our predictions of the future on what we have experienced in the past? Yet, the similarity "in some ways" does not preclude accounting for known changes (François et al., 2019). For example, the empirical approaches can involve non-stationary statistical models (Šraj et al., 2016) and the process based approaches can use scenarios of a future, changed climate (Merz et al., 2014; Vorogushyn et al., 2018). The challenge then is to understand exactly what changes in the flood hazard can be expected at a particular location or in a particular context. Figure 1 illustrates how a change in the flood hazard would be reflected in observed time series of flood peak runoff and the associated frequency plots. A common indicator of the flood hazard is the 100-year flood (or equivalently, a flood with a return period of 100 years), which is the peak runoff that is exceeded with a probability of 1% in any one year at a particular location along a stream.

There is growing concern that the changes in flood hazard could be substantial, not least prompted by the numerous devastating floods that have occurred in Europe and around the world in recent years, such as the April 2022 flood in South Africa, the July 2021 flood in Germany with more than 200 fatalities and an event in Henan, China with more than 300 fatalities in the same month; the July 2020 flood in Bangladesh where the monsoon season was one of the worst on record; and the June 2013 floods in central Europe and in Northern India, the latter with more than 5000 fatalities (Merz et al., 2021). This concern is an important topic in the public debate on natural disasters, both because of the threatening aspect of the recent floods, and because of the enormous dimension of resources and political decisions involved (McGrath, 2021; Matczak and Hegger, 2020). It is therefore not surprising that there is a tendency for the debate to adopt oversimplified narratives to explain the causes of disastrous floods (Pielke Jr., 2007; Merz et al., 2015). As early as in 1929, the Yearbook for hydrology in northern Germany, under the impression of the devastating Rhine floods of 1925 and 1926, stated: "The general public has been surprised by the major floods of the last ten years and it is understandable that, in their search for the causes of this unusual phenomenon, they felt they had to blame the various water management measures. Almost the same concerns were expressed earlier when, after a long period of quiet, unexpectedly large floods occurred." LGH (1929, p. 5).

Previous review articles (Merz et al., 2012; Hall et al., 2014; Blöschl et al., 2015) have suggested that river flood hazard may change for three main process reasons: land use change, hydraulic structures and climate change. These are also the main factors to which increases of the flood hazard are attributed in the media and the public discussion with significant policy implications (Gavin et al., 2011). Starting from these narratives this article therefore addresses three hypotheses (Figure 2):

- Land use change increases the flood hazard,
- Hydraulic structures increase the flood hazard, and
- Climate change increases the flood hazard.

For each of these hypotheses I will examine experimental and modelling evidence and discuss to what extent, and under what conditions, the hypotheses are tenable. The article will therefore review recent advances in understanding how and why

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river floods, and their probabilities, change over time. The review is intended to guide future research and ultimately improve the efficiency and robustness of flood management instruments.

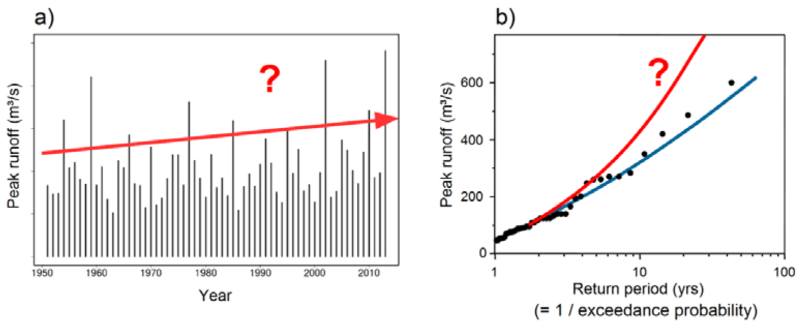

Figure 1. (a) A hypothetical river flood time series. Each bar is the maximum annual peak runoff, and the red arrow indicates an increase in hazard. (b) Flood frequency plot. Each point is the maximum annual peak runoff plotted against its exceedance probability (expressed as its inverse, the return period). Blue fitted line reflects the past situation, the red line a potential increase in river flood hazard. 'Hazard' is defined as the exceedance probability of a river flood level that potentially causes damage.

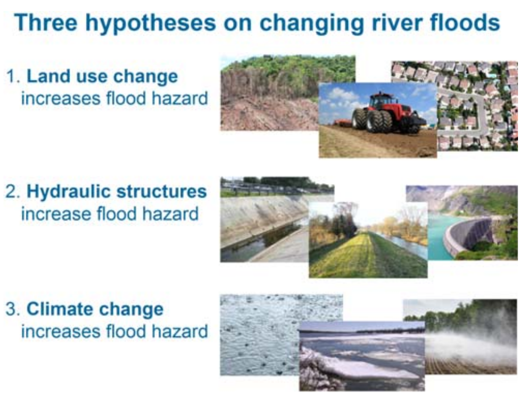

Figure 2. Starting from narratives sometimes discussed by the general public, the article addresses three hypotheses: land use changes, such as deforestation, urbanisation and soil compaction by agriculture, increase flood hazard; hydraulic structures, such as river training, levees and dams, increase flood hazard; climate change increases flood hazard through modified precipitation, snow melt and evaporation.

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2 First hypothesis: Land use change increases flood hazard

Land use change, potentially, has a strong impact on flooding as humans have greatly altered natural landscapes (Rogger et al., 2017). The use of heavy machinery on agricultural land tends to cause soil compaction which reduces soil infiltration, leading to increased surface runoff (Keller et al., 2019). Likewise, urbanisation tends to reduce soil infiltration, and sewage systems may shorten flow paths and thus increase flood peaks (Miller and Hutchins, 2017). Deforestation, such as clear-cutting in forest plantations, may alter soil structure and in turn reduce infiltration (Jones and Grant, 1996; Beschta et al., 2000).

Locally, at the plot scale, these processes are fairly well understood as they are amenable to experimentation. An example is shown in Figure 3, where different plots of land are irrigated with a known intensity of water volume per area, and the surface runoff from the plots is measured. During the experiments, there was almost no runoff from the forest plots (because all the irrigated water infiltrated), while on the grassland plots between 30 and 70% of the irrigated water ran off the surface (Figure 3b). The difference is mainly due to the higher permeability of the forest soils related to macropores, which are thin channels, e.g. created by tree roots, which enhance vertical preferential flow and thus infiltration (Gao et al., 2018). In addition, trees can absorb more water from the soil, thereby reducing soil moisture and increasing soil storage capacity (Figure 3a) (Brown et al., 2005).

At the catchment scale, the impacts of land use change on floods are much less well understood due to the interaction of a number of processes involved in runoff generation (Hess et al., 2010; Rogger et al., 2017; Blöschl, 2022) and due to the inability to measure the exact spatial distribution of the relevant variables in a catchment (Blöschl et al., 2016). Paired catchment studies, where runoff from two nearby catchments, one forested the other deforested, are compared, typically show a greater land use effect on the seasonal water balance than on floods (Brown et al., 2005). Therefore, the usual method for assessing land use change impacts at the catchment scale on floods is to resort to rainfall-runoff modelling (e.g. Kohnová et al. 2019). In these models, the split of rainfall into infiltration and runoff is quantified as a function of soil characteristics (such as its permeability), soil moisture and rainfall characteristics (Beven, 2011). The less permeable the soil and the higher the soil moisture before the event, the higher the runoff. In addition, the models account for evaporation from the soil and the vegetation, which reduce soil moisture.

