

# Understanding flood regime changes in Europe: A state of the art assessment

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Hall, Julia; Arheimer, Berit; Borga, Marco; Brázdil, Rudolf; Claps, Pierluigi; Kiss, Andrea; Kjeldsen, Thomas R.; Kriaučiuniene, J.; Kundzewicz, Zbigniew W.; Lang, Michel; Llasat, Maria C.; Macdonald, Neil; McIntyre, Neil R.; Mediero, Luis; Merz, Bruno; Merz, Ralf; Molnar, Peter; Montanari, Alberto; Neuhold, Clemens; Parajka, Juraj; Perdigão, Rui A.P.; Plavcová, Lenka; Rogger, Magdalena; Salinas, José L.; Sauquet, Eric; Schär, Christoph M.; Szolgay, Jan; Viglione, Alberto; Blöschl, Günter

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# Understanding flood regime changes in Europe: a state of the art assessment

J. Hall<sup>1</sup>, B. Arheimer<sup>2</sup>, M. Borga<sup>3</sup>, R. Brázdil<sup>4,5</sup>, P. Claps<sup>6</sup>, A. Kiss<sup>1</sup>,  
T. R. Kjeldsen<sup>7</sup>, J. Kriaučiūnienė<sup>8</sup>, Z. W. Kundzewicz<sup>9,10</sup>, M. Lang<sup>11</sup>,  
M. C. Llasat<sup>12</sup>, N. Macdonald<sup>13,14</sup>, N. McIntyre<sup>15,\*</sup>, L. Mediero<sup>16</sup>, B. Merz<sup>17</sup>,  
R. Merz<sup>18</sup>, P. Molnar<sup>19</sup>, A. Montanari<sup>20</sup>, C. Neuhold<sup>21</sup>, J. Parajka<sup>1</sup>,  
R. A. P. Perdigão<sup>1</sup>, L. Plavcová<sup>1,\*\*</sup>, M. Rogger<sup>1</sup>, J. L. Salinas<sup>1</sup>, E. Sauquet<sup>11</sup>,  
C. Schär<sup>22</sup>, J. Szolgay<sup>23</sup>, A. Viglione<sup>1</sup>, and G. Blöschl<sup>1</sup>

<sup>1</sup>Institute of Hydraulic Engineering and Water Resources Management, Vienna University of Technology, Vienna, Austria

<sup>2</sup>Swedish Meteorological and Hydrological Institute, Norrköping, Sweden

<sup>3</sup>Department of Land, Environment, Agriculture and Forestry, University of Padova, Padova, Italy

<sup>4</sup>Institute of Geography, Masaryk University, Brno, Czech Republic

<sup>5</sup>Global Change Research Centre, Academy of Sciences of the Czech Republic, Brno, Czech Republic

<sup>6</sup>Department Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Torino, Italy

<sup>7</sup>Department of Architecture and Civil Engineering, University of Bath, Bath, UK

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<sup>8</sup>Laboratory of Hydrology, Lithuanian Energy Institute, Lithuania

<sup>9</sup>Institute for Agricultural and Forest Environment, Polish Academy of Sciences, Poznan, Poland

<sup>10</sup>Potsdam Institute for Climate Impact Research, Potsdam, Germany

<sup>11</sup>Irstea, UR HHLY, Hydrology-Hydraulics Research Unit, Rue de la Doua, Villeurbanne Cedex, France

<sup>12</sup>Department of Astronomy and Meteorology, University of Barcelona, Barcelona, Spain

<sup>13</sup>Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Liverpool, UK

<sup>14</sup>Institute of Risk and Uncertainty, University of Liverpool, Liverpool, UK

<sup>15</sup>Department of Civil and Environmental Engineering, Imperial College London, London, UK

<sup>16</sup>Department of Civil Engineering: Hydraulic and Energy, Technical University of Madrid, Madrid, Spain

<sup>17</sup>Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany

<sup>18</sup>Department for Catchment Hydrology, Helmholtz Centre for Environmental Research – UFZ, Halle, Germany

<sup>19</sup>Institute of Environmental Engineering, ETH Zurich, Switzerland

<sup>20</sup>Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), University of Bologna, Bologna, Italy

<sup>21</sup>Federal Ministry of Agriculture, Forestry, Environment and Water Management, Division VII/5 – Flood Control Management, Vienna, Austria

<sup>22</sup>Institute for Atmospheric and Climate Science, ETH Zürich, Zurich, Switzerland

<sup>23</sup>Department of Land and Water Resources Management, Slovak University of Technology, Bratislava, Slovakia

\* now at: Centre for Water in the Minerals Industry, Sustainable Minerals Institute, The University of Queensland, Brisbane, Australia

\*\* now at: Institute for Systematic Botany and Ecology, Ulm University, Ulm, Germany

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Correspondence to: J. Hall (hall@hydro.tuwien.ac.at)

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## Abstract

There is growing concern that flooding is becoming more frequent and severe in Europe. A better understanding of flood regime changes and their drivers is therefore needed. The paper reviews the current knowledge on flood regime changes in European rivers that has been obtained through two approaches. The first approach is the detection of change based on observed flood events. Current methods are reviewed together with their challenges and opportunities. For example, observation biases, the merging of different data sources and accounting for non-linear drivers and responses. The second approach consists of modelled scenarios of future floods. Challenges and opportunities are discussed again such as fully accounting for uncertainties in the modelling cascade and feedbacks. To make progress in flood change research, we suggest that a synthesis of these two approaches is needed. This can be achieved by focusing on flood-rich and flood-poor periods rather than on flood trends only, by formally attributing causes of observed flood changes, by validating scenarios against observed flood regime dynamics, and by developing low-dimensional models of flood changes and feedbacks. The paper finishes with a call for a joint European flood change research network.

## 1 Floods are changing – are they?

### 1.1 A need for understanding flood regime changes

Europe has experienced a series of major floods in the past years: extreme floods in Central Europe in August 2002 (e.g. Ulbrich et al., 2003) and in England in summer 2007 (e.g. Marsh, 2008), unprecedented flash flooding in western Italy in autumn 2011 (e.g. Amponsah et al., 2013), and more recently extreme floods in Central Europe in June 2013 (e.g. Blöschl et al., 2013a). As these and many other recent floods have exceeded past recorded levels, there is a growing concern that flooding in Europe

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has become more frequent and severe. There is also an increasing apprehension that human actions may play a key role in increasing floods.

This growing concern in the public is mainly caused by increasing flood damages and comprehensive media coverage of extreme events (Barredo, 2009). In fact, flood damages are rising throughout the world, mainly due to an increase in the value of the assets on floodplains, even though flood protection measures have also been strengthened (e.g. Pielke et al., 2008; Di Baldassarre et al., 2010; Seneviratne et al., 2012). Yet, there are strong physical arguments regarding a general intensification of the global hydrological cycle, with a general increase in the intensity and frequency of extreme events, which is likely to ultimately affect floods (IPCC, 2013).

However, not only the value of assets on the floodplains has changed but also the flood discharges may have changed concurrently. Hydrologists have been grappling with understanding and predicting floods since their science began. They are now exploring the question whether floods are increasing and, if so, why. The difficulty lies in the erratic nature of floods, as one big flood event does not indicate an increasing trend in flooding. To be able to prepare flood management strategies, future flood discharges and their exceedance probabilities are of key interest, together with changes in the time of flood occurrence within the year. The flood discharges of a catchment, their exceedance probabilities and their seasonality are collectively termed “flood regime” in this paper.

The purpose of this paper is to review the current understanding of flood regime changes of European rivers, in particular whether changes have been observed in the past, the drivers of change, what changes are likely to be expected in the future and the current methods used. Changes in coastal floods are not considered here as they are mainly linked to land subsidence and sea level rise rather than to river floods. While dam break floods and urban floods may also be very important, this paper specifically focuses on river floods driven by rain and snow melt (sometimes combined with ice jam), as these are the most common flood types in Europe. Changes in flood

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brought about by natural climate variability at different time scales and by anthropogenic induced climatic change.

This paper examines these three groups of drivers with regard to their potential to cause flood regime changes. From a conceptual hydrological understanding of flood processes a strong dependence on spatial scales of the relative impact of these drivers would be expected. The schematic in Fig. 1 shows present day flood discharges in a hypothetical catchment with a wide floodplain attenuating the flood peaks at an intermediate catchment scale. The thin line illustrates the effects of one of the three groups of drivers on the flood peaks.

River training or floodplain removal (Fig. 1a) will increase the flood discharges downstream of the river modification. Land use changes such as urbanisation or deforestation normally occur at small scales within a catchment, so their effects will decrease with catchment size (Fig. 1b). However, throughout history there have been large-scale land use changes such as deforestation in the Middle Ages or changes in agricultural practices around 1990 in the lower Danube basin. Overall, the combined effects can be spatially complex (Kovács et al., 2012), hence the location of land use changes within the catchment will ultimately influence the scale effect. Changes in climate variables such as increasing or decreasing rainfall intensity occur at large (synoptic) spatial scales and may result in consistent changes of various magnitudes within a region, without obvious relation to spatial scales (Fig. 1c). In the specific case of convective precipitation increases, larger increases in the flood peak would be expected at a small catchment scale.

The degree of understanding the effects of the three types of drivers on the flood regime varies. While at the catchment scale the hydrological effects of hydraulic structures are well understood, at least for individual case studies, less is known about the effect of land use/management and climate variability on the flood regime. Therefore, this paper puts particular emphasis on the effects of changing land use/management and climate.

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### 1.3 Methods for understanding flood regime changes

Insights into river flood regime changes can be obtained through two main avenues. The first is a data based approach in which no or little a priori knowledge of the system is required. In this approach, statistical methods are applied to observational flood data to detect whether significant changes have occurred. This is a useful approach if there is an extended and reliable database available even if the physical principles are not well understood. The information obtained is about past flood changes, which may provide the basis for anticipating future changes.

The second avenue for obtaining insights into changes of river flood regimes is a model-based approach, in which the cascade of processes from climate over catchment to the river system is represented by cause–effect relationships. These can be used to simulate scenarios of future flood regimes. This is a particularly useful approach when the physical principles underlying flood generation and flood change are well understood. The information obtained is prognostic and allows inferring statements about future changes.

This paper reviews the data based and model based approaches in Sects. 2 and 3, respectively. Their relative strengths and weaknesses are contrasted and results from the literature on flood changes in European rivers are presented for each of the two methods. In Sect. 4, we offer possible ways forward towards better understanding changes in the river flood regime, and in Sect. 5 recommendations on future research are provided.

