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Detection of trends in magnitude and frequency of flood peaks across Europe

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ABSTRACT
This study analyses the differences in significant trends in magnitude and frequency of floods detected in annual maximum flood (AMF) and peak over threshold (POT) flood peak series, for the period 1965–2005. Flood peaks are identified from European daily discharge data using a baseflow-based algorithm and significant trends in the AMF series are compared with those in the POT series, derived for six different exceedence thresholds. The results show that more trends in flood magnitude are detected in the AMF than in the POT series and for the POT series more significant trends are detected in flood frequency than in flood magnitude. Spatially coherent patterns of significant trends are detected, which are further investigated by stratifying the results into five regions based on catchment and hydro-climatic characteristics. All data and tools used in this study are open-access and the results are fully reproducible.

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1 Introduction

Recently, numerous extreme flood events have been recorded across the European continent, such as the floods in central Europe in summer 2002 and 2013 (Ulbrich *et al.* 2003, Blöschl *et al.* 2013, Schröter *et al.* 2015), floods in the UK in summer 2007 and winter 2013 (Marsh 2008, Muchan *et al.* 2015) and flash flooding in western Italy in autumn 2011 (Marchi *et al.* 2013). These and other recent flood events are being perceived as unprecedented and therefore there is a growing concern that flooding in Europe has become more frequent and severe.

Taking possible changes in floods into account is important for many hydrological applications, such as design of flood protection facilities, risk assessment and risk management (Parry *et al.* 2007, Kundzewicz 2012, Rosner *et al.* 2014). Additionally, accounting for temporal trends in flood series may lead to better flood frequency estimates (Khaliq *et al.* 2006, Renard *et al.* 2006, Vogel *et al.* 2011, Šraj *et al.* 2016).

To detect changes in floods, different analyses have been performed for several regions in Europe. Examples of recent studies include but are not limited to: Hannaford and Buys (2012) for the UK, Murphy *et al.* (2013) for Ireland, Giuntoli *et al.* (2012) in France, Arheimer and Lindström (2015) in Sweden, Blöschl *et al.* (2011) and Jeneiová *et al.* (2016) in Austria, Brázdil *et al.* (2006, 2012), Kundzewicz *et al.* (2013) and Pekárová *et al.* (2016) in Central Europe, and Bard *et al.* (2012) for the Alpine mountain region. Such analyses provide insight into regional patterns of flood changes within selected catchment, national or regional boundaries. Hall *et al.* (2014) performed a meta-analysis of published literature on flood change across Europe. They found large-scale patterns of changes in flood magnitude with similar sign of change, but also concluded that the studies are not fully comparable, due to the different time periods analysed and differences in the methodology applied to derive flood series and to detect flood changes.

When performing trend tests on flood series, one of the main methodological concerns is the definition of the variable "flood" to be tested. Commonly, two methods are used to derive times series of flood series: the annual maximum flood (AMF) series and the peak over threshold (POT) approach.

The AMF series consist of the highest discharge values for each year. The main advantage of this method is that the events selected in two successive years can generally be considered independent. On the other side, the main disadvantage of using the AMF method is that this method neglects flood events that

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Supplementary data for this article can be accessed here.

are lower than the annual maximum in each year but are still relevant for society, particularly in terms of damages.

The POT series consists of flood peaks exceeding a predefined threshold (Cunnane 1973, Madsen *et al.* 1997). If the POT series is used, it is important to ensure that the peaks are independent (e.g. peaks do not occur on the recession curves of the preceding flood peak). In addition to the detection of trends in the mean magnitude of flood peaks exceeding a threshold (trends in magnitude), the POT method also allows the detection of trends in the mean number of flood events per year (trends in frequency).

Large-scale studies investigating flood trends in the POT series using high spatial resolution datasets do not exist in Europe so far. Examples of a continental-scale study for the USA can be found in Hirsch and Archfield (2015) and Archfield *et al.* (2016). In these studies, the authors found no consistent nation-wide flood trend signal but highlighted some regional patterns. In the literature, some studies can be found where flood trends in Europe were detected using the POT approach. However, these studies considered either high spatial resolution databases at a regional scale (Petrow and Merz 2009, Vormoor *et al.* 2016) or a Europe-wide database with only a limited number of stations (Mediero *et al.* 2015). Moreover, in all these studies, the threshold values used to determine the POT series were selected by fixing a mean number of events either per year or per season (in general a mean of one, two or three flood events was selected). To our knowledge, no systematic analysis aimed at investigating the effects of using different threshold values on the detection of significant trends has yet been performed. In this regard, Méndez *et al.* (2006) underlines: "*The selection of the threshold implies a balance between bias and variance. Too low a threshold will likely violate the basis of the model, causing bias; too high a threshold will identify few extremes, leading to high variance.*"

The main objective of this paper is to detect the evidence of statistically significant flood trends across Europe using a high spatial resolution dataset. Flood series are compiled using the AMF and POT approaches, using, for the latter, six different exceedence thresholds. The following three research questions are being addressed:

(1) What are the patterns of trends in flood magnitude and frequency across Europe for the period 1965–2005?
(2) What is the sensitivity of the detected trends to the selection criterion used to define different flood peak series?
(3) What are the larger scale morpho-climatological characteristics of the catchments with significant trends?

The analysis is performed on a large open-source dataset comprising 629 gauging stations recording mean daily discharge (GRDC 2016). All data and tools used here are open-access and available at the SWITCH-ON portal (http://www.water-switch-on.eu).

2 Methodology

Changes in flood magnitude and frequency are detected by performing trend analysis on flood peak series. The flood peak series are compiled using a procedure based on: (i) separating independent events, (ii) selecting the maximum daily discharge within each independent event and (iii) compiling AMF and POT flood series. The first two parts of the methodology are described in Section 2.1, the selection of flood peaks is elaborated in Section 2.2, and the methodologies used for trend detection are presented in Section 2.3.

2.1 Identification of independent peak events

Trend tests are based on the assumption that data are identically distributed and independent (WMO 2009). Two consecutive extreme events can be assumed physically independent when they are caused by different forces, so that the previous event does not condition the occurrence of the second event.

While the AMF approach leads to flood events that are generally considered independent, an objective criterion for the selection of independent events is needed within the POT approach. Generally, the independence criteria are related to the concept of streamflow recession, which states that the independence of two flood events increases over time if a period of decreasing discharge is recorded in between.