An example of such a simulation study in a 622 km² catchment is shown in Figure 4. The simulations show that deforestation increases surface runoff, which is mainly due to the reduced infiltration and partly to higher soil moisture. The effect is slightly larger if the soils are dry at the beginning of the event. On the other hand, afforestation decreases surface runoff but its impact depends on the event magnitude. While, for the smallest events, the peak runoff reduction is about 75%,

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it is close to zero for the largest events simulated. This is because the soil becomes saturated during the largest events, so the soil structure no longer matters. This decrease of land use change effects with event magnitude is echoed by numerous plot-scale experiments and catchment-scale simulation studies, and thus seems to be quite universal (Rogger et al., 2017). As an aside, the effect of land use change on landslides is quite different, since the weakening of soil strength associated with deforestation may increase landslide risk for small and large rainstorms alike (Glade, 2003). As a consequence, the risk of combined landslide-flood events and debris flow events resulting from extreme rainstorms may very well be exacerbated by deforestation (Lorente et al., 2002).

One may think of a catchment to consist of many small plots, similar to a mosaic, so it seems at first glance that catchments should behave similarly to a collection of small plots, regardless of the scale of the catchment. However, this is not the case because there are very important scale effects in flood generation (Blöschl and Sivapalan, 1995; Blöschl, 2022). The main scale effect is as follows. In small catchments of a few hectares, the flood response to a rainstorm tends to be rapid, on the order of ten minutes. This is the time it takes for the raindrops, or the water they push out of the soil, to reach the catchment outlet, and this time is short because of the short flow distances of a few hundred meters. Now, catchments act as filters in the sense that the largest floods are generated by storms whose duration is similar to the catchment response time, everything else (including the rainfall probability) being equal Viglione and Blöschl, 2009). This principle is used in flood design by the Rational Method (Mulvany, 1851). In small catchments, therefore, it is the short storms that produce the largest floods and these are storms with high rainfall intensities, often because of their convective origin (thunderstorms). During short, high intensity storms, the dominant runoff generation mechanisms is infiltration excess (Figure 5, left), i.e. a mechanism in which the soil starts getting saturated from the top, and the wetting front moves down. Surface runoff is generated if the rainfall intensity (which is high) exceeds the infiltration capacity. Since the infiltration capacity is essentially determined by the soil permeability, the surface runoff produced depends heavily on the land use. In small catchments, flood runoff can therefore be expected to be quite sensitive to land use change.

In larger catchments, from a few to thousands of square kilometres, the situation is different. The flood response to a rainstorm tends to take longer, on the order of hours or days, because of the longer flow distances (Gaál et al., 2012), and thus longer duration, lower intensity storms tend to be the most critical. This notion is fully in line with general experience, as the biggest floods in large river basins, such as the Danube, are never caused by local thunderstorms, but rather by regional, persistent rainfall over days (Blöschl et al., 2013). During long, lower intensity storms, the dominant runoff generation mechanisms is saturation excess (Figure 5, right), i.e. a mechanism in which the soil starts getting saturated from the bottom as, initially, the low rainfall intensities can infiltrated easily. The wetting front then moves upward from an impermeable layer in the ground. Surface runoff occurs as soon as the local groundwater table reaches the surface, i.e. surface saturation is reached. Since the depth to the impermeable layer is rarely controlled by land use, the surface runoff

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produced depends very little on land use. In large catchments, flood runoff can therefore be expected not to be sensitive to land use change.

This reasoning is born out by the simulations for a 9700 km² catchment in Figure 6. In this study, stochastic rainfall simulations were combined with a distributed rainfall-runoff model to generate long series of peak runoff, which were analysed statistically. Two scenarios are compared, the current situation and afforestation of all the grassland below 2000 m a.s.l., which is about 11% of the area. The reduction in the 100 year flood is only 4% because saturation excess is the main runoff generation mechanisms for the events relevant at this scale. Unlike Figure 4, at this catchment scale, there is little dependence of the flood reduction on the return period, which is related to usually greater spatial extents of flood producing rainstorms with increasing return period.

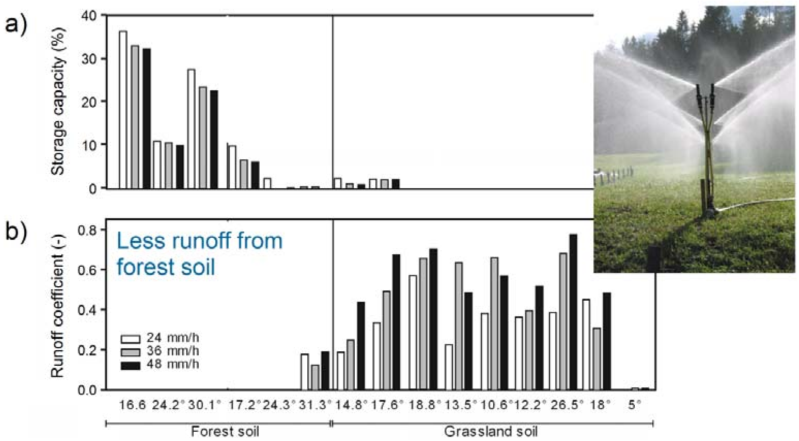

Figure 3. Effect of land use on flood generation from irrigation experiments (see inset photo) in the Bernese Oberland in Switzerland. (a) Storage capacity of the soil (defined as the difference between total porosity and maximal soil moisture measured during infiltration). Each group of three bars gives the results for an experimental site. The grey shades represent different irrigation intensities. (b) Runoff coefficient (defined as the proportion of irrigation water that runs off the surface and does not infiltrate). The forest soils produce much less surface runoff than the grassland soils. Photo: Gerhard Markart. Alaoui et al. (2018).

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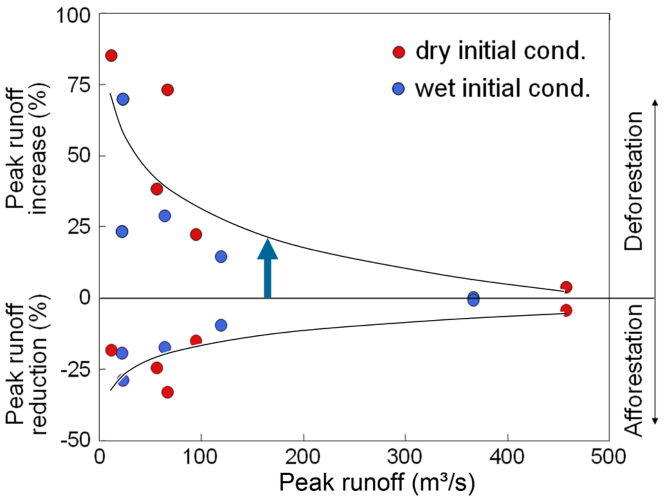

Figure 4. Effect of land use change on flood peak runoff for the 622 km² Kamp catchment at Zwettl in Austria, using a distributed rainfall-runoff model. Upper part of the figure: increase in peak runoff of a scenario of complete deforestation relative to the observed baseline case of 47% forested area, plotted against the peak runoff of the baseline case. Lower part of the figure: same but for afforestation (increase in forested area from 47% to 86%). Each point represents one event, and the initial soil moisture is shown as colour. Deforestation reduces infiltration and thus increases surface runoff. The effect decreases as the event magnitude increases. Modified from Salazar et al. (2012).