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## 2 Detecting changes in flood observations

### 2.1 Methods of change detection

#### 2.1.1 Types of changes

The starting point of any change detection in observed time series is to hypothesise about the type of potential changes. These may include step-changes in the mean of a series at a particular point in time (regime shift), gradual change (trend) in the mean of the series over time or changes in the variability of the series. Based on the hypothesis about the type of change, a null hypothesis ( $H_0$ ) and an alternative hypothesis ( $H_1$ ) are formulated. For the examples above, the respective null-hypotheses would be “the mean flood peaks of two periods are not different”; “there is no trend in the mean magnitude of flood peaks”; and “there is no trend in the variability of the flood peaks”. Changes may also occur in the extreme values of a series, e.g. extreme floods may increase, without clear changes in the mean annual floods. The flood data series of one or a number of stream gauges are then used to test whether the null hypothesis should be rejected or not at a chosen significance level of, e.g. 5 or 10 %, which is the probability of incorrectly rejecting the null hypothesis.

While statistical change detection tests of flood peaks do not allow to directly infer the physical drivers of any change, there are some known causes that affect flood peak series in certain way (Fig. 2). The construction of hydraulic structures along rivers typically produces step changes in flood peak discharges (e.g. peaks may decrease due to the construction of large reservoir storages or may increase due to river training work) as a result of a relatively short construction period compared with the flood record length (Fig. 2a). Land-use changes are often more gradual as they involve lagged responses such as slow changes in the soil properties. In addition, land-use changes such as urbanisation usually proceed over many decades (Fig. 2b). Similarly, climatic change and variability are also usually expected to be more gradual, resulting in relatively slow changes in the mean and in the variability of flood peaks (Fig. 2c).

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## 2.1.2 Variables of changes

Flood peak analysis is a useful primary way of analysing changing patterns in the flood regime. Typically, annual maximum flood discharges are used rather than peak over threshold flood series to avoid the constraint of choosing a constant threshold for the entire flood record, although time varying thresholds can also be used. Going beyond flood discharges, a number of studies have analysed the flood seasonality in order to shed light on changes in the driving processes. Precipitation from synoptic systems, convective precipitation and snowmelt are highly seasonal, so flood seasonality can provide insights into the flood producing drivers and their possible changes. Seasonality analyses are particularly useful when flood seasonality is compared with the seasonality of other variables that are potential drivers and with catchment state indicators such as extreme precipitation and the seasonal precipitation and runoff regime.

Common measures of seasonality are the Julian day of the mean flood occurrence date and the variability of flood occurrences within the year. The occurrence date of a flood within the year (for a particular station) can be plotted on a unit circle to give the angle in polar coordinates (Black and Werritty, 1997; Burn, 1997). The direction of the average vector then represents the mean date of occurrence of all flood events (Parajka et al., 2010). Although, many studies use seasonality analyses to infer flood processes (e.g. Merz et al., 1999; Beurton and Thieken, 2009; Parajka et al., 2010), only a few studies examine their long-term trends (e.g. Macdonald, 2012; Arheimer and Lindström, 2013). One such study is Parajka et al. (2009), who analysed the change in seasonality of floods, extreme precipitation and the monthly rainfall and runoff regime along a transect across Austria and Slovakia over different decades.

Although flood seasonality analysis is often very useful and data tend to be readily available, the application is limited to those flood drivers that have clear seasonal characteristics. To distinguish between different flood drivers within a season, such as different rainfall types, more in depth analyses are needed, such as exploring the

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intra-seasonal variability of rainfall and runoff indicators (e.g. Merz and Blöschl, 2003; Macdonald et al., 2010).

### 2.1.3 Methods of trend detection

A range of statistical tests have been developed for analysing changes in the magnitude of flood peak series. Such tests can focus on (i) change analysis of individual time series, (ii) field significance of an ensemble of local stations, and (iii) analysis of coherent regional change.

- i. Change analysis of individual time series: in the simplest case of change detection, the flood peak records of individual sites are analysed separately. Parametric tests are used for independent data that conform to a particular distribution (e.g. Student's  $t$  test and Worsley likelihood ratio test), and non-parametric tests for independent data without making assumptions about the distribution (e.g. Pettit's test, Mann–Whitney  $U$  test for step changes or Mann–Kendall test (MK) and Spearman's rho test for gradual changes). For a review of additional trend detection methods used for hydrological extremes and their influence on the trend results, see Clarke (2013a).

As hydrological time series are usually neither normally distributed nor independent, non-parametric tests and block re-sampling methods are often preferred (Kundzewicz and Robson, 2004; Yue et al., 2012). In the case of gradual trends, the rank-based MK test is regarded as a robust non-parametric test and widely used (Petrow and Merz, 2009). However, if a positive serial correlation exists, the probability of detecting a false significant trend increases (Yue et al., 2002), in which case pre-whitening methods need to be applied to remove the serial correlation. To avoid eliminating part of the temporal trend itself (which would result in underestimating the probability of detecting a significant trend), the trend-free pre-whitening (TFPW) and modified TFPW methods have been developed (Yue

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hypothesis of no shared regional trend with the alternative hypothesis that all the sites of a region are affected by the same trend (Renard et al., 2008). The trend with the highest likelihood is then brought out from all possible trends and considered as representative of that region. In order to improve the robustness of the estimators against outliers and other non-linearities transformed the original multivariate dataset can be transformed to distributions close to normal (Renard et al., 2008).

Renard et al. (2008) compared these three groups of tests and concluded that the methods have comparable testing power in detecting coherent regional trends. If the at-side trends within a region are consistent (i.e. same direction), all methods can detect the dominant change but the test results obtained from the regional variable and the regional statistic are very sensitive to the stations included. For regions with inconsistent trends, they showed that the regional variable and the regional statistics favour the dominant trend and mask minor trends, whereas the regional likelihood ratio method does not detect any trend at all. If the aim of the study is to detect whether a consistent trend over a homogenous region exist or not, they recommend the regional likelihood ratio method. Additionally, a procedure for obtaining a regionalised, spatially averaged trend in hydrological time series with both serial and spatial correlation is presented in Clarke (2013b).

## 2.2 Flood regime changes in Europe

### 2.2.1 Floods during the instrumental period

Numerous trend detection studies have been performed on systematic flood records in Europe. In these studies, different high flow indicators were derived from observed discharge time series, some dating back to ~ 150 yr. The results provide insights into small-scale regional patterns of increasing, decreasing, or non-detectable changes (at a specific significance level) in flood regimes.

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Overall, it is difficult to issue a general statement on flood changes in Europe due to the diversity of processes, different observation periods, and the variety of methods applied. However, a review of the most recent studies suggests some broader patterns, which are summarised below according to three climate regions relevant to flooding:

(i) Atlantic western Europe and northern Europe, (ii) Central Continental Europe and eastern Europe, and (iii) the European Mediterranean (southern Non-Atlantic Europe) (see Fig. 3). If applicable, mountainous catchments located in these regions are mentioned separately due to mixed climatic and orographic influences.

i. Western Europe and northern Europe: in central Spain, Mediero et al. (2013) found generally decreasing trends of annual maximum floods during 1959–2009, with the exception of a few gauging stations in the north-western part of Spain which showed significantly increasing trends for that period. Similarly, decreasing trends in annual maximum floods were found in the Douro basin during 1961–2005 (Morán-Tejeda et al., 2012). In France, most regions did not show a consistent change (1968–2000), with three exceptions: increasing flood peaks in the northeast, decreasing high flows in the Pyrenees, and earlier snowmelt-related floods in the Alps (Renard et al., 2008). For the period 1968–2008, Giuntoli et al. (2012) found increasing trends in annual maximum floods in the north, and decreasing trends in the south of France. In the UK and Ireland, Pinskiw et al. (2012) found clearly increasing trends of annual 7 day high flows (1985–2009); similar patterns were found by Stahl et al. (2012) during 1962–2004. Increasing trends in the UK were also found in Q5 (Qn corresponds to flow equalled or exceeded in n% of the daily mean flows) during 1969–2008 (Hannaford et al., 2012), and in annual maximum floods in Ireland during 1976–2009 (Murphy et al., 2013). However, an earlier period (1940–1990) did not show significant trends for 890 stations in the UK (Robson et al., 1998). A long-term analysis (1883–2009) of the flood series of the lower Thames (UK) showed an increasing trend in Q5 but no significant change in the annual maximum floods which was partly attributed to a declining contribution of snowmelt to major floods (Marsh and Harvey, 2012).

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Scandinavian time-series longer than 100 yr show a variable pattern and it is difficult to draw any general conclusions about flood regime changes (e.g. Lindström and Alexandersson, 2004). In Norway, 57 % of the stations show decreasing autumn flood magnitude (1920–2005). For shorter periods, such decreases are only found at the west coast. In northern Sweden, sominat positive trends in autumn flood magnitude are found for the period 1961–2000) (Wilson et al., 2010). The magnitude of spring high flows in Finland did not show significant changes for the period 1912–2004, although the mean discharges increased (Korhonen and Kuusisto, 2010). Stahl et al. (2012) suggested that high flows in Denmark and southeastern Norway decreased (1962–2004) despite increasing trends in annual flow. For the Baltic region, spring floods decreased and occurred earlier (but without a systematic trend) due to earlier spring snowmelt and reduced snow storage (Thorsteinsson and Björnsson, 2012).

- ii. Central Europe and eastern Europe: in Central Europe, overall, Pinskiwar et al. (2012) and Kundzewicz et al. (2013) found a tendency towards increasing large floods for the period 1985–2009 which reflects the recent major floods in the area. In southern, western, and central Germany, annual maximum floods in 28 % of the catchments with areas  $> 500 \text{ km}^2$  showed increasing trends, particularly apparent in the winter floods, while this was not the case in the rest of Germany (1951–2002) (Petrow and Merz, 2009). For the Elbe and Oder Rivers, the occurrence rate of heavy winter floods during 1852–2002 decreased, whereas there was no trend for summer floods (Mudelsee et al., 2003).

In Poland, the mean and the variance of the annual maximum floods decreased during 1921–1990 (Strupczewski et al., 2001) and spring floods decreased for the majority of Poland's major rivers (Kaczmarek, 2003). However, after a long period without major floods, several flood events were reported in Poland from 1997 to 2010, which results in an increase of the number of regional floods (large areas of the country being flooded) for the period 1946–2010 (Kundzewicz et al., 2012). In Bohemia (Czech Republic), floods were particularly frequent and high



snowmelt during the past 40 yr. The snowmelt season started earlier and the volume and peaks of snowmelt floods from glaciers increased.