When using the POT approach, one possible criterion to define the independence between two successive events is to fix a minimum number of days between them. This can be achieved either by using a predefined period, such as 15 days (Mallakpour and Villarini 2015), or by determining a time lag between the two successive events as a direct function of the catchment size (Svensson *et al.* 2005). The USWRC (1982) introduced an additional criterion concerning the intermediate discharge magnitude between two successive peaks. In this case, two successive discharge peaks can be considered independent if the minimum daily discharge value recorded in between is lower than three-quarters of the smaller peak, as for example applied in Mediero *et al.* (2015).

In the present work, the criterion of independence is fulfilled using a baseflow-based algorithm that models streamflow recessions explicitly. The algorithm allows the separation of independent discharge peak events by comparing the recorded total flow and the estimated baseflow. The maximum daily mean discharge within each separated event is finally considered to be an independent discharge peak.

The traditional procedure for baseflow estimation involves the identification of those points in time at which the direct runoff component of a hydrograph (i.e. surface runoff) starts and, successively, ends. The start of the event is identified as the point in time when the flow starts to increase. The end of an event is determined as the point in time when a plot of logarithmic transformed discharge values against time becomes a straight line.

In this study, the Chapman digital filter (Chapman 1999) was applied for baseflow estimation. The digital filter estimates the baseflow as a simple weighted average of the direct runoff and the baseflow at the previous time interval:

$$Q_{b(i)} = k \cdot Q_{b(i-1)} + (1-k) \cdot Q_{d(i)} \quad (1)$$

where $Q_{b(i\text{-}1)}$ and $Q_{d(i)}$ are the baseflow at time interval i – 1 and the direct runoff at time interval i, respectively, and k is the recession constant during periods of no direct runoff. Assuming that the recorded total flow $Q_{(i)}$ is the sum of baseflow $Q_{b(i)}$ and direct runoff $Q_{d(i)}$, then $Q_{b(i)}$ can be estimated as:

$$Q_{b(i)} = \frac{k}{2-k} \cdot Q_{b(i-1)} + \frac{1-k}{2-k} \cdot Q_{(i)} \quad (2)$$

In order to estimate the recession constant k for each catchment, the approach suggested in Vogel and Kroll (1996) and successive applications (Thomas *et al.* 2013) is used here. The approach consists of the following steps:

(1) Identification of the start/end of the discharge recession, defined as the point in time when a 3-day centred moving average begins to decrease/increase.
(2) Rejection of the recessions shorter than 10 days.
(3) Removal of the first three points of the recession to eliminate the effect of the moving average.
(4) For each recession identified, a regression ln(Q) = ln(Q_0) + ln(k_i)·t + residual is fitted, applying the ordinary least squares method.
(5) The average of the estimated regression slope k_i is computed. This average approximates the recession constant k.

Once the recession constant k is estimated, the baseflow Q_b is calculated using the Chapman filter. The direct runoff Q_d is the difference between the recorded total flow and the estimated baseflow. Discharge events are considered independent if they are separated by intervals within which the direct runoff is lower than the baseflow or lower than the mean annual direct runoff (to remove the instances when discharge or baseflow equals zero). The maximum discharge value within each discharge event is then selected as an independent flood peak.

Figure 1 shows a sample application of the baseflow-based algorithm for the peak separation in the River Teme at Tenbury, western UK (catchment area: 1134 km^2) for the year 1968. The figure shows the total discharge time series, the estimated baseflow, the start and end points of the identified discharge event and the independent flood peaks for each separated event.

2.2 Selection of flood series

Once the independent discharge peaks are identified for all the time series, the flood series are compiled using the AMF and POT selection approaches.

Annual maximum floods are commonly identified by using a so-called "block maximum" approach (Gumbel 1958). This method requires the time series to be divided into blocks of equal length (for AMF the unit block is a year) and the highest value within each block is selected. The main advantage of the AMF method is given by the immediate correspondence with the "return period" concept, since one year is considered as the time unit. However, the main limitation of the method is that annual peaks with very small values may be included (e.g. in drier years), whereas in years with several larger floods only the highest value is considered.

The POT method identifies all flood events that exceed a given threshold. Unlike the AMF approach, the POT methodology allows the analysis of both trends in magnitude (POT-M) and trends in frequency (POT-F).

When performing trend analysis on flood series using the POT approach, the number of peaks to be included in the flood series is determined by selecting an appropriate threshold. Many studies use a fixed mean number of exceedences per year (λ) to identify this appropriate threshold value. For example, if a 40-year time series is

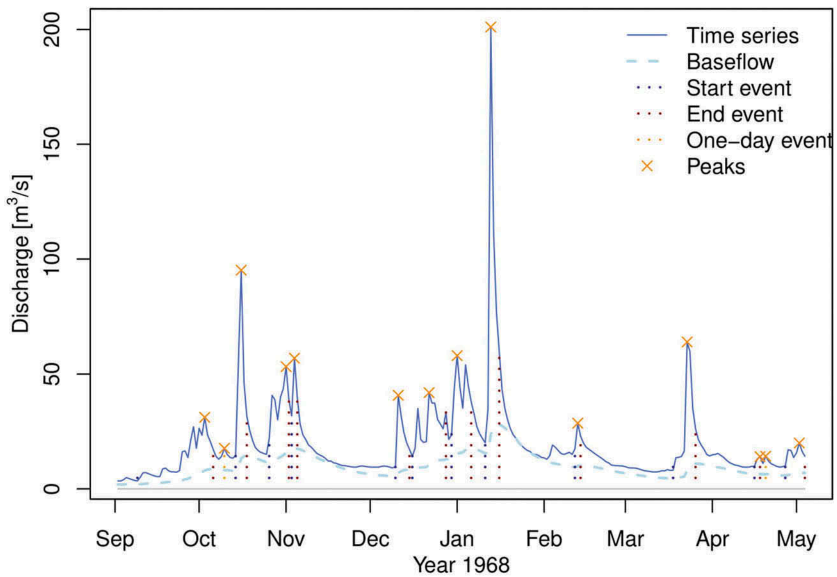

Figure 1. Example of discharge series and peak flows (crosses) for the River Teme, at Tenbury station (UK). A discharge event starts (vertical dotted dark blue line) when the direct runoff is larger than the baseflow (light blue dotted line), and ends (vertical dotted red line) when it is lower. One-day-long events are shown with vertical dotted orange lines, peak discharges identified as independent with orange crosses (see online for colour version).

analysed and λ is chosen to be one (POT1), the highest 40 discharge peaks in the time series are considered to form the flood series. By formulating the hypothesis that flood events follow a Poisson process, λ represents the event rate (or frequency) per unit time of the distribution.