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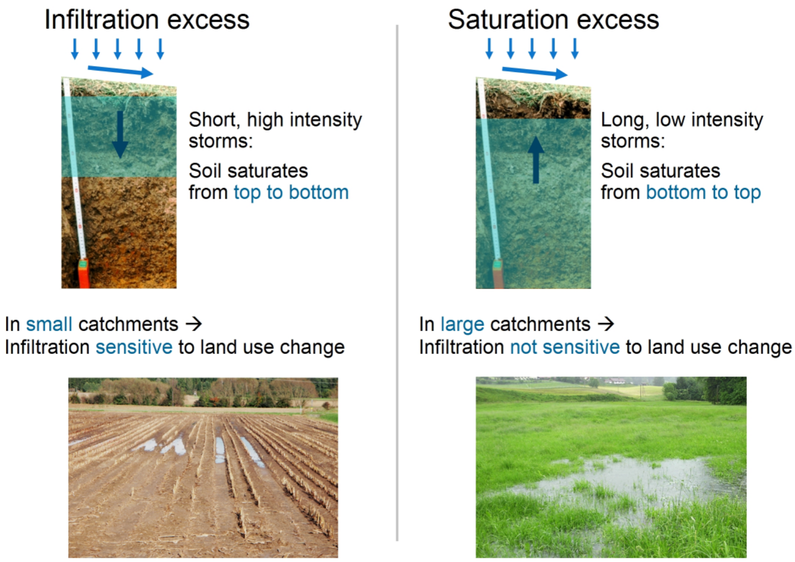

Figure 5. Two runoff generation mechanisms and their impact on the sensitivity of flood runoff to land use change. Left: The infiltration excess runoff generation mechanism often occurs in small catchments because the most critical storms tend to be short and of high intensity. In this mechanism the soil saturates from the top the bottom, and surface runoff is generated if the rainfall intensity exceeds the infiltration capacity. Right: The saturation excess runoff generation mechanism often occurs in large catchments because the most critical storms tend to be long and of lower intensity. In this mechanism the soil saturates from the bottom to the top, and surface runoff is generated once the entire soil column is filled. Photos: Erwin Murer, Erwin Zehe.

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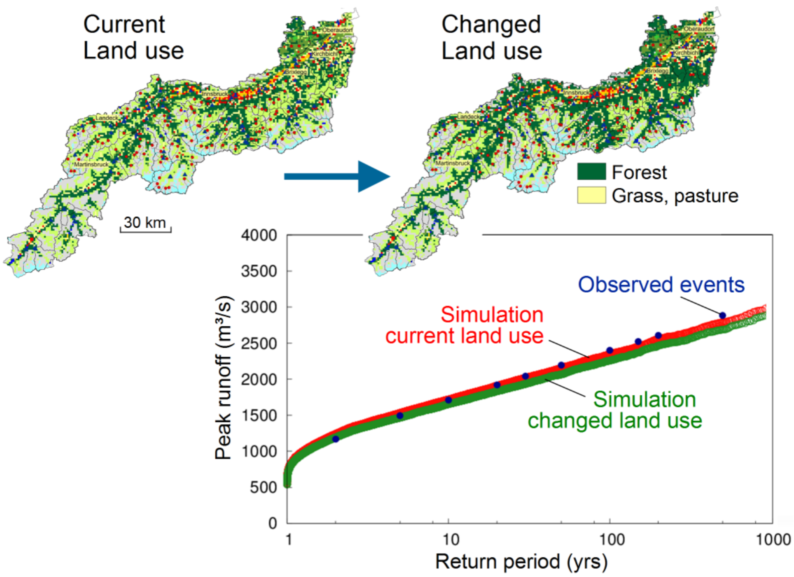

Figure 6. Effects of afforestation on floods for the 9700 km² Inn catchment at Oberaudorf in Austria using a distributed rainfall runoff model. Given the catchment area is large, the relevant runoff generation mechanism is saturation excess and thus the effect of land use change (an additional 100 000 ha of forest) is small. The flood peak runoff associated with a return period of 100 yrs is reduced by only 4%. Blöschl et al. (2018).

3 Second hypothesis: Hydraulic structures increase flood hazard

The effect of hydraulic structures and engineering works on increasing flood hazard is fairly well understood. This is because, in some instances, their effect can be simply estimated by mass balance. In other instances, the hydrodynamic equations of moment balance need to be additionally used, for which accurate parameter estimation methods and efficient numerical schemes exist (Horváth et al. 2020; Buttinger-Kreuzhuber et al., 2019). These techniques, along with recent advances in computing power, have enabled hyper-resolution modelling. For example, in the HORA (Hochwasserrisikozonierung Austria) project, flood hazard zones have been estimated by running a two dimensional hydrodynamic model at 2 m resolution for all of Austria (Figure 7). The main inputs to these models are the flood frequencies, at all locations along the stream network, as shown in Figure 1b and Figure 6.

Dams and the associated reservoirs on a stream are usually constructed for flood control, hydropower generation and/or water supply. These dams create online storage, i.e. during an event, part of the flood water is held back in the reservoir with the aim of reducing the peak runoff downstream of the structure. Because of this, dams rarely increase and usually decrease the downstream flood hazard. The magnitude of the reduction depends on the storage volume that can be leveraged during the flood relative to the volume of the flood wave (Wang et al., 2017; Volpi et al., 2018; Gao et al., 2019). For this reason, flood retention basins are most effective in small catchments where the most relevant flood events tend to be short, as mentioned above, and thus the volumes are small. As the catchment scale increases, events tend to be longer and retention basins, or polders, become less and less effective. The event magnitude also plays an essential role (Figure 8). Retention basins are usually designed in a way to bypass small floods of return periods of a few years, as these are not relevant for flood mitigation. On the other hand, very large floods will fill up the reservoir early in the event (Vorogushyn et al., 2012). At the time of the peak, the reservoir is full, so the available storage volume is zero, and the flood wave passes through the reservoir with little reduction in the flood peak runoff. The greatest reduction is thus achieved for floods with medium return periods, typically around 100 years. Also, the greatest reductions are achieved immediately downstream of the dam, and the effects diminish rather quickly further downstream (Volpi et al., 2018).