In the Baltic States, annual maximum floods from 1922–2008 generally decreased (Reihan et al., 2012) with an earlier occurrence of spring floods associated with snowmelt (Reihan et al., 2007; Kriaučiūnienė et al., 2012; Thorsteinsson and Björnsson, 2012; Sarauskiene et al., 2013). 1963–1977 was a particularly flood-poor phase. In the last two decades, most spring floods were less than the long-term mean. Decreases in high flows were also found in Romania for the periods 1961–2009 and 1975–2009 (Birsan et al., 2013), and other Eastern European countries (1962–2004) (Stahl et al., 2012).

iii. Mediterranean: in Spanish Mediterranean catchments, generally decreasing trends in annual maximum floods during 1959–2009 were found (Mediero et al., 2013). In Catalonia, flash-floods increased during the period 1982–2007 (Llasat et al., 2010), but decreased when the study was updated until 2010. In the French Pyrenees and central parts of the Spanish Pyrenees decreasing trends in floods were found during the periods 1968–2000 and 1955–1995 (López-Moreno et al., 2006; Renard et al., 2008), which is consistent with the decreasing trends (1952–2004 and 1962–2004) obtained by Stahl et al. (2010). For the Po River (Italy) there was no clear trend in annual maximum floods during 1920–2009 but a tendency of floods to occur in clusters (Montanari, 2012). In Greece, around Athens, an increase in flood frequency was observed in recent decades, when analysing the period 1880–2010, which was associated with increases in extreme daily precipitation (Diakakis, 2013).

## 2.2.2 Historical floods

The study of historical floods provides very valuable information for the period prior to systematic flow observations, which typically started in the 19th century on the large European rivers. Documentary data often suffer from spatial and temporal discontinuity,

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and stream gauge failure. Equally important, the time period for which the flood data are available may disproportionately influence the outcome of the trend analysis and may lead to observation biases. Hydrometric monitoring networks are often installed in response to recent floods or recent droughts, which will then not appear in the observational data. In the UK and Ireland, for example, the gauging network expanded from the 1970s onwards, a period with particularly few floods which may lead to biases in the trend analyses (Hannaford and Marsh, 2008; Murphy et al., 2013; Prosdocimi et al., 2013). Due to changing societal priorities and/or financial constraints, gauges sometimes have to be closed down (e.g. Fig. 5), which may result in similar biases. Another example is Italy, where the number of stream gauges declined sharply in the 1970s when the hydrological service was split into regional services. Diakakis et al. (2012) illustrated this observation bias for the case of Greece and related an apparently increasing number of floods over the last few decades to more detailed reporting on floods. Changes in media coverage may also contribute to biases in the perceptions of flood occurrence (Barnolas and Llasat, 2007b; Lara et al., 2010).

For historic flood data, observation bias may be even more important. Generally, the further one goes back in history the fewer documentary sources or measured data are available. Smaller floods could be overlooked since, usually, only floods that caused loss of life or material damage were deemed important enough to be recorded. The observation bias is particularly challenging when historical records are used for flood frequency analysis. There are two principal approaches to compensate for missing data. The first is the selection of a timeframe over which the largest events are likely to have been recorded (Parent and Bernier, 2003; Macdonald et al., 2006, 2013). The second approach is to only include a fixed number of events above a perception threshold (Stedinger and Cohn, 1986; Viglione et al., 2013a). While it is usually difficult to estimate flood discharges from flood marks (water levels), particularly if the stream morphology has changed over time or buildings with epigraphic marks have been rebuilt, Viglione et al. (2013a) noted that the number of floods exceeding a threshold is a more important piece of information in flood frequency analysis than the discharges



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and centuries as highlighted in the review of the historic flood data. If the time scale of variability is longer than the observation period, oscillations can look like a trend (Blöschl and Sivapalan, 1995; Koutsoyiannis and Montanari, 2007; Chen and Grasby, 2009). This point is illustrated in Fig. 6. If only the dark blue data is available (Fig. 6a) an increasing trend will be detected. If the data set is extended back in history (Fig. 6b) it becomes clear that the concept of a trend is not useful in this case. Instead, it is more appropriate to consider the existence of flood-rich and flood-poor periods. It is therefore suggested that future flood change analyses of systematic data should actually focus on identifying flood-poor and flood-rich periods instead of only detecting whether trends exist. Trend analysis can be misleading as the results invariably depend on the observational window and homogeneity of the flood series.

This issue becomes particularly apparent when multiple windows of long-term flood records are analysed, as shown for two examples in Fig. 7. There is an overall tendency of decreasing flood trends for the River Vltava, some of which become statistically significant at the 5% level for periods ending after 1960. The annual maximum floods at Prague were particularly high in 1845, 1862, 1872 and 1890; afterwards there was a decrease in floods, particularly for winter floods (Brázdil et al., 2005). Low flood magnitudes are typical of the second half of the 20th century, which partly coincides with the construction of several reservoirs along the river upstream of Prague, the so-called “Vltava cascade”. The effect of the August 2002 flood, the biggest flood of the instrumental record, is also evident. In contrast, the Danube tends to show increasing trends, particularly if the most recent floods are included. It is important to note that these analyses test the trends in the mean of the records; mean floods and extreme floods do not necessarily exhibit the same time patterns. Indeed, for the Danube the small and medium floods have increased for some of the periods due to increased precipitation and the loss of retention areas (Blöschl et al., 2013a, b), while there is no evidence of trend in the extreme floods (Blöschl and Montanari, 2010). This suggests that changes in extreme floods should be tested separately from changes of the mean. However, as pointed out by Frei and Schär (2001) the detection probability of extreme events is



in the flood data and their drivers is not clear, information-theoretic diagnostic tools can be invoked to identify non-linearity and non-normality (Pires and Perdigão, 2012, 2013), and address the non-linear and non-normal response of regional scale flood regimes to synoptic scale climate patterns (Pires and Perdigão, 2007).

Equally important as the statistical methods are deterministic methods to explain the presence of flood-rich and flood-poor periods. One approach is to identify the features of the underlying system from the flood record, including structural stability, degree of complexity (i.e. number of drivers) and overall phase-space structure (possible states assumable by the system, e.g. flow characteristics and underlying mechanisms). The time series of a single variable contains implicit information from other variables, whose contribution can be retrieved by phase-space reconstruction (Nicolis and Nicolis, 1984; Abarbanel, 1996). Geometric properties of the phase-space may indicate the presence of regimes such as flood-rich and flood-poor periods. Identifying potential flood-rich and flood-poor stable regimes could then lead to a better understanding of why the system would be locked in such regimes for several years.

### 3 Scenarios: predicting future changes in floods

#### 3.1 Methods of scenario analysis

Unlike the change detection based on systematic and historic flood data, the scenario approach links flood changes to their causal processes based on flood simulations. Usually, a statement is made about possible future flood changes and their reasons. Sometimes the approach is also used to better understand past flood changes. In most instances, two groups of cases are compared (i) the present, and (ii) possible futures. The differences between the two then sheds light on changes in the flood regime.

The modelling of the scenarios represents knowledge about the causative mechanisms of how hydraulic structures, land use and climate affect floods. Since rainfall and snowmelt are the main drivers of river floods, the simulations invariably involve

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alternative forecasts each of which includes (rather than excludes) the main uncertainties. Often the term “projections” is used to highlight that a range of alternative futures is represented (Niehoff et al., 2002), but it is not always clear what they actually entail. In the context of climate sciences, the terms “prediction” and “projection” are explicitly distinguished, depending upon whether an attempt is made to include predictions of internal variations (e.g. IPCC, 2013). It is suggested here that there is a gradual transition between forecasts/predictions/projections and scenarios (in the original sense of Shell), and between predictions/forecasts and projections (in the sense of the IPCC), depending on where the main uncertainties are placed. If they are captured within one scenario, it is appropriate to talk about forecasts (or predictions), if the scenarios differ by the main uncertainties then it is appropriate to talk about a scenario approach in the original sense. Perhaps it would be useful to be more explicit about the nature of the statement about the future that is made with the scenario approach.

Below the main methods used for understanding the causative mechanisms of flood change effects in or near the stream (hydraulic structures and stream morphology), in the landscape (land use) and of atmospheric processes (climate change) are briefly reviewed.

### 3.1.1 Rivers: hydraulic structures and stream morphology

Changes of the flood regime resulting from stream bed and floodplain processes are mainly associated with river training works; the construction of hydraulic structures such as levees, polders or retention basins, and changes of the streambed or the floodplain morphology, resulting from aggradation – raising of the streambed by deposition of stream sediment, or degradation when sediment supply is less than the transport. In the scenario approach, usually, cases representing the present are compared with those representing the future. In some instances, it is also of interest to represent the situation in the past before some structures have been installed.

Given the focus on the river and the floodplain, the main component of the scenario simulations is a hydrodynamic model. These models are based on the equations

representing conservation of mass and momentum in the fluid (the Navier–Stokes equations) which are solved numerically for pressure and flow velocity by finite difference, finite volume or finite element methods (see Krámer and Józsa, 2004 and Alcrudo, 2002 for overviews). To this end, the domain needs to be discretised in both space and time. To increase the numerical efficiency, the Navier–Stokes equations are usually integrated vertically to form the two-dimensional shallow water equations, in which case the hydrodynamic model represents a two-dimensional rather than a three-dimensional domain.

In setting up the hydrodynamic model, a number of issues need to be considered.

- i. Numerics: first and foremost, the numerical schemes need to be stable, accurate and conserve mass and momentum (e.g. Murillo et al., 2007). In the case of floodplain inundations, this is a non-trivial task to achieve since the wetting-drying transitions tend to cause numerical instabilities. A number of methods have been developed to provide stable solutions (e.g. Brufau et al., 2002; Zokagoa and Soulaïmani, 2010). It is important to test the model code against benchmark data sets such as analytical solutions in order to ensure the suitability of the code (e.g. Liang and Marche, 2009; Zokagoa and Soulaïmani, 2010).
- ii. Geometry: in a second step, the geometry of the terrain needs to be specified. This is usually done based on airborne LiDAR (light detecting and ranging) techniques that produce a detailed digital terrain model. Additionally, any hydraulic structures and operation rules of hydraulic gates need to be included.
- iii. Parameters: the third step is to set the model parameters. The main parameters are the roughnesses of the streambed and the flood plain, which may vary in space and time. The hydraulic resistance of submerged vegetation may exhibit complex patterns which are not fully understood and represent an active area of research (Stephan and Gutknecht, 2002; Green, 2005; Nepf, 2012). In addition, the roughness of the streambed may change depending on the sediment size distribution (Fischer-Antze et al., 2008). Roughnesses are usually obtained

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by calibration, i.e. varying the roughness values until the hydrodynamic model reproduces the observed water levels and/or inundation areas of a particular river reach or floodplain (Grayson et al., 2002). Unfortunately, this is not always possible for the largest floods of interest as observation may not be available. In that case, roughness is usually estimated from smaller floods or similar floodplains, but this procedure involves uncertainties. Roughness can also be estimated by alternative methods, such as interpreting high resolution LiDAR data (Hollaus et al., 2011; Vetter et al., 2011). However, some level of calibration may still be needed.