In this paper, the sensitivity of the trend results to the selection of the threshold is assessed considering a mean number of exceedences per year (λ) ranging from one to six (POT1 to POT6). Additionally, trends in the flood magnitude series of POT1 are compared to those of AMF.

Since in this research trend detection is performed on different flood series, a factor called the multiple index (MI) is introduced. The MI compares the mean intensity of flood series against the mean annual flow at each individual station, and is defined as:

$$\mathrm{MI} = Q_F/Q_A \qquad (3)$$

where Q_F is the mean discharge value of a flood series and Q_A is the mean annual discharge recorded for an individual station. Higher MI indicates a stronger divergence of the flood series from the mean flow. For small λ, only the highest flood events are considered and low MI values are obtained. The MI is used to support the description of the flood regimes in different European regions, which span from dry to wet climates.

2.3 Trend analysis and test for statistical significance

Trend detection can be performed using parametric or nonparametric approaches. Parametric tests, such as a simple linear regression over time, can be used for easy representation and interpretation of trend results (Merz *et al.* 2012). However, such tests imply an *a-priori* assumption on the regression function and require specific statistical characteristics, such as normal distribution of the residuals and constant variance (Helsel and Hirsch 2002). If those conditions are not satisfied, nonparametric procedures, such as the Mann-Kendall test (Kendall 1938) have to be preferred. In the present analysis, the Mann-Kendall rank correlation test is used to detect monotonic trends in flood magnitude together with the Theil-Sen slope algorithm (Sen 1968) for trend slope estimation.

To detect trends in flood frequency of the POT series, the Chi-squared test on parametric Poisson regression is used. The Mann-Kendall test should not be used on POT frequency (POT-F) series, since the rank correlation procedure may fail in finding a hierarchy in count series containing several paired values (Frei and Schär 2001, Vormoor *et al.* 2016). The Poisson regression is a generalized linear regression model able to fit count series. The model assumes the counts to be Poisson distributed with the logarithm of their expected value varying linearly with time. The Chi-squared significance test assesses whether the slope parameter of the regression is significantly different from zero, which, in this case, means that a significant trend in flood frequency is detected.

Trends presented in this paper are detected using two-tailed tests at a 10% significance level. This means that tests have a 10% probability of detecting significant trends, either positive or negative, by chance. A two-sided test at 10% significance level is equivalent to a one-sided test at 5% significance level. In a one-sided test, the direction of the trend (either positive or negative) has to be specified beforehand. If a 5% significance level is considered, for each direction of the trend there is a 5% probability of detecting significant trends by chance (summing to 10% if the two tails are considered). Two-sided tests at 10% level of significance are preferred here since the direction of the trend to be tested *a priori* is unknown. However, it is noteworthy that in these tests the probability of detecting significant trends by chance in each direction is only half of the significance level of the test (thus 5%).

The presence of autocorrelation within time series is checked for the AMF and POT-F series using the Breusch-Godfrey (Breusch 1978) test. The test is performed since serially correlated time series tend to exhibit "artificially" significant trends (Von Storch 1999). A test to detect serial correlation in the POT magnitude (POT-M) series is not performed, since this would require advanced interpolation methodologies (Rehfeld *et al.* 2011), which are out of the scope of this research.

3 Data

3.1 A Pan-European peak discharge dataset

The daily discharge time series analysed in this research are extracted from the European subset of the Global Runoff Data Centre database (GRDC 2016). The European subset consists of over 1200 gauging stations with an average record length of 54 years. However, the number of records available for each year varies considerably, due to different periods of record available and gaps in the time series of the stations (Fig. 2).

A common time window of 41 years (1965–2005) is chosen (Fig. 2) to maximize both the spatial and temporal coverage of the discharge time series. In order to minimize inhomogeneity within the data, time series having more than 2 years of data missing are excluded from this selection. This results in 629 gauging stations to be included in the trend analysis.

This study focuses on comparison of the large-scale spatial patterns of trends detected in different flood peak series. Therefore, all time series satisfying the above-mentioned criteria are included and no attempt is made to further identify the possible causes of the observed trends (such as climate change, river training or dam construction).

3.2 Catchment characteristics

This study also aims at determining the relationship between large-scale morpho-climatological characteristics of the catchments and the significant trends

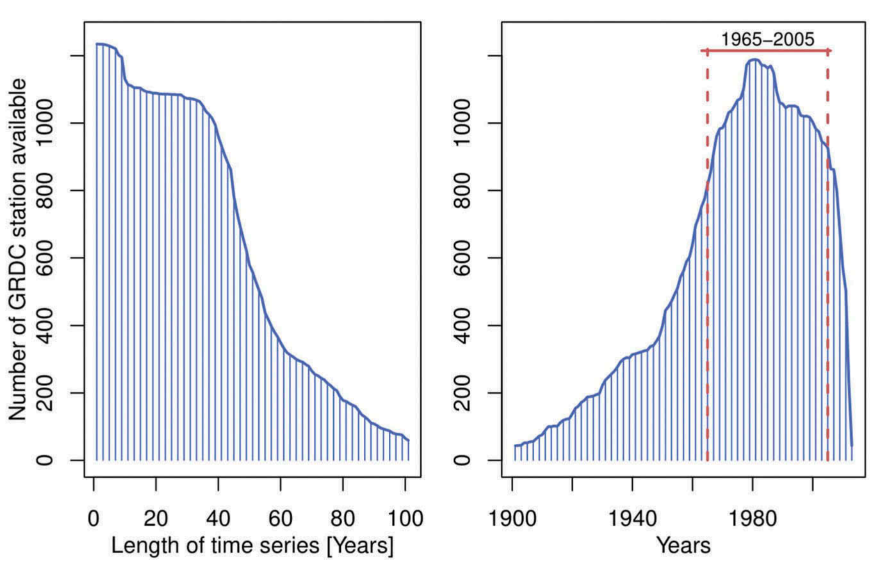

Figure 2. Length and available time periods of daily discharge time series contained in the European Global Runoff Data Centre (GRDC) subset in the period 1900–2010. Length of the time series for each station (left), and number of stations available in each year (right). Red lines indicate the time window, 1965–2005, selected for the trend analysis (see online for colour version).

detected in the flood series. To answer the third research question, the following four catchment characteristics are estimated and considered: catchment area, mean catchment elevation, mean annual rainfall and mean annual air temperature (both evaluated over the period 1965–2005).