River training, or channel straightening, by artificial cutoffs has been a widely used method, in particular in the 19th and first half of the 20th century, for reducing the frequency of overbank flooding by enlarging channel capacity (Blazejewski et al., 1995). Regarding the impact on peak runoff, two situations need to be considered separately, the local reach where the channel is straightened, and the downstream reaches. Locally, the increase in channel capacity and sometimes channel incision resulting from enhanced erosion of the river bed usually translate into less frequent floodplain inundation but little change in peak runoff (Wyzga, 1996; Erskine, 1992). Downstream, on the other hand, flood peak runoff and therefore flood hazard may increase because of the loss of flood plain storage. Analogously to the retention basin case, the magnitude of the increase depends on the storage volume that can no longer be leveraged relative to the volume of the flood wave. Conversely, allowing flood plains to inundate after river restoration works (e.g. removing levees, unstraightening rivers) will only help in proportion to the storage volume leveraged, i.e., $\Delta Q / Q \approx \Delta V_{fp} / V_{flood}$, where $\Delta Q / Q$, ΔV_{fp} and V_{flood} are the relative peak runoff reduction, the storage volume leveraged and the runoff volume of the flood event, respectively. This means, large floodplain areas will need to be reactivated for tangible effects.

The event magnitude also plays an essential role in flood hazard increases from loss of flood plain storage, as illustrated in Figure 9 for a Danube reach in Bavaria. For small floods with return periods of a few years, in the historic situation of the year 1800, the flood plain gets flooded and the storage dampens the flood peak runoff. In the modern situation of 2015 the channel capacity is higher, the flood plain is no longer flooded, so the flood peak runoff is higher. For large floods with return periods of hundreds of years, however, the situation reverses. In the historic situation the flood plain is filled early

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during the event, so little retention takes place at the time of peak. In the modern situation the flood plain is filled later, and significant storage takes place at the time of peak, which reduces the peak runoff as compared to the historic situation. While river training thus tends to increase the downstream flood hazard associated with small events, it may actually reduce it for large events.

From a long term perspective, the interactions between human decisions on building hydraulic structures and changing flood hazards are very relevant. Let us consider the case of the Danube at Vienna (Blöschl, 2014). Up to the mid 19th century, the Danube was a braided river as illustrated at the top of Figure 10. Due to repeated floods (such as those in 1830 and 1862), the government decided to construct a cut through channel in 1870 to increase the channel capacity and thus reduce the flood hazard in the former flood plains. The increased sense of security triggered significant urban development in the decades that followed, as illustrated in the photo from 1930. When a major flood hit the city in 1954 the damage was therefore immense, which made the government build a relief channel in the 1970s. The latter triggered even more urban development. This phenomenon of human-flood interactions is known as the levee effect (Burton et al., 1968; Viglione et al., 2014), where the attempt of increasing protection increases rather than decreases the damage potential and the flood risk. Such unintended consequences are studied in socio-hydrology (Sivapalan et al. 2012; Sivapalan and Blöschl, 2015; Barendrecht et al., 2019) with the aim of more holistically understanding changes in flood hazard.

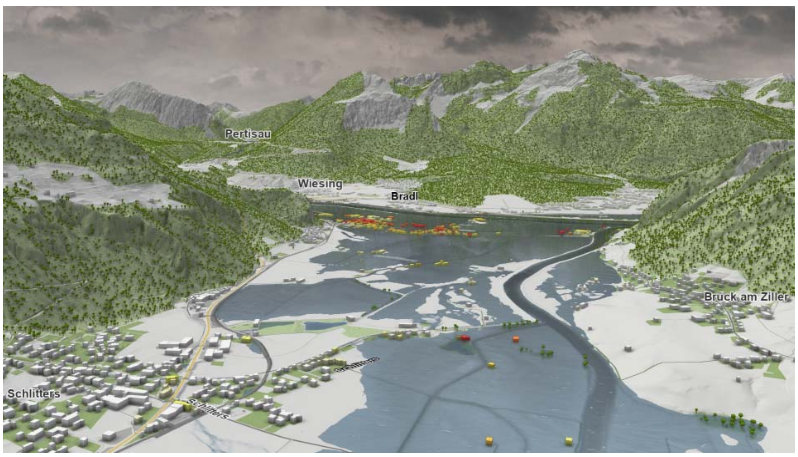

Figure 7. Flood inundation modelling at hyper-resolution in Austria using a two dimensional hydrodynamic model at 2 m resolution nationwide. The flood hazard zones are associated with a return period of 100 years of the peak runoff. Published by the Ministry of Agriculture, Regions and Tourism as part of the HORA flood risk zoning project on https://www.hora.gv.at (website visited on 1 June, 2022). Blöschl et al. (2022).

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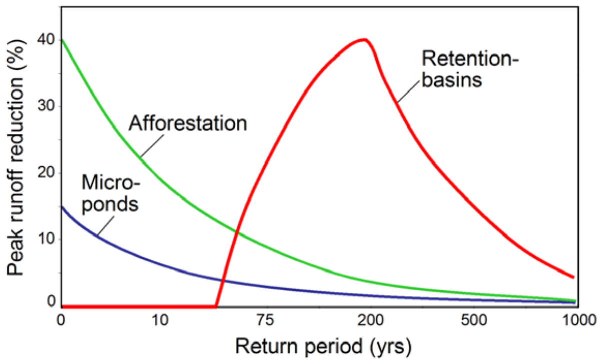

Figure 8. Effect of retention basins, microponds and afforestation on reducing flood peak runoff (schematic). Retention basins typically have little impact on small floods as they pass through the basins without alteration, little impact on the largest floods as the retention basins tend to fill up early in the event, and most impact on medium floods. The effect tends to be largest for small catchments that produce short flood events with small runoff volumes. Salazar et al. (2012).

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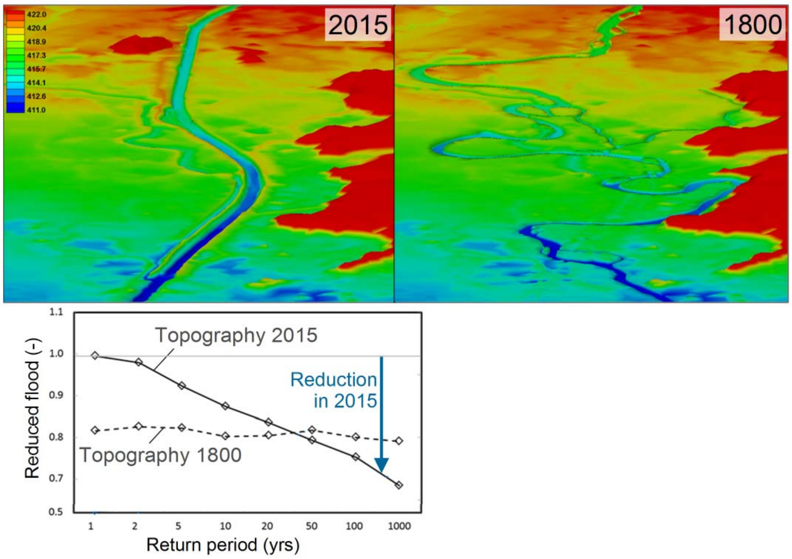

Figure 9. Effect of river training on peak runoff for a reach of the Bavarian Danube near Donauwörth using a 2 dimensional hydrodynamic model. Top left: topography of the Danube and its flood plain in 2005, reflecting the straight channel due to river training.
305 Top right: topography in 1800, reflecting the meandering morphology of the stream. Colours are elevation (m). Bottom: Flood peak relative to a reference case (1 indicates no change from the current situation with a return period of 1 yr. The loss of storage volume in the flood plain between 2015 and 1800 mainly concerns small events, while for large events the river training has little effect on peak runoff. Skublics et al. (2016).