- iv. Behaviour of hydraulic structures: another issue that needs to be considered is the behaviour of levee failure. While, strictly speaking, soil mechanical models are appropriate for modelling the occurrence of levee failure, usually simplified probabilistic representations are more suitable to examine dam failures in the context of the flood regime (e.g. Apel et al., 2004, 2006). Additionally, operation rules of hydraulic structures need to be included, where appropriate, to represent the effect of their management strategies (e.g. Ahmad and Simonovic, 2000).

### 3.1.2 Catchments: land use and land cover

The effects of land use and land cover changes on runoff- and flood-generating processes can be presented in a scenario modelling approach similar to changes induced by hydraulic structures and stream morphology. The evolution of vegetation and soils is usually strongly interlinked through macropore formation, nutrient cycling and other processes (Markart et al., 2004), so changes in the land use or land cover may lead to changed infiltration characteristics, which may have significant effects on the flood regime.

Land use and land cover changes such as deforestation/afforestation or urbanisation are usually represented in the hydrological models through changes in the model parameters (Brath and Montanari, 2000). In fact, the essential step in scenario modelling is to choose appropriate model parameters for changed land use or land cover,



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units (HRUs) on the basis of land use and soil type and estimate the model parameters from stream flow and other hydrological characteristics (Blöschl et al., 2008; Hundecha et al., 2008; Samaniego et al., 2011; Arheimer et al., 2011). This method is particularly suitable for conceptual hydrological models (for a summary see Blöschl et al., 2013c and Parajka et al., 2013). However, a drawback of the method is that one usually assumes that the spatial differences in soil parameters apply immediately to the location where land use has been changed, while soils may take decades to respond to land use changes (Runyan et al., 2012).

There is a wide range of hydrologic models available for simulating land use and land cover changes, however for a robust scenario modelling approach the model structure and parameterisation need to account for various factors and feedbacks associated with the change. Models need to be able to link land use/cover, soil characteristics and unsaturated zone dynamics that control infiltration process; account for temporal and spatial dynamics of rainfall-runoff process and consider initial conditions of the flood event, in particular antecedent soil moisture (Niehoff et al., 2002) in the case of event models.

Land use/cover scenarios may assess historical changes in the catchment. For example, by comparing flood responses in the Oder basin, associated with different land use scenarios, namely land use derived from historical maps from 1780 with that from 2001 (De Roo et al., 2003). They represented afforested areas by increased interception and urbanised areas by zero infiltration in the model. The scenarios can also relate to future, hypothetical changes. Niehoff et al. (2002) assigned hypothetical changed land use categories to each grid cell of a catchment model in a spatially explicit manner and analysed the effect of increasing urban extent on flood volume and peaks. In a similar manner, Salazar et al. (2012) assessed the effect of afforestation on the flood regime in three middle-sized catchments in Spain, Germany and Austria. A more process-based assessment of hypothetical land-use change effects is presented by Naef et al. (2002). By selecting the four main dominant runoff processes in a catchment, (i.e. infiltration excess and saturation excess overland flow, shallow lateral subsurface

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flow and deep percolation) they were able to separate different effects on floods in terms of the location and spatial extent of the dominant processes. They stressed that a reduction of storm runoff by changing land use/cover and management practices is only feasible for catchments where infiltration and matrix wetting can be enhanced through such measures. These examples illustrate that a robust interpretation of land-use scenario modelling requires simple but process based model structures that are able to account for the main features of soil-vegetation-atmosphere interactions.

### 3.1.3 Atmosphere: climate

The effects of changes in the climatic system on floods are commonly explored by climate change scenarios. They represent a cascade of atmospheric processes from the global scale (different greenhouse gas and aerosol emission scenarios to drive global climate models, GCMs), to the regional scale which are then used as input to hydrological models that simulate the flood regime. From a flood hydrology perspective, the essential steps in the procedure are (i) atmospheric modelling and downscaling from the global to the regional scales, (ii) correcting any biases of the outputs of the atmospheric model, and (iii) the hydrological modelling of the flood regime (Raff et al., 2009).

- i. Atmospheric modelling and downscaling: downscaling is used to bridge the gap between the grid scale of GCMs ( $\sim 100$  km) and the hydrological scale (Cohen et al., 1990). Dynamical downscaling approaches consist of nesting a regional climate model (RCM) into the GCM to more accurately represent surface topography and other land surface characteristics, and yields a better approximation of the atmospheric energy-cascade including the formation of precipitating systems, fronts and rainbands. An alternative are statistical downscaling technique where relationships are established between one or more large-scale variables provided by the GCMs (predictors, such as pressure) and the observed local surface variable (predictands, such as precipitation) (Wilby et al., 1998; Giorgi and

Mearns, 1999; Wood et al., 2004; Blöschl, 2005; Chen et al., 2011). In addition, combinations of the two approaches are possible.

For Europe, large sets of regional climate model simulations using a wide range of different GCMs and RCMs are available with horizontal resolutions of 50 km, 25 km and 12 km (Christensen and Christensen, 2007; Van der Linden and Mitchell, 2009; Jones et al., 2011). While they do not explicitly represent convective precipitation and associated feedback processes, which are important for the European summer weather, it is expected that within a decade new scenarios with explicit convection at horizontal resolutions of around 1 km will become available (Hohenegger et al., 2008, 2009).

ii. Bias correction: correcting biases of the outputs of atmospheric models is important as the biases tend to be large and hydrological flood model output shows sensitivity tends to them. In applying bias correction methods, it is usually assumed that the model biases of the past climate will remain the same in the future (Teutschbein and Seibert, 2003) although it is, of course, not possible to directly check this assumption. Relationships between observed and simulated precipitation (and other climate variables) are therefore estimated for the reference period in the past and applied to the future. The bias correction methods differ in how these relationships are defined:

- Local Intensity Scaling: a linear relationship between observed and simulated precipitation is defined for precipitation intensities larger than a threshold. The threshold is selected in a way to match observed and simulated wet day frequencies and the slope of the relationship is selected to match mean monthly precipitation (e.g. Schmidli et al., 2006).
- Non-linear correction: a power law relationship between observed and simulated precipitation is assumed and the parameters are estimated to match observed and simulated mean monthly precipitation as well as the coefficient of variation of daily precipitation (Teutschbein and Seibert, 2012).

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- Distribution Mapping (also quantile-quantile mapping): this is a non-parametric method in which the distribution of the simulated precipitation is transformed to match the distribution of the observed precipitation (e.g. Yang et al., 2010).

Teutschbein and Seibert (2012) and Chen et al. (2013) noted that the selection of the bias correction method could have a major effect on the flood simulations. They recommend distribution mapping because of their ability to generate realistic statistical characteristics, particularly for extreme events. However, bias corrections are sensitive to the reference period, the sampling of the seasonal cycle (Bosshard et al., 2011), do not usually account for cross-correlation between temperature and precipitation and for changes in the temporal structure of precipitation (Dahné et al., 2013; Donnelly et al., 2013), which may be relevant for flood simulations.

- iii. Hydrological modelling: hydrological modelling generally assumes stationarity of the model parameters and the model structure. Merz et al. (2011) noted that this assumption might constitute an important oversimplification. They calibrated a conceptual rainfall runoff model to six consecutive 5-yr periods for numerous catchments in Austria and found significant temporal changes in the calibrated parameters representing snow and soil moisture processes, which led to biases in the high flows of more than 30%. They therefore recommended testing model stationarity based on the hydrological data of past decades.

In terms of the hydrological modelling setup, one can proceed along one of three avenues:

- Direct use of atmospheric model output: climate model output for past and future periods are directly fed into a hydrological model. In this approach, the use of downscaling and bias correction procedures is particularly important, as the raw model output, generally lacks the appropriate statistical characteristics. If the biases of the atmospheric model (in particular for precipitation



extremes) are small, the first method (direct use of the atmospheric model output) is a prudent choice as it can account for changes in the temporal structure of precipitation. If the biases are large, the bias correction method may introduce artefacts into the analysis (Teutschbein and Seibert, 2012).

- Delta-change methodology: the climate change signal is extracted from a pair of control and scenario simulations. The hydrological scenarios are then obtained from two hydrological model simulations, one driven by observed data, the other driven by the same observed data with the climate change signal superimposed. This approach is straightforward and widely used, but it retains the variability of the observed climate time series used.
- Use of weather generators: instead of using only observed climate data, one can use output of weather generators (multivariate stochastic models) that have been calibrated to observed climate data and modified for the scenarios. The use of such approaches is widespread in single-station applications, but more difficult when both temporal and spatial consistency is required, as in many hydrological scenarios. They are particularly appealing for flood scenarios as they allow reliable representation of the higher order statistics of precipitation extremes (i.e. the shape of the extreme value distribution).

### 3.2 Flood change projections in Europe

This section reviews possible changes in future flood regimes supported by process understanding and existing causalities presented by models that can be related to Sect. 3.2.1 hydraulic structures and stream morphology, Sect. 3.2.2 land use and land cover, and Sect. 3.2.3 climate change. For Sects. 3.2.2 and 3.2.3 the findings have been organised by the hydro-climatic regions in Europe (shown in Fig. 3), as the changes are related to the spatial distribution of climate and landscape characteristics. For Sect. 3.2.1 this is not the case as the local conditions are much more important. The findings are therefore discussed by the type of river modification.

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effect becomes relatively less important. The modelling study of Di Baldassarre et al. (2009) at the River Po (Italy) found that the increase in high water levels in the past decades was mainly due to the heightening of the levee system, as previously hypothesised by Marchi et al. (1996). For the Danube, Blöschl et al. (2013a, b) noted that during the September 1899 flood, approximately 1000 km<sup>2</sup> of floodplain along the Danube and tributaries were inundated, whereas only a few 100 km<sup>2</sup> of floodplain storage were available during the June 2013 flood, which had significant effects on the flood peaks. Floodplain removal may also increase the celerity of the flood waves as shown for the Danube by Mitková (2002) and Blöschl et al. (2013a, b) and for the lower Morava by Szolgay et al. (2008). Current river restoration efforts aim to remove or push back levees in order to offer more space for natural river dynamics and thus reduce flood peaks. Hooijer et al. (2004) and Bronstert et al. (2007) concluded that upstream water retention measures in the Rhine basin could significantly reduce the frequency of small and intermediate floods in small basins, and contribute to the reduction of medium floods in large basins. However, no significant effects were noted for extreme floods in large basins and downstream areas. In these restoration measures, riparian vegetation can be planted to increase roughness. These increases in the roughness may increase the local water levels, but their downstream effects tend to be very small, as the main control on flood peak attenuation is the volume of water stored on the floodplain at the time of the peak, relative to the flood wave volume (Valentová et al., 2010).