For each catchment, the mean elevation is calculated from the European Digital Elevation Model provided by the European Environment Agency (EEA 2016a), with a spatial resolution of 1000 m, while the mean annual precipitation and air temperature are derived from the E-OBS gridded dataset (Haylock *et al*. 2008). Catchment boundaries for each gauging station are determined from the Catchment Characterisation and Modelling version 2.1 (CCM2) dataset (Vogt *et al*. 2007).

The calculated catchment characteristics and the shape files of the catchment boundaries are openly accessible and included in the Supplementary material for this paper.

3.3 Hydro-climatic regions

In order to stratify the results of the flood trend detection across Europe, the stations are grouped into five regions: Alpine, Atlantic, Boreal, Continental and Mediterranean. This subdivision is based on the bio-geographical regions singled out by the European Environment Agency (EEA 2016b). The five hydro-climatic regions are shown in Figure 3 together with the selected gauging stations. A description of the regions is given in Table 1, where the predominant regional climate is defined based on a digital dataset of the Köppen-Geiger climate classification (Köppen 1884, Kottek *et al.* 2006). The five regions can be characterized as follows.

The Alpine region includes the main mountain ranges in Europe: the Alps, the Scandes, the Pyrenees and the Carpathians. Despite its different geographical positions, the Alpine region exhibits a number of

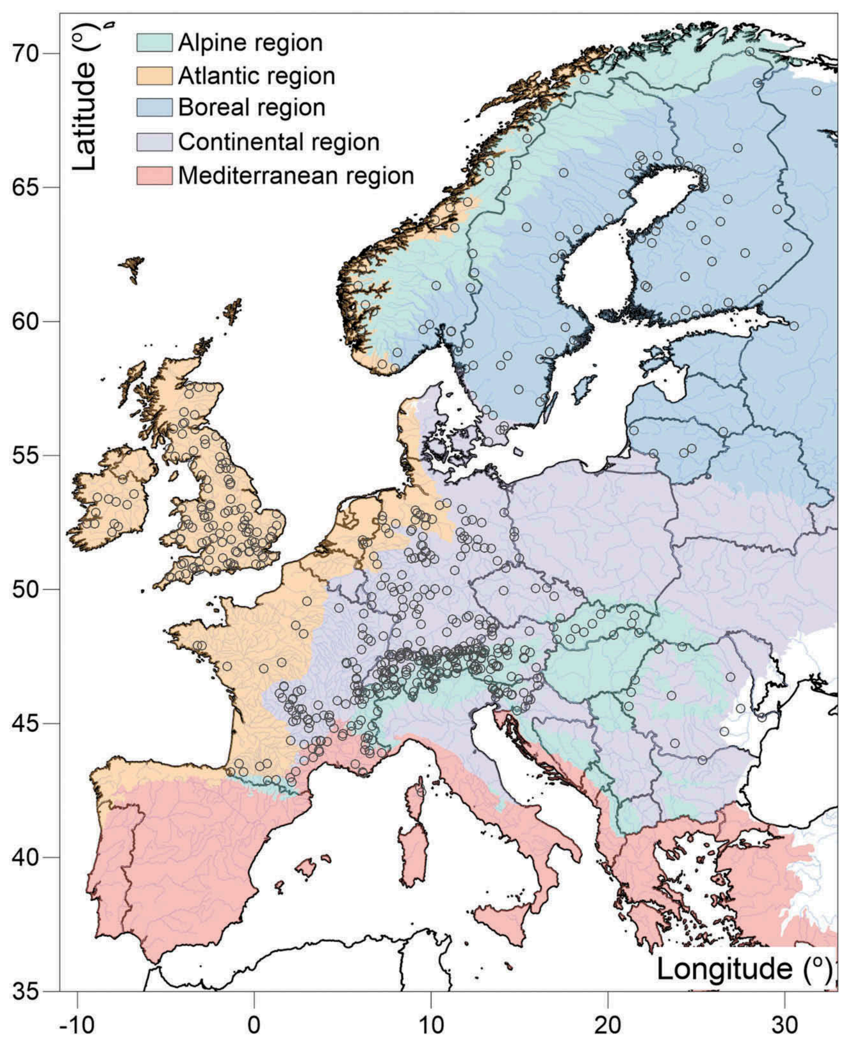

Figure 3. Five hydro-climatic regions in Europe based on a bio-geographical classification provided by the EEA. Circles indicate the locations of the 629 gauging stations (see online for colour version).

Table 1. Description of the five hydro-climatic regions (see also Fig. 3). The table contains the name, the main geographical position, the number of stations located within the region, the CCM2 windows that cover the region and the predominant Köppen-Geiger climate classification.

Region	Geographical position	Number of stations	CCM2 windows	Predominant Köppen-Geiger climate
Alpine	Central range systems	202	2000, 2002, 2003, 2005, 2007, 2008	Snow and polar
Atlantic	Northern islands/coasts	150	2000, 2001, 2003, 2008	Warm temperate – fully humid
Boreal	Northern Europe	71	2000, 2007, 2008, 2013	Snow – fully humid
Continental	Central Europe	186	2000, 2003, 2005, 2013	Warm temperate and snow – fully humid
Mediterranean	Southern Europe	20	2002, 2003	Warm temperate – summer dry

common features, including altitudinal gradients, climatic influence, soil types, geology and vegetation types. The Alps influence the climate of central Europe and divide the Mediterranean region in the south and the temperate region in the north. The Alps are the origin of many major European rivers such as the Adige, Danube, Po, Rhone and Rhine. About 70% of the Alpine region is influenced by human activities (EEA 2002) and the majority of rivers are affected by production of hydro-electric power. The Alpine region encompasses the highest number stations that are included in the analysis.

The Atlantic region is situated along the Atlantic coast and includes the UK, Ireland, the Netherlands, the northern shores of Spain and Portugal, and the coastal parts of Germany, Denmark, Belgium and France. The region mainly consists of small hills or flatland and is influenced by an oceanic temperate climate, resulting in relatively mild winters and summers and high rainfall rates throughout the year (EEA 2002). In the region, several large rivers such as the Gironde, Loire, Rhine, Seine, Schelde and Thames drain into the Atlantic Ocean.

The Boreal region covers Estonia and Latvia, south-eastern Norway and most of Sweden, Finland, the northern parts of Lithuania and Belarus and parts of eastern Russia. It is a transition zone between the Arctic and temperate regions of Europe. The climate can be described as cool-temperate mainly sub-continental, with relatively long periods of snow cover (several months) and relatively short growing season (EEA 2002). Most of the region is situated below 500 m a.s.l.