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Figure 10. Long term human-flood interactions illustrated for the Danube at Vienna, Austria. In 1830 the river near Vienna was braided. As a consequence of devastating floods, a cut through channel was constructed in 1870, as seen in the 1930 photo. The enhanced protection triggered urban development on the flood plain, which required an additional relief channel constructed in 1970, which eventually led to further urban development. The attempt of increasing protection has thus increased rather than reduced the damage potential. These unintended consequences are studied in socio-hydrology. Barendrecht et al. (2017).

4 Third hypothesis: Climate change increases flood hazard

Climate change may increase river flood hazard through altering precipitation, snow melt and evaporation. Future changes are usually assessed on the basis of a model chain in which scenarios of projected socioeconomic global change are used to drive climate models, which produce projections of precipitation, temperature and other variables. These are used as inputs to rainfall-runoff models (Hall et al., 2014) to simulate long series of runoff. The change is then evaluated by comparing the simulated flood runoff peaks of the scenarios with simulations representing the current situation. Such simulations have been performed globally, regionally and locally (see, e.g. Do et al., 2020; Swain et al., 2020). Typically, the smaller the scale, the more detailed information on flood generation processes can be included. The meta-analysis of Merz et al. (2021) of recent

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regional studies around the world indicates increases in the 100 year flood peak runoff during the twenty first century for much of sub-Saharan Africa, eastern and southern Asia, north-western Europe, northern Russia and some regions in South and North America. Decreases are projected for eastern Europe, south-western Russia and northern Africa.

The reliability of such projections naturally depends on the extent to which the flood generating processes in the atmosphere, on the land and in the subsurface are captured (Blöschl, 2022). It is therefore of interest to study the climate induced changes of the past and understand their process controls. Figure 11, again a meta-analysis, shows observed flood trends around the globe in the past six decades for medium sized and large catchments. Increases have been observed in north-western Europe, parts of Japan, Amazonia and southern Brazil, while decreases have been observed in the Mediterranean, India, China, Australia, South Africa and north-eastern Brazil.

When analysing trends, the particular study period is often of crucial importance, as flood peak runoff rarely changes exactly linearly over time (Lun et al., 2020). More commonly, there are decades when floods occur more often and with larger magnitudes than usual. In these long-term fluctuations, oceans may play an important role through climate modes such as El Nino (Liu and Zhang, 2017). This is because the residence times of water and thus the memory of the oceans are on the order of decades or more. The residence times of atmospheric water, on the other hand, are only a few days, and those in catchments are months to years (Szolgayova et al, 2014; Zhang et al., 2022), so they cannot easily explain decadal or centennial flood hazard variability. Figure 12 shows the flood rich periods in Europe during the last five centuries. These periods were identified from more than 100 high-resolution historical flood series based on documentary evidence, such as chronicles, annals and legal records, covering all major regions of Europe. The most severe flood-rich period was 1760–1800 and it covered most of Europe, followed by 1840–1870 (western and southern Europe) and the recent period 1990– 2016, which covered western and central Europe. The recent period, perhaps still ongoing, is thus among the most flood-rich periods in the last 500 years.

For the last six decades there are more detailed flood observations available in Europe which are analysed in Figure 13 in terms of the trends in flood peak runoff for medium sized and large catchments. There are very clear patterns of change. In north-western Europe, the median flood peak has increased by more than 5% per decade for stations with significant changes. In the East and South there are decreases of similar magnitudes. The median flood (corresponding to a return period of 2 years) as shown Figure 13, can be estimated relatively robustly from data, but from a flood management perspective, the hazard associated with more extreme events (such as the 100 year flood) is more relevant. Bertola et al. (2020) therefore analysed the same data set as a function of the return period. They found that, in small catchments in north-western Europe, the 100 yr flood increases more than the 2 yr flood, in southern Europe the 100-year flood decreases less than the median flood, and in eastern Europe the decreases depend little on the return period.

There is of course an extensive literature on the role of climate change in atmospheric processes that give rise to changes in heavy precipitation (see, e.g., Field et al., 2012; Masson-Delmotte et al., 2021). In the context of flood hazard changes, we need to again treat small and large catchments separately, similar to the effect of land use and hydraulic structures. In small catchments of a few hectares, short duration, high intensity storms (usually of convective origin) are most relevant, and there is evidence for the intensities to increase with air temperature (Fowler et al. 2021). The rate of increase found by empirical studies often corresponds to the increasing water holding capacity of the atmosphere (i.e. the Clausius–Clapeyron rate of (~7% K^{-1}). In some regions, the rate is greater, probably because of enhanced feedbacks in convective clouds (Molnar et al. 2015; Lochbihler et al., 2017; Fowler et al. 2021). A general assessment is however difficult, because long series of high resolution (e.g. hourly) precipitation are rather rare and not very accurate, and because summer-winter differences in heavy precipitation are sometimes interpreted to imply decadal correlations. Nevertheless, there are reasons to believe that climate change may indeed increase the flood hazard in small catchments. For large return periods, the increase may be of a similar magnitude to that of precipitation since the rainfall-runoff relationship tends to become linear, while for smaller return periods the relative increase may be larger (Viglione et al., 2009; Breinl et al., 2021).

In larger catchments, from a few to thousands of square kilometres, the situation is different in that convective precipitation is rarely important, but longer duration, lower intensity storms, so the data base is better (e.g. Contractor et al., 2021). In order to shed light on the driving processes, Blöschl et al. (2020) correlated European flood occurrence in the last 500 years with air temperatures and found that most of the flood-rich periods shown in Figure 12 were around 0.3 °C colder than the intervals in between. This finding is in line with a tendency in summer for higher cyclonic precipitation to be associated with lower temperatures because of the enhanced cloud cover and lower solar radiation (Gagen et al., 2016), while the opposite may be true in winter (Hurrell and Van Loon, 1997). In contrast, the flood-rich period of the last three decades was about 1.4 °C warmer than usual. While, sometimes, the higher water-holding capacity of a warmer atmosphere is brought forward as a main reason of increasing floods, the different temperatures of the recent and past flood-rich periods suggest otherwise, pointing to a more important role of dynamic climate circulation processes in modifying flood hazards in medium and large catchments. Similarly, the presence of both increasing and decreasing flood peaks in Europe (Figure 13) indicates processes quite different from an increased atmospheric water-holding capacity at that scale.

In Central Europe, so called “Vb cyclones” that follow a path across the western Mediterranean into central Europe (Van Bebber, 1891), have caused major flood disasters, such as the August 2002 and June 2013 events (Ulbrich et al., 2003; Blöschl et al., 2013). There has been a concern that the frequency of Vb cyclones may have increased in the current flood rich period in Europe, contributing to an increase in flood hazard. However, an evaluation of atmospheric reanalysis data suggests that the frequency of Vb cyclones was high in the 1960s and has remained at a lower level since then (Figure 14a). On the other hand, Vb cyclones do produce much larger extreme precipitation than other cyclone types. For example, in the Erzgebirge region at the German-Czech border, the precipitation exceeded on 5% of the days associated with Vb storms is

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62 mm/day, while it is much lower for other storm types (Figure 14c). The onset of Vb cyclones has been found to be related to a superposition of the polar and the subtropical jet streams over the Western Mediterranean (Hofstätter and Blöschl, 2019), and it is possible that the efficiency of a given Vb cyclone to produce extreme precipitation may have increased.