- iii. Retention basins: retention basins tend to have a similar effect as restoring retention volume in the floodplains (Fig. 8c). Their effect is largest for medium sized floods for which the retention basins have been designed. The effectiveness is usually calculated as part of the planning process of the retention basin. Important for their effectiveness is the timing when they are filled as illustrated by the comparative study of Salazar et al. (2012) in three middle-size catchments in Spain, Germany and Austria. If the retention basins are filled too early, at the

beginning of the event, their effectiveness may significantly diminish. This is also the reason why unregulated micro-ponds located in the landscape are much less effective than regulated reservoirs along the stream (Salazar et al., 2012, also see Arheimer and Wittgren, 2002).

- 5 iv. Other changes to the river and the floodplain system: for future flood changes, the effects of the rising numbers of reservoirs or dams built for hydroelectric power production are also important, particularly the effect of trapping of sediment in reservoirs (Vörösmarty et al., 2003; Nilsson et al., 2005; Syvitski et al., 2005). Sediment starved rivers, which are often found below reservoirs, tend to degrade and narrow, while excessive sediment load leads to river bed aggradation, with adverse effects on the flood conveyance capacity. The feedbacks between floods and sediment transport and timescales of channel adjustment are complex but can be understood from an integrative catchment perspective, which includes the estimation of catchment sediment production, storage and transfer, as well as anthropogenic effects on these processes (e.g. Molnar et al., 2002; Syvitski, 2003).

15 The effects of hydraulic structures and stream morphology are quite well understood at the reach scale, and hydrodynamic models are used widely to predict the effects on flood magnitudes. At the scale of large river basins, the processes may combine in a non-linear way, so assessing the effects is more complicated. Yet, with the implementation of the European Flood Directive (EU, 2007) it is becoming increasingly more important to account for the combined effects of all alterations within a river basin.

### 3.2.2 Catchments: land use and land cover

25 Europeans have also altered their landscapes for many centuries. The main motivations have been to produce arable land and, more recently, urbanisation. A number of recent scenario studies have examined the potential of future land use/cover changes (mostly afforestation) for mitigating floods as well as the effects of future urbanisation

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on floods. The studies provided below are summarised according to the hydro-climatic regions defined in Fig. 3.

- i. Western Europe and northern Europe: in the UK, a number of recent studies have examined the effect of de-intensification of farming and the provision of storage through reactivation of floodplains or construction of on-farm storage ponds on flooding (Hulse et al., 2009; Wheeler and Evans, 2009; Foresight Land Use Futures Project, 2010; Wilkinson et al., 2010; Jackson et al., 2013). At the field scale, O'Connell et al. (2004) and Jackson et al. (2008) project potentially large changes in flood volumes and peaks associated with de-stocking, tree planting and drainage management. However, the simulated effects were highly variable depending on when and where the change is implemented (McIntyre et al., 2013). In some specific examples, even the directions of drainage and the location of tree planting within the field may make a substantial difference to the change in floods (Jackson et al., 2008). In the small catchments examined (up to 10 km<sup>2</sup>), afforestation may lead to a reduction of about 10 % of median flood discharges (Bulygina et al., 2009, 2011). At larger catchment scales (> 10 km<sup>2</sup>), the effects of land use changes on floods are generally small and highly variable (McIntyre et al., 2012). When clear-cutting two forested catchments in the order of one km<sup>2</sup> in Sweden by 70 and 100 %, Brandt et al. (1988) observed runoff increases of 200 mm yr<sup>-1</sup>. These findings were used for model parameterisation in scenario analyses at larger scales, showing that 10 % clear-cutting increased the flow peaks by 5–10 %. Summer and autumn floods were increased while snowmelt peaks could be either higher or lower, depending on clear-cut allocation in the catchment. Similarly, the effects of afforestation on floods can be dynamic, for example depending on tree maturity and forestry management practices (Robinson, 1998)
- ii. Central Europe and eastern Europe: Salazar et al. (2012) assessed the effectiveness of afforestation in flood peak reduction for three medium-sized catchments in Germany, Austria and Spain using scenario simulations. For the smallest floods,

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they simulated a 30 % reduction, but the effect decreased with increasing flood magnitudes to a few percent. They also found that the land use change effect on floods was larger for dry antecedent soil moisture than for wet conditions. Solín et al. (2011) correlated observed flood frequencies in small catchments in Slovakia for the period 1996–2006 with the associated land use changes. While significant land use changes occurred, these were not significantly correlated with flood changes. Long-term experimental forest research in the Czech Republic also showed that deforestation may be a less important control of flooding than climate, and the practical management of clearing forests (such as road and ditch construction) may play a larger role in changing floods (Bíba et al., 2006; Solín et al., 2011).

- iii. Mediterranean: a model linking land use in the Mediterranean region with climatic perturbances at the European scale has been developed and tested (Millán et al., 2005). They point out that surface drying due to land use changes such as deforestation results in a local-to-regional vertical recirculation over the Mediterranean Sea. This leads to a decreasing trend and local loss of summer storms and summer floods but also results in more frequent flash floods in autumn in the Western Mediterranean. Additionally, the model showed that accumulated water vapour over the sea can participate in major precipitation events, and flooding episodes in other parts of Europe. The comparison of two land use maps of the the Mella River basin in northern Italy by Ranzi et al. (2002), showed an increase in the forested areas in the upper part of the basin and in the urban development in the valley, resulting in a decrease of the cultivated areas during 1954–1994. The surface runoff, derived from a distributed hydrological model, changed insignificantly at the catchment scale, but with slightly reduced flood peaks and volumes under current land use conditions, due to the increased water storage in forested areas, which offset the expansion of urban areas. From their scenario analysis, Brath et al. (2006) conclude that the effects of land use change the Bologna district, in Northern Italy (1955 and 1992) are not significant for the natural river network,





projections provided below are summarised according to the hydro-climatic regions shown in Fig. 2.

i. Western Europe and northern Europe: for Atlantic western Europe, Lehner et al. (2006) and Rojas et al. (2011) project that today's 100-yr floods will become more frequent by 2070s, but with regional differences in the change, but for Atlantic France decreasing (Lehner et al., 2006; Dumas et al., 2013) and increasing (Rojas et al., 2011) frequencies are projected. The general tendency for the 100-yr flood to become more frequent in Western Europe has also been suggested by Hirabayashi et al. (2008) and Dankers and Feyen (2009). In Portugal, the flood magnitude and frequency are projected to increase by the end of the century (Santos et al., 2002). In Northern France, no significant change in the 100-yr flood are projected for the 21st century (Ducharne et al., 2011). Whereas at a national level, results suggest a unclear evolutions of flood characteristics (including magnitude and duration) in France (Chauveau et al., 2013). Flood frequency was projected to increase in Belgium for catchments with dominating surface flow (Gellens and Roulin, 1998). For the British Isles, floods are generally projected to increase. Winter floods with high return periods in Ireland are projected to occur more often in fast responding catchments during the period 2021–2060, whereas catchments with dampened hydrographs show a mixture of greater or smaller return periods (Steele-Dunne et al., 2008). Kay and Jones (2012) suggest significantly increasing flood discharges in most parts of the UK while Scotland showed decreasing tendencies. Lehner et al. (2006) and Rojas et al. (2011) anticipate increasing floods in northern and north-eastern Europe, Arheimer et al. (2012) project very little change overall in water discharge for the region, while Dankers and Feyen (2009) and Hirabayashi et al. (2008) project lower return periods. In south-eastern Norway, the annual mean flood is projected to decrease by about 5% due to lower snow accumulation in winter (Erichsen and Sælothun, 1995). If no seasonal change occurs (i.e. no shift from spring flood to an autumn flood regime), there is no projected increase in the return period of

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extreme floods. For Sweden, overall, a decreasing trend in spring flood peaks has been projected (Andréasson et al., 2004) together with an increase in rain-fed autumn/winter floods (Arheimer and Lindström, 2013). Similar findings are obtained for the 100-yr floods where median projections showed no changes in the northern part of Sweden, but downwards trends in the centre, mainly resulting from decreasing snowmelt floods in spring, while rain-fed floods in the south showed the opposite tendency. However, the spread in the ensemble of flood projections (25–75 percentiles) ranged between  $\pm 50\%$  (Bergström et al., 2012). The 100-yr floods in the snowmelt dominated regions in Finland are projected to decrease or remain unchanged (Veijalainen et al., 2010); in Denmark, they are projected to increase modestly (Thodsen, 2007).

- ii. Central Europe and eastern Europe: in central Europe mixed changes in flood regimes and return periods have been projected depending on the river and river reach (Dankers and Feyen, 2009; Rojas et al., 2012). For the Meuse River (France, Belgium and the Netherlands), decreasing 100-yr floods are projected (Leander et al., 2008). In Germany, the changes depend on the seasonal climate. Overall, the Q5 flows in north-western Germany (winter floods) may increase due to increasing precipitation in winter, while in the snow melt dominated rivers of the south with summer floods the pattern is more complex (Bosshard et al., 2013b; Huang et al., 2013). For the Alpine region, projected changes are also complex. Kundzewicz et al. (2010) reviewed two studies, with one showing decreasing return periods of the 100-yr flood and the other showing a mixed change (decreasing and increasing), whereas an increase has been projected by Rojas et al. (2011). If-then scenarios in Austria analysed different flood change mechanisms, suggesting higher flood discharges in the northeast and small changes in the rest of the country (Blöschl et al., 2011). The mean annual floods in Switzerland are projected to increase in most parts of the country for the periods 2025–2046 and 2074–2095 with a stronger change signal in the latter period, but to decrease in the southern alpine catchments (Köplin et al., 2013). An intercomparison of

results for the Alpine Rhine – using different climate models, downscaling procedures, and hydrological models – has shown that all these factors significantly contribute to the total uncertainty (Bosshard et al., 2013a).

A mixed pattern of increasing and decreasing flood frequencies across Eastern Europe is projected depending on the river system analysed. For the eastern reaches of the Danube River a strong increase in the 100-yr flood has been projected (Dankers and Feyen, 2009; Rojas et al., 2012), but a decrease in the Baltic region (Dankers and Feyen, 2009; Rojas et al., 2011, 2012).

iii. Mediterranean: in the Mediterranean, the 100-yr flood is projected to mainly increase (Rojas et al., 2012), particularly in the eastern Mediterranean, with a less clear signal in the Mediterranean (Rojas et al., 2011). For Mediterranean France, Dumas et al. (2013) projected increased 100-yr floods, particularly for the lower Rhone basin, similarly for the eastern reaches of the Po River (Dankers and Feyen, 2009; Rojas et al., 2012). For the Upper Soča River in Slovenia, increasing high flow magnitudes have been projected as well (Janža, 2011).

Overall, the patterns of the flood change projections over Europe are not very clear. There may be important local effects that are masked at the European scale. In addition, there are differences in the methods and assumptions. A more coherent analysis would be desirable.