The Continental region covers large areas between Denmark and Sweden in the north and Italy and the Balkan region in the south. The region intersects parts of the Alpine region. The climate is continental with strong contrasts between warm summers and cold winters in the central and eastern parts. Precipitation occurs mainly during the summer months. In the north, the landscape is flat and it becomes increasingly hilly in the south, with large flood plains along the large rivers (e.g. the Danube, Desna, Dnepr, Dnestr, Elbe, Loire, Oder, Pripyat, Rhine, Vistula and Volga) (EEA 2002).

The Mediterranean region is situated between the Atlantic region in the west and the Continental and Alpine regions in the north. The climate is dry and warm, with hot summers and mild winters. Hills and mountains dominate the landscape, with the low mountain ranges being intersected by inland plateaus. In the Mediterranean region, there is a pronounced variability in climate and topographic characteristics due to a variety of small-scale landscape characteristics such as slope, exposition, geology and the distance to the sea (EEA 2002). The largest rivers draining into the Mediterranean Sea are the Adige, Drin-Bojana, Ebro, Neretva, Rhone and Tiber. This region contains the smallest number of gauging stations.

4 Results

4.1 Frequency of discharge peak events

The mean number of independent discharge peaks per year is derived for each station using the procedure presented in Section 2.1. Figure 4 presents the spatial pattern of this statistic in Europe. The panels around the map show examples of a typical 2-year discharge time series for each of the five hydro-climatic regions.

Complementary to the map, Figure 5 summarizes the variability in the mean number of independent discharge peaks per year, identified across the five hydro-climatic regions.

The highest number of discharge peaks is identified in the Atlantic and Alpine regions, with a median value of approx. 16 events per year. In the Atlantic region, the upper 10 percentile of stations exhibit a mean number of peaks per year larger than 30, most of which are situated in northern England and Scotland, UK (Fig. 4).

A lower median mean number of peaks per year (14) is found in the Continental region. In this region the upper 10 percentile of stations exhibit a mean number of peaks larger than 16.

In the Boreal region, the median mean number of peaks per year is the lowest and only a few catchments exhibit on average more than five independent peaks

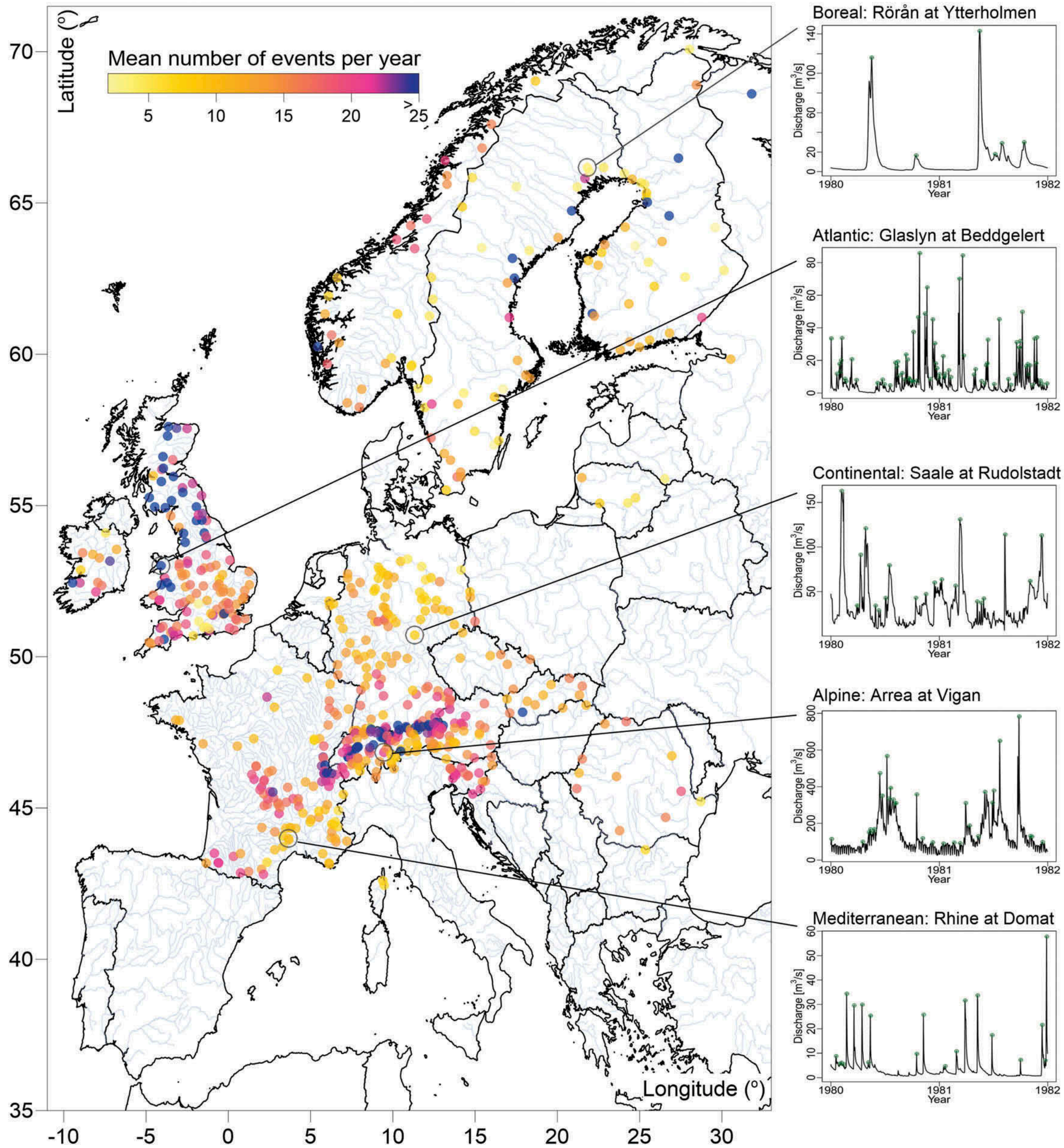

Figure 4. Mean number of independent discharge peaks per year at the selected 629 GRDC gauging stations. Panels on the right show examples of runoff hydrographs and discharge peaks for five gauging stations representative of the five hydro-climatic regions (see online for colour version).

per year. The low number of peaks is caused by a runoff regime that is mainly dominated by snow accumulation and melting processes.