Other precipitation changes in recent years can be more clearly linked to the atmospheric circulation. The expansion of the Hadley cell (i.e. a belt of air surrounding the globe that rises along the equator and descends at 15-30° north latitude) towards the North Pole has led to a northward shift of the subtropical jet stream and associated storm tracks (Lu et al. 2007; Archer and Caldeira 2008; Kang and Lu, 2012; Xian et al., 2021). This shift has contributed to decreasing precipitation in the South of Europe and increasing precipitation in the North, which is consistent with the flood trend pattern of Figure 13.

While heavy precipitation obviously plays a key role in understanding climate-related increases in river flood hazard, other processes are equally important as illustrated in Figure 15. Under the hypothesis that floods were directly related to heavy precipitation without other effects, their timing within the year would have to be identical, but this is not the case. Floods in northwestern Europe usually occur in winter, a few weeks after the most frequent heavy rains, when the soils are wetter than before. In Northern Europe the most relevant floods occur in spring as a result of snowmelt, while the most extreme precipitation occurs in summer. In other regions of Europe, more subtle, seasonal interactions of soil moisture, snow and extreme precipitation control the timing and thus the magnitude of flooding (Sivapalan et al., 2005; Blöschl et al., 2017). In order to understand changes in flood hazard it is thus not enough to understand the atmospheric processes, but also the seasonal hydrology involved.

A more formal attribution of observed flood changes to changing precipitation, soil moisture and snow melt is shown in Figure 16. In northwestern Europe, the main driver of increasing flood hazard is an increase in heavy precipitation while increases in soil moisture play a more minor role. In southern Europe, the reduction of soil moisture due to increased evaporation is the main control of decreasing flood hazards, and decreases in precipitation are somewhat less important. In eastern Europe, warmer temperatures have resulted in less snowmelt and smaller snowmelt floods which has decreased the flood hazard, and neither heavy precipitation nor soil moisture changes play a relevant role (Kemter et al., 2020). Bertola et al. (2021) suggested that flood peak runoff increases by about 1% if heavy precipitation increases by 1 % (equivalent to an elasticity of 1%/%), and there is little dependence on the return period. In contrast, the elasticity to soil moisture decreases with return period, as would be expected because it approaches soil saturation (see e.g. Grillakis et al., 2016; Wasko and Nathan, 2019), and ranges from about 0.5 %/% in southern Europe to smaller values in the rest of the continent. The elasticity to snowmelt in northeastern Europe is greater that 1 %/% and decreased slightly with the return period.

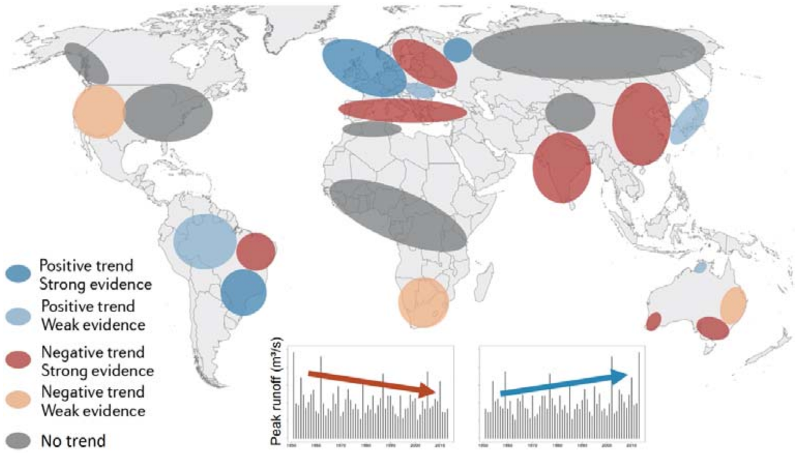

Figure 11. Observed flood trends in the period of approximately 1960-2010 based on the analysis of runoff data. Blue colours indicate an increasing trend, reddish colours a decreasing trend in mean flood peak runoff. The patterns are based on a literature meta-analysis. Globally, there are both increasing and decreasing trends of flood hazard. Merz et al. (2021).

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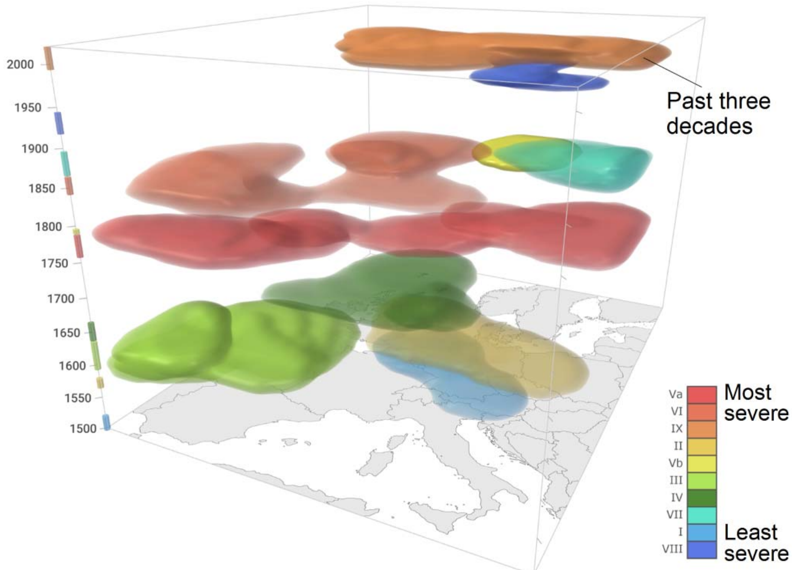

Figure 12. Flood-rich periods in last 500 years in Europe defined as periods and regions in which floods are much larger and more frequent than usual. The flood-rich periods were identified from 103 high-resolution historical flood series based on documentary evidence. The past three decades were among the most flood-rich periods. Blöschl et al. (2020).

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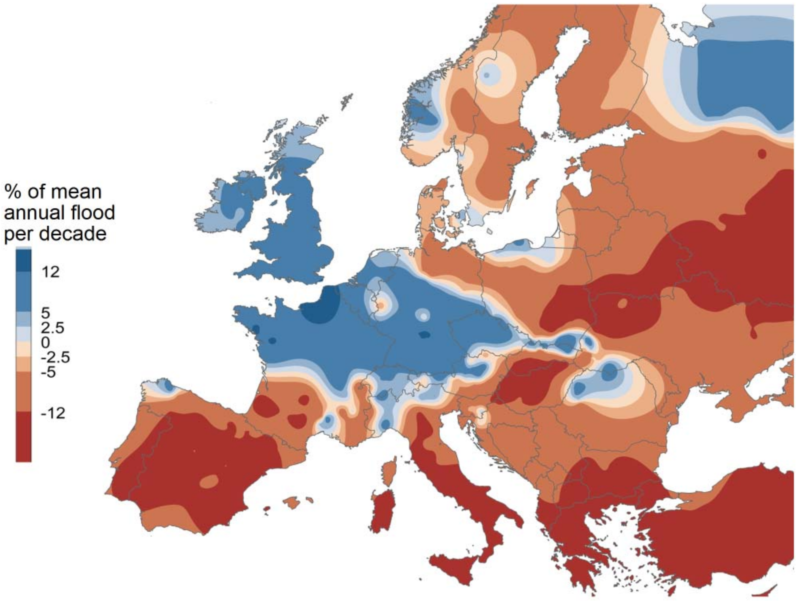

Figure 13. Observed flood trends in the period 1960-2010 based on the analysis of runoff data. Blue colours indicate an increasing trend and reddish colours a decreasing trend in the median flood peak runoff. Only stations with significant trends (significance level α = 0.1) were used in the spatial interpolation (664 stations). Blöschl et al. (2019).