### 3.3 Flood change projections in Europe

Similar to the change detection methods in Sect. 2.3, there are challenges and opportunities for the scenario approach. They have been organised into Sect. 3.3.1 hydrological model uncertainty, Sect. 3.3.2 ensemble spread and Sect. 3.3.3 feedbacks.

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### 3.3.1 Hydrological modelling uncertainty

An important feature of flood projections from the scenario approach is that they cannot be validated against observed data because of the long lead times of decades. This is different from short-term forecasting where today's flood forecasts can be checked on the following day (Nester et al., 2012a, b). The uncertainties involved in the scenario approach, therefore, need to be carefully assessed.

One of the main assumptions in the scenario modelling is that the model structure and the model parameters equally apply to the present and the future conditions (Klöcking and Haberlandt, 2002; Merz and Blöschl, 2009; Blöschl and Montanari, 2010). This may not always be a good assumption and may be difficult to check due to issues with controlled experiments, short record lengths, the high natural variability and scale problems (DeFries and Eshleman, 2004; Blöschl and Sivapalan, 1995). Consequently, relationships between model parameters and relevant land use characteristics may not be identifiable except in small experimental catchments (Kostka and Holko, 2006; O'Connell et al., 2007; McIntyre and Marshall, 2010; Ewen et al., 2013; McIntyre et al., 2013; Pattison and Lane 2012). Similar concerns apply to changed climate conditions as hypotheses need to be introduced how the hydrological system will respond to changes (e.g. Hundecha and Bárdossy, 2004; Bulygina et al., 2009; Brigode et al., 2013). Merz et al. (2011) note that very substantial biases might be introduced into the model parameters when calibrating them against trending hydrological records in a changing climate. Also, rainfall input and its correspondence with other variables (such as air temperature and vegetation dynamics) may be uncertain, particularly when moving to extremes (Seneviratne et al., 2012).

These uncertainties can be explicitly considered in various ways in the scenario approach. One option is to propagate the uncertainty of the inputs through the model combining it with the uncertainty in the model parameters and the model structure (Montanari et al., 2009). Montanari and Koutsoyiannis (2012) propose an operator-based framework for estimating the associated distributions based on data and expert

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judgement. While the approach is appealing, as the probabilities are made transparent, assumptions need to be made how to estimate and combine them. An alternative to the uncertainty propagation method is to analyse spatial gradients as widely done in ecology (e.g. Ter Braak and Prentice, 1988) and increasingly in hydrology (Wagener et al., 2010; Peel and Blöschl, 2011). The idea of this approach is that, under changed land use or climate conditions, hydrological processes in a catchment may become similar to those experienced in other catchments under current land use or climate conditions. However, as Peel and Blöschl (2011) note, using spatial gradients has limitations, as other relevant catchment characteristics may not be similar.

While there is no one-fits-all approach to accounting for uncertainties, it is very important to estimate and communicate the uncertainties involved in the scenario approach. In particular, the “signal to noise ratio” is an important characteristic that is useful to communicate, to ascertain whether the simulated impact is significantly larger than the uncertainties of the model. Also, in the spirit of the original idea of the scenario approach (as opposed to forecasts) (Van Der Heijden, 1996), it would be useful to frame the problems in such a way that the scenarios differ by the main uncertainties rather than trying to accommodate all the uncertainties into a single scenario, as they then become de facto forecast.

### 3.3.2 Ensemble spread in climate variables

Climate models involve a range of uncertainties (e.g. Viner, 2003; Stainforth et al., 2007; Hawkins and Sutton, 2009) and large biases can be found for some RCM-GCM, so caution needs to be exercised when downscaling and applying projections (Turco et al., 2013). Among others, the uncertainties stem from: (1) limited predictability of internal variations: The climate system is highly nonlinear with interactions over a wide range of temporal and spatial scales, which render some of the internal variations intrinsically difficult to predict (e.g. Palmer, 2000; Nicolis et al., 2009). (2) model imperfections: due to incomplete knowledge of the underlying dynamics, insufficient computational resolution and imperfect model parameterisation schemes that leave out

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important sub-grid processes (e.g. Murphy et al., 2007) climate models tend to show substantial errors (in terms of means and variations) in particular at small space-time scales. (3) Scenario uncertainties: scenarios of greenhouse gas and aerosol emissions make implicit assumptions about demographic and societal developments, which may limit the accuracy of projections (see Sect. 3.1). (4) Role of extremes: as extremes are per definition rare, it is difficult to validate them in the models, and implies sampling uncertainties when estimating trends or changes from model output. Yet, understanding all of these uncertainties is essential for assessing flood regime projections in a realistic way.

To account for these uncertainties and biases, the likelihood of a model run is normally assessed from the difference between simulations and observed data. However, in the case of climate projections, there are no future observations available; therefore differences between many simulations of different GCMs (ensembles) are generally used to obtain an uncertainty measure (Blöschl and Montanari, 2010; Bosshard et al., 2013b). Such an approach only accounts for a limited range of possible futures, which may underestimate the real spread or uncertainty of the projections. For a complete uncertainty estimation, all possible futures, including those outside the space covered by the GCMs, should be accounted for. As Taleb (2007, p. 51) noted, it is important not to confound “no evidence of possibility” with “evidence of no possibility”.

Bayesian methodologies represent one option for framing the uncertainty of climate scenarios. The Bayesian assessment can be conducted directly on the climate variables (e.g. Fischer et al., 2012) or at the end of the uncertainty chain on the floods themselves. Another option, already used in weather forecasting, consists of dynamically pre-processing the ensemble of initial conditions with data assimilation schemes (e.g., Pires et al., 1996; Rawlins et al., 2007). The purpose of the procedure is to obtain a new distribution of inputs that, once fed into the dynamical model in forecast mode, can maximise the spread of the output.

Yet another approach is a group of concepts referred to as the “scenario-neutral” framework (Prudhomme et al., 2010), the vulnerability approach or the bottom-up

approach (Wilby and Dessai, 2010; Blöschl et al., 2013d). The scenario-neutral framework involves sampling changes in future climate variables that include but are not limited to the range of GCM projections. The idea is to broaden the spectrum of possible futures and identify sensitivity thresholds in the catchment response to changed climate inputs. In a similar fashion, the vulnerability and bottom-up approaches start at the local scale of households and communities to explore what conditions enable successful coping with floods (Wilby and Dessai, 2010). The focus is on the vulnerability and resilience of the risk-related system itself rather than on climate projections (Hall and Murphy, 2011; van Pelt and Swart, 2011) with the aim to develop robust and flexible strategies for dealing with changing floods.

### 3.3.3 Feedbacks

Catchments tend to respond to changes in land use and climate in a non-linear way involving a multitude of interlinked processes. Feedback processes involved in the co-evolution of soils, vegetation, climate and landscapes may result in complex patterns of flood response (Gaál et al., 2012). Heavier rainfall may increase erosion over the hill slopes, which in turn may cause landslides and enhanced flooding. Vegetation may respond to changes in precipitation and air temperature over months or years by changed rooting depths and stomata conductance while over longer time scales, genetic adaptation, and migration of species may occur. Changing the vegetation type (e.g. by deforestation) may invoke a complex causal chain of process changes and bistable dynamic behaviour (Runyan et al., 2012) affecting flooding via interception, evapotranspiration and infiltration changes. Feedbacks between soil moisture and precipitation occur from local to global scales and may have very significant effects on the magnitude of precipitation (Hohenegger et al., 2009; Van der Ent and Savenije, 2011). Similarly, feedbacks exist between human actions and floods, such as the levee effect where people tend to move into the flood risk area when levees are built as they feel protected (White, 1945; Di Baldassarre et al., 2013a).

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One way of shedding light on the feedbacks is the use of comparative studies (Falkenmark and Chapman, 1989; Blöschl et al., 2013d). The idea is to learn from the similarities and differences between different catchments. Gaál et al. (2012), for example, explored the role of landscape co-evolution processes in flood event response by contrasting catchments with different climates and landforms. The comparative approach can be combined with traditional scenarios to help find general patterns in spite of the particularities of individual catchments. As concluded by Robinson et al. (2003) a relative consistency of results between regions gives confidence in the generality of the findings.

If the feedbacks can be specified it is possible to model them with complex process models of the system. An example is modelling the response of natural vegetation to changed climatic conditions (e.g. Bonan et al., 2003; Gerten et al., 2004; Gray and Hamann, 2012; Hanewinkel et al., 2012), although the models are sometimes not fully coupled. Another example are land surface-atmosphere feedbacks of precipitation that are relevant to flooding (Hohenegger et al., 2009), as floods are driven by both event precipitation and antecedent soil moisture, so feedbacks will have a major effect on flood magnitudes. Afforestation can also not only change the runoff properties of the catchment, but also the stream morphology. Reduction of sediment erosion at the scale of the basin does influence the bedload sediment within the rivers (Kondolf et al., 2002; Piégay et al., 2004). At the opposite, the increasing of temperature is expected to induce a general melting of glaciers. That will increase the extent of mountainous areas with a large amount of available sediment for bank erosion.

An alternative consists of low-dimensionality models where the focus is on the main features of the coupled dynamics rather than on the process details. For the cases of water-plant feedbacks, these models are playing an important role in eco-hydrology (e.g. Eagleson, 1982); for the case of water-people feedbacks, these models are playing an important role in socio-hydrology (e.g. Sivapalan et al., 2012; Montanari et al., 2013). For example, Di Baldassarre et al. (2013b) developed four coupled non-linear differential equations to represent the evolution of a settlement in a floodplain with the



options of building flood protection measures and/or moving away from the stream. The model was able to simulate observed macro-scale interaction patterns, such as the levee effect. The model was also used to show that the development of the community in the floodplain might be dependent on the sequence of the flood occurrence rather than on the probabilities of the flood magnitudes alone (Viglione et al., 2013) and that bistable dynamic behaviour may occur for some parameter combinations. While these models are investigative rather than predictive, they are an appealing opportunity for better exploring the flood evolution patterns resulting from the coupled process dynamics in order to complement existing scenario runs and case studies of past flood changes.

## 4 Towards better understanding flood changes

### 4.1 A synthesis of approaches

Sections 2 and 3 have reviewed change detection and scenario approaches to analysing flood regime changes, respectively. Each of the approaches has strengths and limitations. Change detection methods are strongly data based, and therefore represent real variability to a large degree, but they do not necessarily easily infer the causality of flood changes. Conversely, scenario methods are strongly model based, so causality is included, but sometimes it is not clear how well reality is actually represented. The two methods are complementary, so there may be value in combining their respective strengths. On one hand, there is scope for learning about flood change causality in the context of change detection methods. On the other hand, there is scope for improving the realism of scenarios to better match real flood regime dynamics. These opportunities are schematically visualised in Fig. 10 and each of them are discussed below.