Finally, the variability in the mean number of independent peaks per year is the lowest in the arid Mediterranean region (Fig. 5) where the median number of peaks is on average 10 per year.

4.2 Trends in AMF and POT1 series

The results of trend analysis in annual maximum flood series (AMF) are presented in Figure 6. Significant positive and negative trends in the AMF series are detected at 61 (10%) and 48 (8%) stations, respectively, considering a 5% significance level in each direction of the test. The other 520 stations show no evidence of a significant trend. The high number of significant trends detected means that, when considering the whole dataset, the number of significant trends are more than what could be expected by chance. In addition, large-scale spatially coherent patterns of trends with the same direction can be identified. These trend patterns are of practical importance and indicate the possibility of existence of common drivers.

A description of the trends found in the five European regions is given below. The highest number

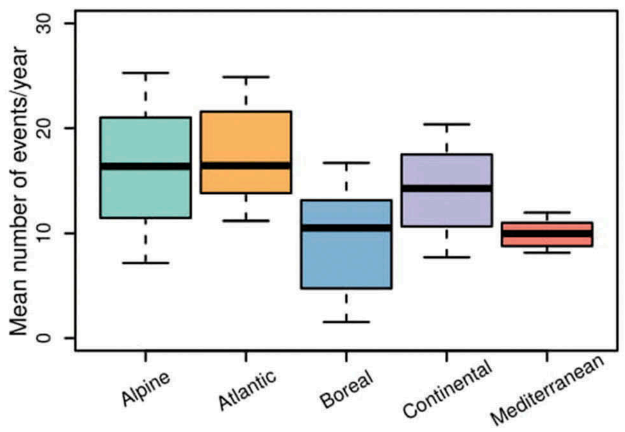

Figure 5. Mean number of independent discharge peaks per year identified by the baseflow-based algorithm, for each of the five hydro-climatic regions. The bold line represents the 50% percentile; boxes and whiskers show the 25 and 75% percentiles, and the 10 and 90% percentiles (see online for colour version).

of stations (23) exhibiting significant positive trends in the AMF series is found in the Atlantic region (21 stations in the UK and two in western France). Only six stations (three in England and three smaller catchments in southern France) exhibit significant negative trends in the same region.

In the Continental region, a large number of stations exhibiting either significant increasing (16 stations) or decreasing (13 stations) trends in the AMF series is detected. Increasing trends are observed in eastern France, in the upper Danube and in three large catchments in Central Germany (Lahn, Neckar and Rhine rivers). Decreasing trends are observed in large catchments (Schwarze Elster, Havel and Oder rivers) in eastern Germany and in a few small catchments in southern France.

Significant decreasing trends are detected mostly in the Alpine region (19 stations). These catchments are located in southeastern France (close to the border with Switzerland) and southward of the main ridge of the Central Alps in Austria, and the Tatra Mountains in Slovakia. Increasing flood trends in the Alpine region are detected in small catchments in central Switzerland, Tirol and southern Bavaria, with a mean catchment area of approx. 200 km^2.

In the Boreal region, four and seven stations show increasing or decreasing trends, respectively. While increasing flood trends are detected in two catchments in Finland and two catchments in southern Sweden, negative trends are detected in three small catchments (catchment area: <10 km^2) located in the southern part of Sweden and four larger catchments in southern Finland and eastern Sweden.

In the Mediterranean region, no clear spatial pattern of flood trends can be found: only six catchments exhibit significant flood trends, three increasing and three decreasing.

Interestingly, stations exhibiting significant changes in the AMF series present a mean number of independent peaks per year very close to the median mean values of each respective regional distribution. Exceptions are those catchments that exhibit significant trends in the Atlantic region, where the mean number of independent peaks per year is generally higher than the regional distribution.

The trend analysis results of the POT series are presented in Figure 7, where a mean of one event per year (POT1) is considered to set the threshold. Figure 7 shows the results of trend detection with respect to trends in flood magnitude (POT1-M, left panel) and trends in flood frequency (POT1-F, right panel).

The total number of stations exhibiting significant trends in the POT1-M series is slightly lower than that in the AMF series. The AMF (exactly one flood event per year) and POT1 (an average of one event per year) series can be compared, given the same sample size and significance level of the tests. Trends in the POT1-M series and AMF series are not always detected in the same catchments, which results in a different spatial pattern of flood change in the two cases.

Significant positive and negative trends in POT1-M series are detected in 57 (9%) and 40 (6%) stations, respectively. Similarly to the results of the analysis performed on the AMF series, the number of detected trends is more than what could be expected by chance when the whole dataset is considered. Spatially coherent patterns of trend can be found in POT1-M series as well. The majority of catchments with increasing trends are situated in the Continental (31 stations, mostly in Germany) and Alpine (16 stations, situated mostly in Bavaria and Tirol) regions. Only eight catchments in the Atlantic region exhibit increasing trends in the POT1-M series, which is a relatively small number compared to the number of significant trends detected in the AMF series.

Significant negative trends in the POT1-M series are detected in 19 catchments in the Boreal region (Scandinavia), which is almost three times more than those detected in the AMF series. Moreover, less negative trends in the POT1-M series are detected (10 stations) in the Alpine region (southern Austria, Slovenia) compared to the AMF series.

Significant trends in the POT1-F series (Fig. 7, right) are detected in 133 stations. In particular, an increasing trend in the POT1-F series is detected in 68 (11%) stations, and a decreasing trend in 65 (10%) stations. This suggests that the trends in frequency are significant for