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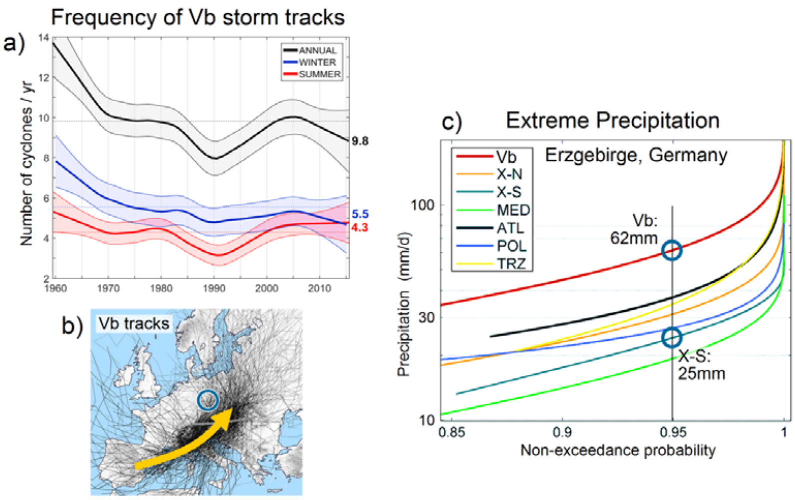

Figure 14. (a) Frequency of Vb storm tracks in the period 1960-2020. (b) Vb tracks (according to Van Bebber, 1891) follow a path across the western Mediterranean into central Europe and are responsible for some of the largest floods on record, such as the August 2002 and June 2013 floods. (c) Vb storms produce much larger heavy precipitation than other track types, as illustrated by the frequency distribution of daily precipitation in the Erzgebirge region, Germany. X-S are storm types that approach from the southeast. Cyclone track analysis based on a combination of sea level and 700hPa pressure from JRA-55 reanalysis data. Hofstätter et al. (2016, 2018); Hofstätter and Blöschl (2019).

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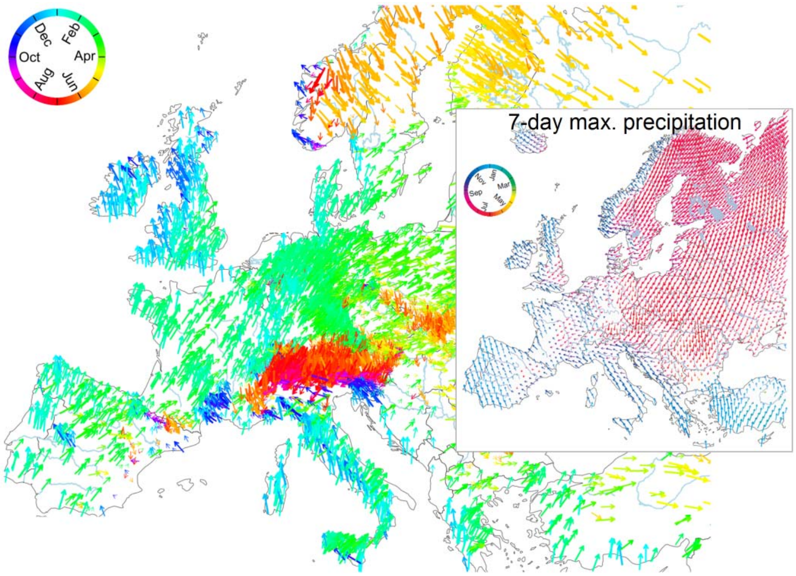

460 **Figure 15.** Average timing of floods within the year to understand changes in flood hazard. Blue arrows pointing upwards indicate winter floods, red arrows downward summer floods. Based on data from 4062 stations, 1960-2010. Inset image shows a similar plot, but for 7-day maximum annual precipitation based on the eobs data set. The flood seasonality differs significantly from that of precipitation, which is because of the seasonal interplay of soil moisture, snow and extreme precipitation. Blöschl et al. (2017).

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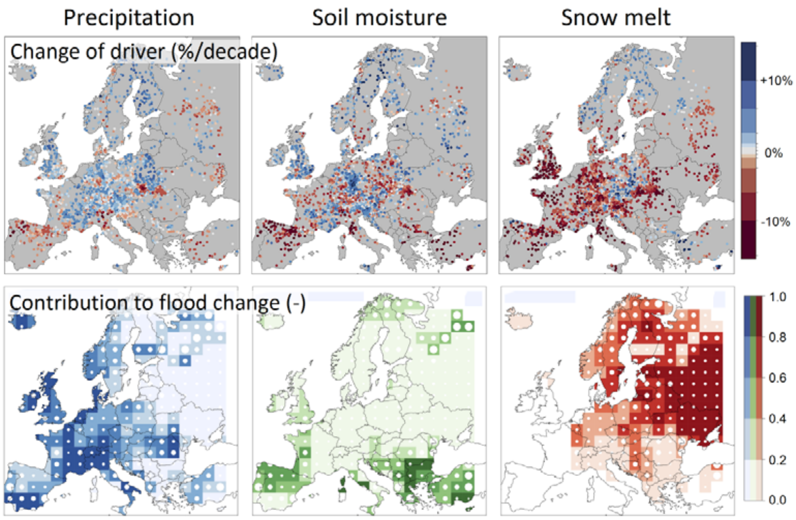

Figure 16. Attribution of observed flood changes at 2370 stations in the period 1960-2010 to their climatic drivers based on Bayesian inference. Top panels: observed trends of 7-day maximum annual precipitation, soil moisture and snow melt. Each point represents a catchment. Blue colours indicate an increasing trend, reddish colours a decreasing trend. Bottom panels: Attributed contribution to the changes in the 100-yr flood for precipitation, soil moisture and snow melt. Strength of colour shows the relative contribution. For example, a value of 0.5 indicates that half of the observed flood trend is due to that driver. White circles indicate the reliability of the attribution, with small circles referring to a more reliable attribution. Bertola et al. (2021).

5 Conclusions

This review article examines three hypotheses sometimes raised in the public debate: land use change increases the flood hazard; hydraulic structures increase the flood hazard; and climate change increases the flood hazard.