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### 4.1.1 Going beyond trend analysis of floods

The traditional change detection methods give some insight into flood regime changes but the results strongly depend on the observational window and the assumption about the nature of the change (e.g. monotonic trends, step changes). It is therefore important to go beyond the traditional trend detection and analyse other forms of change such as fluctuations and other nonlinear variations in hydrological series. Recently, new methods have been developed that are better suited for detecting non-linearities in time series. For example, the information-theoretical measures of Pires and Perdigão (2007) and Brunsell (2010) can be used to identify spatio-temporal patterns, and the empirical mode decomposition and maximum entropy spectral methods of Sang et al. (2012) can be used to identify complex periodicity in the time series. These methods may also give additional impetus for identifying flood-rich and flood-poor periods in the records rather than trend methods alone.

As long duration records offer better insights into non-linearities and fluctuations compared to short records, there is potential in combining systematic flood records with historic flood data from a diverse set of sources. To obtain a truly continental-scale overview, systematic research in multiple catchments is required where good documentary sources are available (to create long flood time series) coupled with the broad co-operation of researchers from various countries. The ability to reconstruct peak discharges for past floods, based on epigraphic and other documentary sources, represents an important development in incorporating historical information into flood change analyses (e.g. Herget and Meurs, 2010; Elleder et al., 2013).

### 4.1.2 Attributing causes to observed flood changes

The detection of changes in flood time series is a good starting point, but for predicting future changes in the flood regimes, it is even more important to understand the underlying mechanisms. For this purpose, the synergies with the model based (scenario) approach should be exploited more thoroughly. A number of options exist, for example,

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of past climates to assess systematically the relative importance of different climate variables in explaining the detected flood changes. This approach tests the hypothesis that observed flood changes are climate driven (proof of consistency). Other opportunities for exploiting the synergies of the two types of methods include the use of macro-scale information, such as the observed seasonality of floods, to strengthen modelling approaches and to improve flood regime predictions.

#### 4.1.4 Low-dimensionality change models for flood changes

An alternative to the traditional scenario approach is to link the attribution of past changes and future projections directly through causalities. Delgado et al. (2010, 2012, 2013) explore this avenue for the Lower Mekong River. They found that average floods have slightly decreased during the last few decades, but that the variability of the annual maximum floods has increased significantly. Using wind velocities as proxies for monsoon activity, they identified the variance of the western North-Pacific monsoon intensity as a main driver of changes in flood variance, which they used to model non-stationary flood probabilities as a function of monsoon intensity. This approach opens the possibility to estimate future flood regime changes directly from GCMs, which is appealing as monsoon intensity is based on average wind velocities over large areas, which are reasonably well simulated by GCMs, bypassing the use of precipitation, which is usually poorly simulated by climate models. A similar idea of combining attribution and projection was proposed by Kwon et al. (2008) who used a Bayesian hierarchical model to estimate flood probabilities in Montana from sea surface temperature indices, snowpack depth and GCM season-ahead forecasts of precipitation. The approaches presented above offer the possibility for establishing direct causality links for observed and projected European flood changes. Low dimensionality models have also the potential of representing feedbacks of driver-impact linkages in the spirit of socio-hydrology models (e.g. Di Baldassarre et al., 2013b) and are appealing to complement the traditional scenario approach.

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## 4.2 A synthesis of approaches

### 4.2.1 Need for a European wide effort

In order to better understand flood regime changes in Europe, a regional perspective of floods and their drivers is needed. A European collaborative effort may target both the regional differences in flood drivers across Europe and the patterns of change that span across national boundaries as shown above. Pan-European collaboration brings benefits for both broader scientific assessments and efficiency gains by targeted exchange of methods and results. Identifying hydrological patterns beyond the catchment or national scales will help with attributing changes in hydrological regimes influenced by large-scale processes such as climate change (Whitfield et al., 2012). By comparing and contrasting observed and projected flood regime changes in a comparative way across European sub-regions, new insights in deciphering flood generating processes, controls and changes can be gained. Also, as the European Flood Directive (EU, 2007) is putting more emphasis on harmonising flood risk management measures across river basins (Quevauviller et al., 2011, 2012), a European wide research effort is becoming increasingly important.

Another important role of European wide efforts is to share data relevant to understanding flood regime changes across Europe. There are a number of European projects that have compiled and made available flood data across Europe such as the HYDRATE (Hydrometeorological Data Resources and Technology for Effective Flash Flood Forecasting) project (Gaume et al., 2009; Borga et al., 2011) and the COST Action on European procedures for flood frequency estimation (Kjeldsen, 2011; Salinas et al., 2013). However, a number of barriers may hinder collaboration at a European scale. The survey of Viglione et al. (2010b) conducted in 32 European countries suggests that these barriers may include restrictions imposed by hydrometric authorities, legal constraints and economic reasons due to the costs of the data, conflicting interests between data providers and data end-users, and the awareness of data misuse. Understanding such barriers is a first step towards enhancing the data exchange. The

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INSPIRE Directive on free exchange of environmental spatial information will likely contribute to a more coherent access to European data relevant to flood changes. Nevertheless, more informal collaboration across Europe is needed.

#### 4.2.2 Building blocks of a European flood change research network

To foster a joint European effort on flood research, a platform is needed that facilitates collaboration across trans-boundary catchments and national boundaries. An informal and open “Flood Research Consortium” has been proposed recently to extend the COST initiative on flood frequency estimation, within the ERC Advanced grant “Flood-Change – Deciphering river flood change”. The purpose of the consortium is to foster joint cross-border research on understanding flood processes and associated changes at the European scale. It is suggested that a number of building blocks are needed for such a consortium to work in a sustainable way:

- i. Common framework: one of the essential features of merging information and research across countries is a common scientific framework. There should be a common understanding of what research questions to address, even though a diversity of approaches may exist which, in fact, may enable obtaining more robust research results.
- ii. Common protocol: a common protocol on how to proceed in hypothesis testing (Laio et al., 2009) would enhance the coherence of the research of the consortium. Equally important is a common protocol on presenting and sharing data (Hannah et al., 2011) and on reporting scientific results in the hydrological literature (Parajka et al., 2013).
- iii. Common commitment: a common commitment across such a consortium is needed to ensure coherent research approaches, data quality, and sufficient access to metadata, with every member willing to participate. This is why regional and national research by individuals and their local knowledge will still play an

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important role, however, by collaborative research a broader picture of flood research can emerge.

- iv. Incentives: a consortium member will benefit through joint research based on exchange of data, models, expertise, and staff. By working and publishing together on a common study object, i.e. European floods, the opportunity to go beyond one's own spatial region of expertise may provide motivation along with an increase in the scientific visibility and credibility.

Examples of powerful informal networks are the Decades of the International Association of Hydrological Sciences (IAHS). The Predictions in Ungauged Basins (PUB) Decade has been instrumental in synthesising hydrological research that had been fragmented before (Blöschl et al., 2013c; Hrachowitz et al., 2013), and a similar decade is under way on hydrological change and its connection to society, entitled "Panta Rhei – Everything Flows" (Montanari et al., 2013). Such informal networks can form the basis of more formal networks in which international collaborations are established to work together in a planned manner. Both kinds of networks will be important stepping-stones towards better understanding the processes of flood regime changes in Europe.

## 5 Towards better understanding flood changes

Based on the review in this paper, the following recommendations that exploit the synergies between the change detection and scenario approaches are offered:

- Combining systematic flood data with documentary flood data from diverse sources is recommended as an opportunity to gain insight into long-term flood regime dynamics.
- Change analyses of flood data should focus on identifying flood-rich and flood-poor periods instead of just detecting whether trends exist. The process reasons of flood-rich and flood-poor periods (e.g. Hurst phenomenon) should be explored.

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**Table 1.** Examples of potential drivers of change in flood regimes and associated variables (modified from Merz et al., 2012).

| Compartment | Processes  | Variables   | Drivers of change   |
|-------------|--|---|---|
| Rivers      | Flood wave propagation, superposition of flood waves | River morphology, conveyance, roughness, water level and depth, discharge, floodplain storage, river channel vegetation   | In-stream channel engineering, reduction in river length, construction of dikes, groynes and weirs, operation of hydropower plants and reservoirs |
| Catchments  | Runoff generation and concentration (flow path)      | Evapotranspiration, infiltration capacity, runoff coefficient, water storage capacity, practices, drainage of wetlands and agricultural areas, construction of flood retention basins | Urbanisation, transport infrastructure, deforestation, ditch construction, wildfires, agricultural management                                     |
| Atmosphere  | Atmospheric forcing of catchment water fluxes        | Temperature, total precipitation, precipitation intensity/duration, snow cover and snowmelt, short and long-wave radiation climate variables  | Natural climate variability at different time scales, anthropogenic climate change  |

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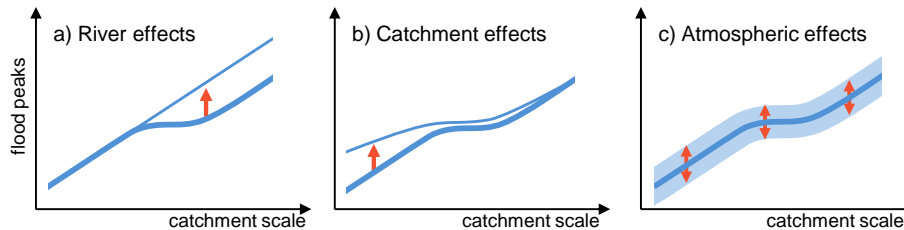
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**Fig. 1.** Hypothesised impact of three types of drivers on relative flood peaks as a function of catchment scale. **(a)** River: removing floodplain storage. **(b)** Catchment: land use change such as urbanisation, **(c)** atmosphere: climate change such as changes in rainfall characteristics (based on Blöschl et al., 2007).