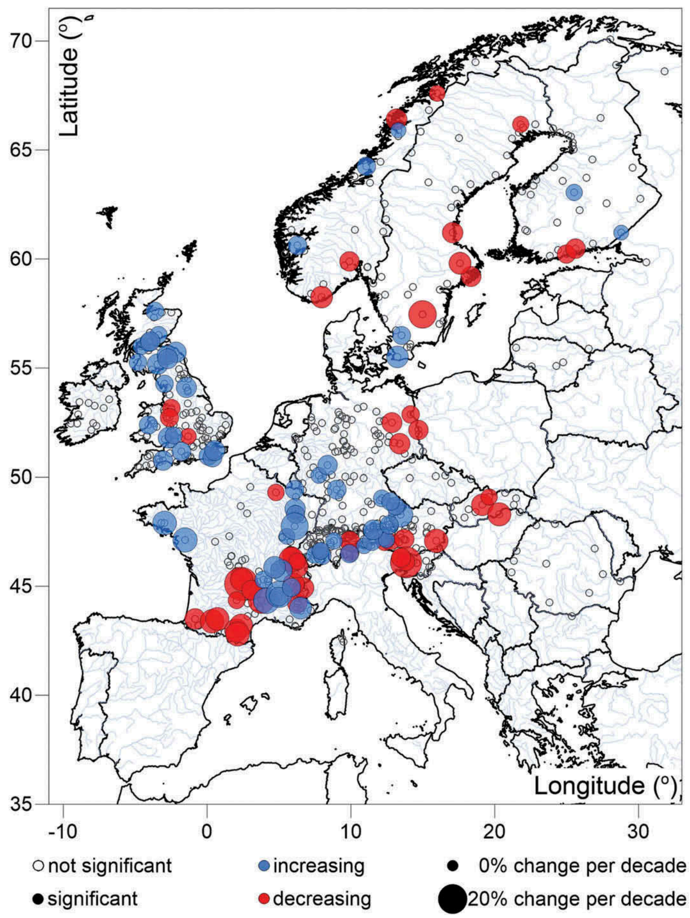

Figure 6. Trends in annual maximum flood series (AMF) for the period 1965–2005. Filled symbols indicate statistically significant positive (blue) and negative (red) trends at 10% level of significance. Symbol size indicates the magnitude of change in the mean flood magnitude (% per decade).

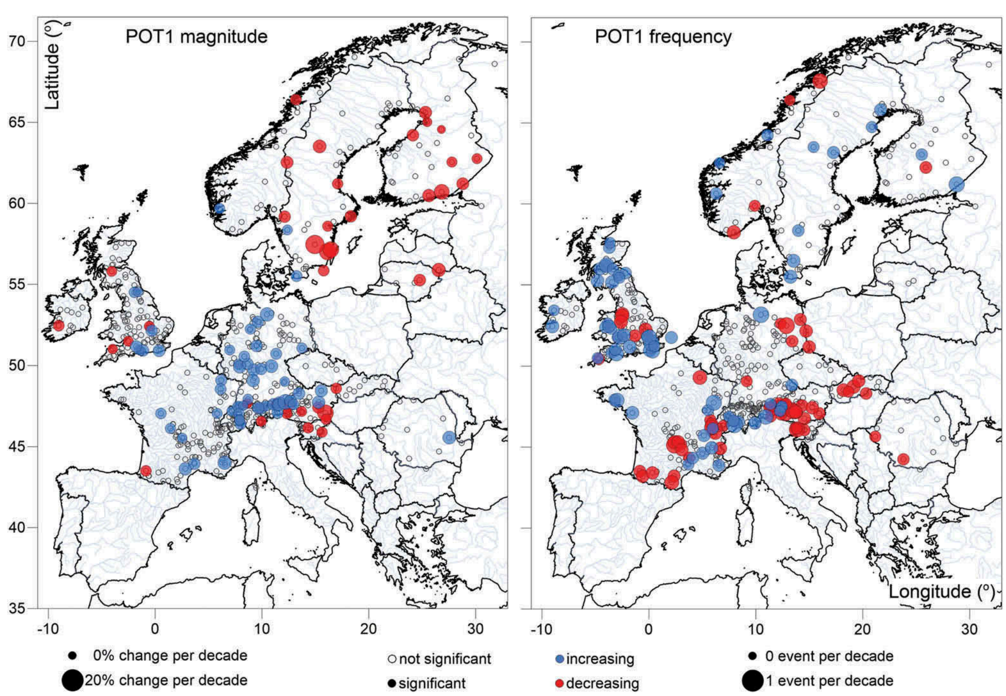

Figure 7. Trends in POT1 series. Left/right panel shows trends in flood magnitude/frequency. Filled symbols indicate statistical significant positive (blue) and negative (red) trends at 10% level of significance. Symbol size indicates the change in the mean flood magnitude (left), mean number of floods (right) exceeding the threshold in % per decade and in events per decade, respectively.

Europe as a whole. Again, when considering the hydro-climatic regions independently, discernible spatial patterns of positive and negative trends are apparent. The highest number of catchments exhibiting either positive or negative trends in POT1-F series are situated in the Atlantic region (29 stations in the UK out of 37 in the region) and in the Alpine region (35 stations, mostly in the Central and East Alps, Slovenia and rivers originating in the Tatra Mountains in Slovakia), respectively.

4.3 Sensitivity of flood trends to the selection of different flood series

The trends in flood magnitude in the AMF and POT1-M series (Figs. 6 and 7) indicate different spatial patterns of flood changes across Europe. This section investigates the sensitivity of trends in the POT series to the selection of different exceedence thresholds, λ.

The exceedence threshold (λ) affects the number of discharge peaks considered in a flood series. While the POT1 ($\lambda = 1$) series consist of the highest floods recorded at each gauging station, an increase in λ establishes a lower threshold and therefore implies an increase in the number of (smaller) peak events.

Figure 8 shows the variability of the multiple index (MI) (the ratio between the mean discharge magnitude of a flood series and the mean annual discharge for individual stations) estimated for the AMF and the different POT-M flood series in each of the five hydro-climatic regions. The MIs of the POT1-M series are the highest, followed by the MI of the AMF series and the remaining POT series. The smallest MIs are calculated for the POT6-M flood series.

The median value of the MI in the POT1-M series ranges between 4 (i.e. four times the mean annual flow) in the Boreal region to more than 23 in the Mediterranean region. This result can be interpreted based on the different hydrological flood characteristics in Europe. The arid climate of the Mediterranean region causes generally low mean discharge during the year which is offset by intense precipitation events leading to high discharge values. Moreover, the subset of stations in the Mediterranean region considered here is mainly composed of small catchments, which show an intrinsic high variance in the daily hydrograph. In the Boreal region, snowmelt processes induce high discharges. In this case, the volume of the peak is large but the maximum intensity reached remains in the order of magnitude of the mean discharge regime.

The sensitivity of trends in the POT series to the selection of different exceedence thresholds (λ) is assessed for a mean number of floods per year ranging from one to six (i.e. POT1 to POT6). Tables 2 and 3 present the absolute number of significant trends detected in the flood series for each region.