Not surprisingly, the answer to all three hypotheses is: "*it depends*". There is clearly no affirmative answer to all three of them in all cases, and neither a negative one. All three changes have the *potential* to increase flood hazard, but also the potential to reduce it. For all three changes, the main factors for this potential to be realised are:

- catchment scale,
- event magnitude,
- the extent of the impact, and the
- local (or regional) hydrological situation.

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Land use: Small catchments of a few hectares are those where short, intense storms are most critical for flooding because of the short travel times of the raindrops. In these catchments, deforestation, urbanisation and soil compaction by agriculture are likely to significantly increase flood hazard, as the main runoff generation mechanism is usually of the infiltration excess type, controlled by infiltration capacity which is very much affected by land use change. There is a tendency for the land use change effect to be greatest for small and moderate magnitude storms, while it diminishes for extreme storms when the soil is close to saturation. For extreme storms, however, geomorphologic processes, such as debris flow and landsliding, may become relevant, which may be substantially enhanced by deforestation. On the other hand, in large catchments with a size of a few to thousands of square kilometres, longer, lower intensity storms tend to be more relevant in producing regional floods. In these catchments, land use change has much less potential to increase the flood hazard, as runoff generation often is of the saturation excess type (at least in temperate climates), which is very little impacted by land use, but is rather controlled by soil depth and the spatial distribution of soil saturation areas. Figure 17 shows schematically the diminishing land use change effects with catchment scale. Also, large catchments are less likely to undergo complete land use change than smaller catchments (Rogger et al., 2017, Blöschl et al. 19xx unesco), which may further reduce impacts, consistent with a general finding that, at large scales, land use change effects on flood hazard are much smaller than climate change effects (see, e.g. Yang et al., 2021).

Hydraulic structures: In small catchments, flood hazards may be efficiently reduced by the construction of flood retention basins because the critical storms are short, and thus the flood volumes small. These basins work best for floods with medium return periods, while they become ineffective for the largest floods since they fill up early during the event. In large catchments, retention basins are much less effective, so river training, or channel straightening, and levees are often used as flood management alternatives along medium and large rivers, as illustrated in Figure 17. Locally, i.e. along the reach they are constructed, these measures reduce the flood hazard (this is the reason why they are built!), at least for small and medium flood magnitudes. Immediately downstream, however, such measures may have unintended consequences. Because of the loss of floodplain storage, the downstream hazard associated with medium sized floods (return periods ~10-100 yrs) may significantly increase, and the magnitude of this increase is related to the ratio of the volumes of the floodplain and the flood event. For extreme floods, however, there is often little flood hazard increase as flood plains are flooded early during the event and/or the levees are over-flown. When assessing the future flood hazard, the long-term interactions between people and floods should be taken into account, as two-way feedbacks may substantially modify the flood hazard situation.

Climate change: In small catchments, short duration, high intensity storms (often of convective origin) tend to increase with air temperature, which likely increases the flood hazard in a warmer climate, both for small and large return periods, although no final word has been spoken on this matter, since these changes are difficult to observe. For larger catchments, the data basis is much better, and both increases and decreases in flood hazard have been observed around the world. Over a time scale of centuries there is a tendency for flood-rich periods to occur during which floods are more frequent and of larger magnitudes. In Europe such periods were colder than usual, which the exception of the last three decades which were particularly flood rich in Central Europe, but warmer. At the regional scale, flood hazard changes are not necessarily directly linked to precipitation, nor are they directly linked to rising air temperatures, but are driven by the seasonal interaction of soil moisture, snow and extreme precipitation via runoff generation. In northwestern Europe, the main driver of increasing flood hazard in the last decades is an increase in heavy precipitation. In southern Europe, the decreasing flood hazard is related to drier soils and somewhat less precipitation, while in Eastern Europe, decreasing flood hazards result from less intense snow melt. While the effect of heavy precipitation and snowmelt on flood hazard does not change much with the return period, that of soil moisture tends to decrease as the soils reach saturation. As highlighted in Figure 17, climate change may affect flood hazard at all catchment scales, even though the flood generation processes are fundamentally different.

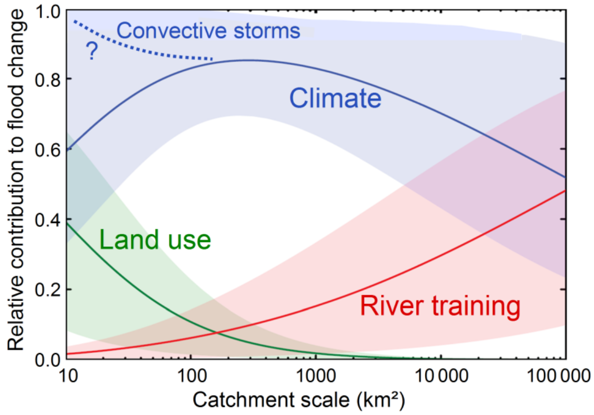

Figure 17. Synthesis of the relative contributions of land use change, river training and climate change to flood hazard changes as a function of catchment scale. Land use change is most relevant for small catchments, river training for large catchments and climate change at all catchment scales. For small catchments, an increase in the frequency of convective storms may further exacerbate climate change effects on floods. Viglione et al. (2016).

The assessment of the three hypotheses has a number of implications. First and foremost, it is clear that significant progress has been made in recent years in understanding the role of land use, hydraulic structures and climate in changing river flood hazards. Given that powerful mathematical modelling has become feasible and easily affordable, often more so than monitoring and experimentation, there is a tendency for overreliance on mathematical models. This review has adopted a data based approach, where possible, and it is strongly believed that modelling and observations need to be in balance.

Modelling has of course an important role to play in assessing the affect of future management options (Hamilton et al., 2015), but there is always a danger of attracting a bit of the "garbage in, garbage out" syndrome.

The second implication concerns the choice of flood management instruments for reducing flood hazards. In choosing flood management instruments, we need to be realistic about their ability to *really* reduce flood hazard. The discussion on nature-based solutions (Kumar et al., 2021; Reaney, 2022) is not always clear on this. Afforestation may be desirable for many reasons, including aesthetical, ecological, touristic and economic, but we need to be aware that its effect on flood hazard tends to diminish to virtually zero for large events. Similarly, green roofs, wetlands and river restoration can only be expected to mitigate floods in proportion to the volume stored relative to the flood event volume, and again, their effect on extreme floods tends to be small, in particular in large catchments. The efficiency of most other instruments of course also depends on the event magnitude, so, while clearly recognising the limits of individual measures, a integrated portfolio of diverse methods is often a prudent choice for minimising flood hazards.

The third implication regards the public debate on natural disasters, and demonstrates a clear need for avoiding oversimplified narratives. As is often the case, reality is more complex than one would like to think, and flood hazards are no exception. Perhaps we scientists need to better live up to our responsibility of making the public debate more evidence based. Clearly, communication beyond the scientific community is essential. Hydrologists play a particularly important role here, since hydrology is an integrative science and deals with issues such as flood hazard change at the core of its discipline (Sivapalan, 2018; Blöschl et al., 2019). While ecologists and foresters, hydraulic engineers and climatologists have specific expertise in land use, hydraulic structures and climate, it are the hydrologists who are tasked with "bringing it all together" to understand, and communicate, flood hazard changes. It is crucial to consider all three change factors in flood risk management and communicate them to the public in a nuanced way.

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