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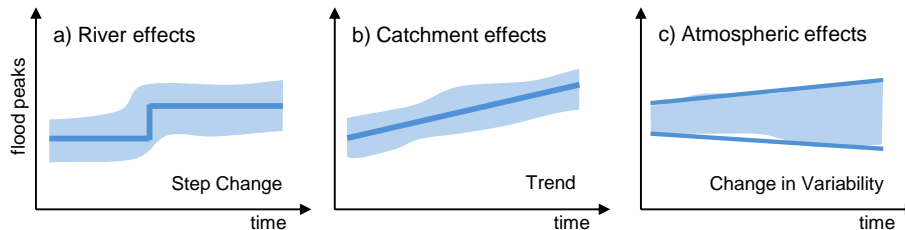
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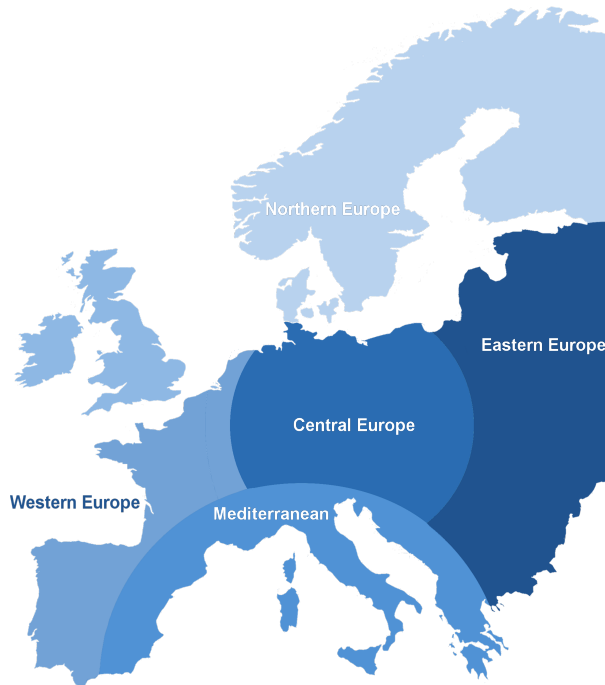
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**Fig. 2.** Typical types of changes in flood peaks over decades or centuries as caused by **(a)** construction/removal of hydraulic structures, **(b)** gradual land use change, **(c)** increasing variability of extreme rainfall. Shaded areas represent intra-decadal variability.

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**Fig. 3.** European sub-regions used in this review: Atlantic western Europe and northern Europe, Central Continental Europe and eastern Europe, and the European Mediterranean.

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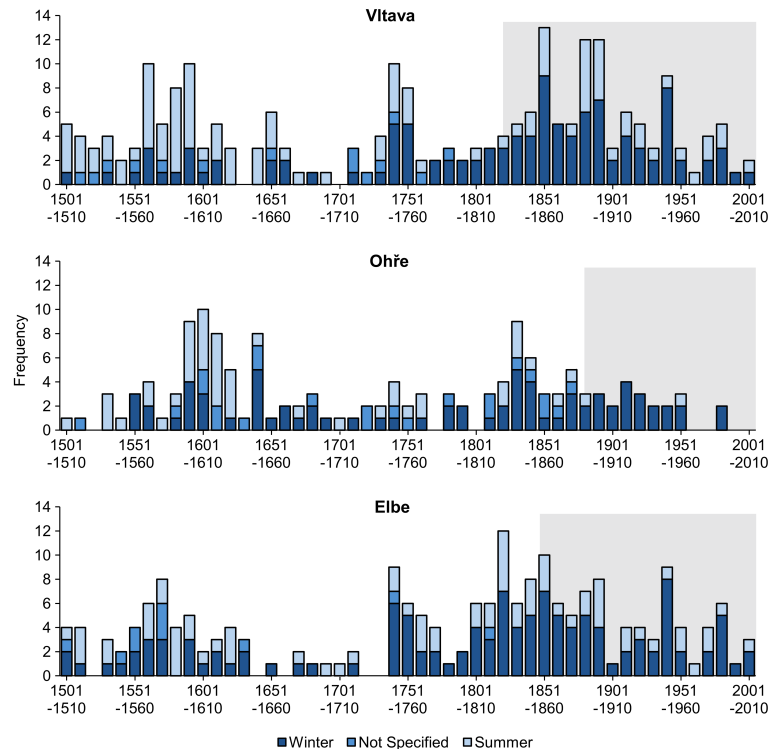
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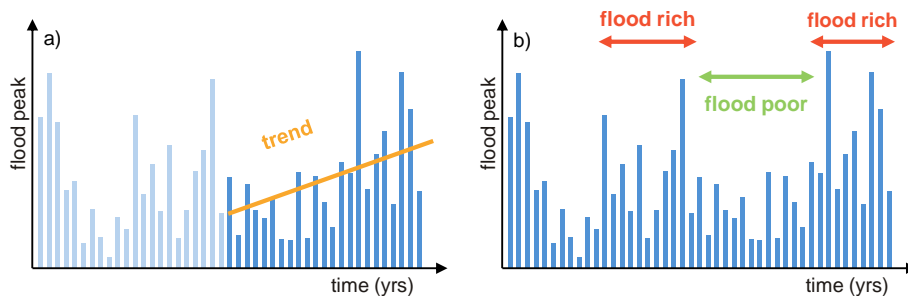
**Fig. 4.** Decadal frequencies of floods for Bohemia (the Czech Republic) from 1501–2010 stratified by season (winter; November–April, summer; May–October): the River Vltava (from Česká Budějovice to its confluence with the Elbe), the River Ohře (from Kadaň to its confluence with the Elbe), the River Elbe (from Brandýs to Děčín). Gray shaded areas mark the instrumental period. For the instrumental period discharges larger than the 2-yr flood are counted, for the pre-instrumental period floods mentioned in the documentary sources are counted (modified from Brázdil et al., 2012).





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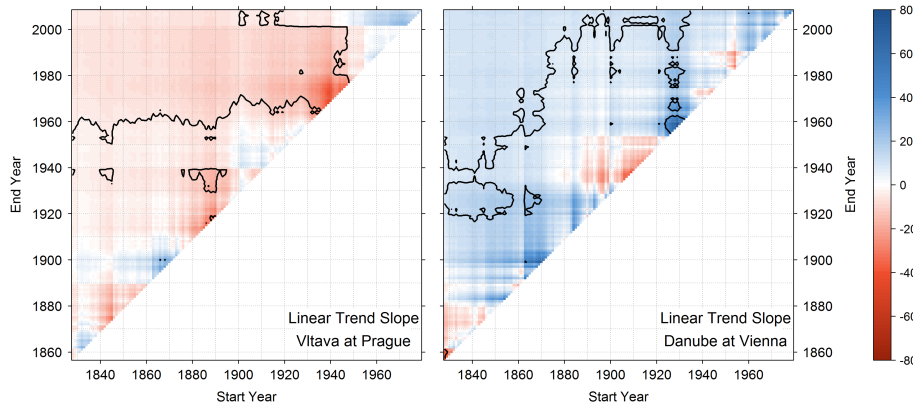
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**Fig. 6.** Evaluation of flood peak changes over time. **(a)** Monotonic trend analysis; **(b)** identification of flood-rich and flood-poor periods. Dark blue colour indicates data available for analysis.

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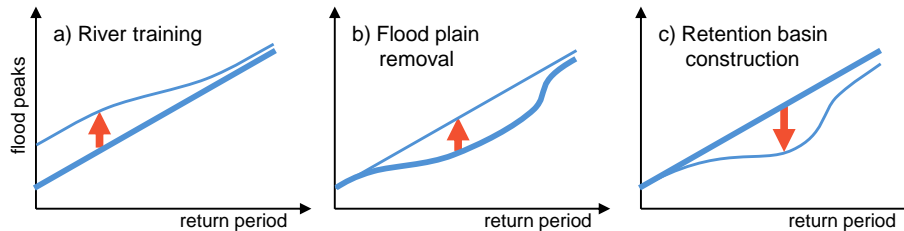
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**Fig. 7.** Linear trends of the annual maximum floods for the Vltava at Prague (left panel,  $\sim 26\,700\text{ km}^2$ ) and the Danube at Vienna (right panel,  $\sim 101\,700\text{ km}^2$ ). Trend slopes ( $\text{m}^3\text{ yr}^{-1}$ ) are derived from 30-yr moving windows for all possible combinations of start and end years between 1828 and 2008. Blue colours indicate increasing trends, red colours decreasing trends. The black line encloses combinations of start and end years with significant trends at the 5% level (predominately top left).

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**Fig. 8.** Hypothesised impact of three types of hydraulic engineering activities on the flood frequency curve. **(a)** River training tends to increase the small floods. **(b)** Removing floodplain storage by constructing levees tends to increase the medium sized floods. **(c)** Constructing retention basins tends to reduce the medium sized floods.

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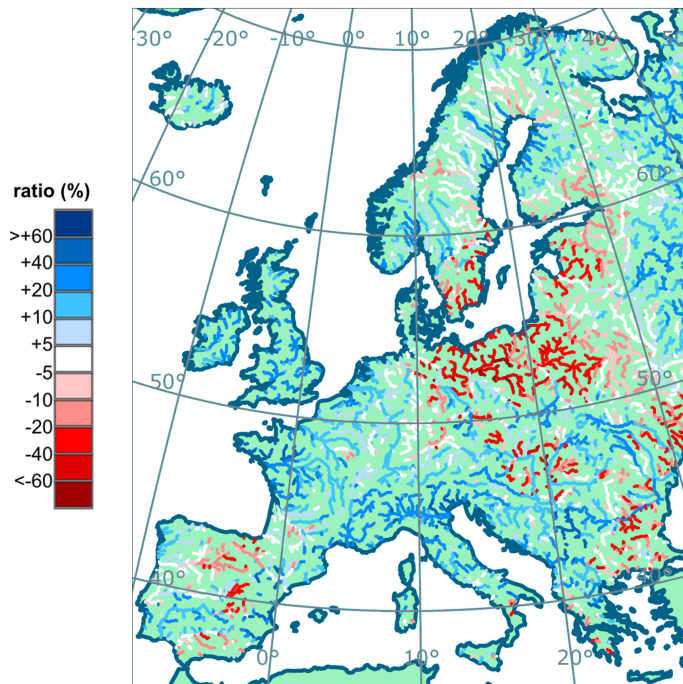
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**Fig. 9.** Example of estimated ensemble average change in the 100-yr flood discharge between 2071–2100 and 1961–1990 (Rojas et al., 2012). Note that other studies are not necessarily consistent with these projections.

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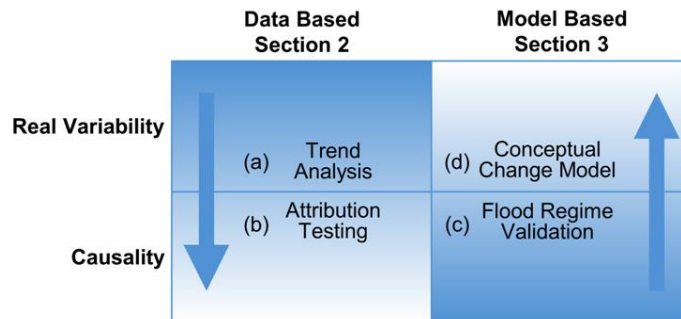
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**Fig. 10.** Synthesis of approaches to analysing flood regime changes. Dark blue indicates strengths of the data based (change detection) and model based (scenario) methods. The proposed synthesis items **(a)** to **(d)** correspond to the Sects. 4.1.1 to 4.1.4.

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