Figure 9 shows the percentage of stations exhibiting significant positive or negative trends at 10% significance level across the six different exceedence thresholds. Stations are grouped into the five hydro-climatological regions. The almost horizontal lines in Figure 9 suggest that the trend analysis results of the POT series are not very sensitive to the selection of the threshold, with the exception of trends in flood frequency in the Mediterranean and Boreal region. In particular, for increasing λ values, a higher number of significant negative trends in flood frequency are

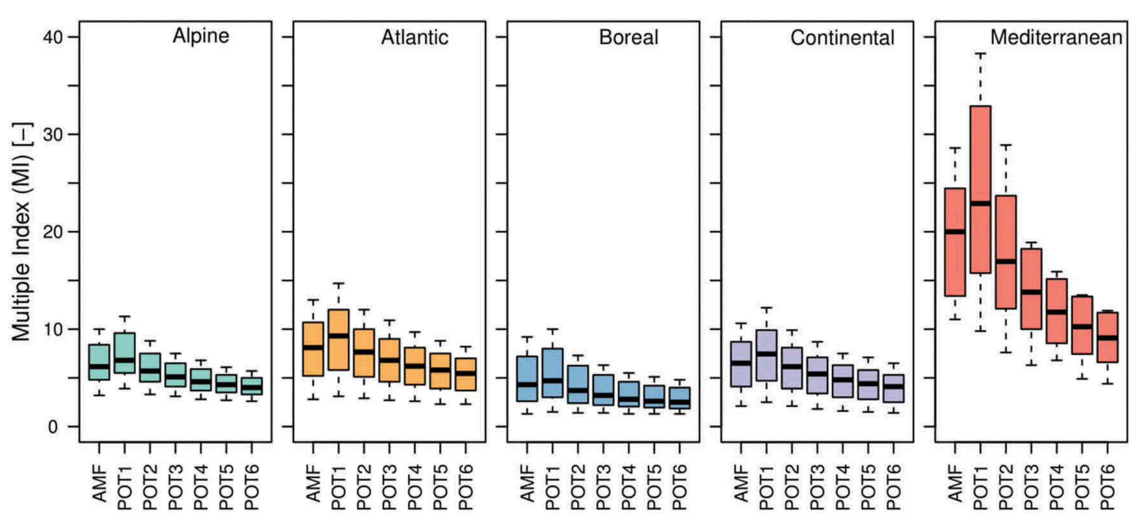

Figure 8. Multiple index (MI) of the annual maximum flood (AMF) and the different peak over threshold (POT) flood series. For POT, thresholds of λ (mean number of peaks per year) range from one (POT1) to six (POT6) (see online for colour version).

Table 2. Absolute number of stations exhibiting significant positive/negative trends at 10% level in flood magnitude detected in the POT-M series with a threshold, λ (mean number of events per year) ranging from one (POT1-M) to six (POT6-M). The stations are grouped into the five different hydro-climatic regions.

	Alpine	Atlantic	Boreal	Continental	Mediterranean
Number of stations	202	150	71	186	20
POT1-M	16/10	8/6	1/19	31/5	1/0
POT2-M	14/19	24/7	5/15	9/7	4/1
POT3-M	18/18	27/4	3/10	11/6	4/1
POT4-M	25/36	22/6	2/11	12/9	4/2
POT5-M	16/35	25/5	6/11	7/12	4/2
POT6-M	12/44	32/4	6/15	5/17	3/1

Table 3. Same as Table 2, but for trends in the flood frequency.

	Alpine	Atlantic	Boreal	Continental	Mediterranean
Number of stations	202	150	71	186	20
POT1-F	14/35	37/8	7/1	7/20	3/1
POT2-F	15/42	32/10	17/1	4/30	2/4
POT3-F	16/52	24/11	24/5	5/39	1/4
POT4-F	14/41	26/13	27/4	5/48	1/6
POT5-F	19/46	22/19	29/3	5/45	0/6
POT6-F	23/43	23/21	29/3	4/45	0/7

detected in the western part of the Mediterranean region (i.e. southern France), while the number of significant positive trends increases in the Boreal catchments situated on the coast.

The top panel of Figure 9 shows the percentage of significant increasing and decreasing trends in the POT1-M to POT6-M series. The percentage of stations exhibiting significant trends differs significantly between the regions.

In the Alpine and Boreal regions, decreasing trends dominate, with the exception of the POT1-M series in the Alpine region. The highest number of stations exhibiting decreasing trends in the Alpine region is observed for the POT6-M series, while the POT1-M series exhibit the highest percentage of negative trends in the Boreal region.

The general tendency in the Atlantic region is the opposite, where, apart from the POT1-M series, significant increasing trends are observed at more than 15% of stations.

The Continental region exhibits the highest percentage of significant positive trends in the POT1-M series. However, when considering higher λ thresholds the regional tendency differs. From the POT1-M to POT4-M series, positive trends dominate. When including smaller floods in the POT5-M and POT6-M series, a larger number of stations exhibiting decreasing trends is found.

In the Mediterranean region, a prevailing tendency towards increasing flood magnitude is found. However, the number of stations included in this region is too small to draw any general conclusion.

The bottom panel of Figure 9 shows the significant trends detected in the POT-F series. A clear tendency towards increasing flood frequency is found in the Atlantic region, which is most evident when considering lower λ values (POT1-F or POT2-F series).

Consistent significant negative trends in flood frequency are detected in the Continental and Alpine regions. In these regions, decreasing trends are more apparent in all the POT-F series if compared to the unclear trend signal detected in the POT-M series.

Significant positive trends in flood frequency are found in the Boreal region and the percentage of stations exhibiting this tendency is increasing for increasing λ. For the POT3-F to POT6-F series, significant positive trends in flood frequency are observed in more than one-third of the stations. Interestingly, only a very small number of catchments exhibit concurrent significant trends in both flood frequency and magnitude.

The opposite signal is found in the Mediterranean region, where a higher percentage of significant decreasing trends are detected for increasing λ.

While regionally significant trends can be considered not very sensitive to the selection of the threshold (apart from the few cases described above), trends detected at individual stations can change considerably across the different flood series with regard to their trend significance.

Figures 10 and 11 summarize, for each individual station, the trend detection results for the flood magnitude (comparing AMF and POT-M) series and flood frequency series (POT-F series only), respectively. The diverging colour scale indicates the intensity of the decadal change (% per decade) detected in the different flood series. Negative trends are depicted with yellow to red colours and positive trends with light to dark blue colours. Only those stations that exhibit a significant trend, at 10% significance level, in at least one of the flood series are presented in the figures.

When trends in flood magnitude are considered (Fig. 10), between 33% of the stations (in the Atlantic region) and 45% of the stations (in the Boreal region) exhibit trends in at least two different flood series. An exception is the Continental region, in which only 21% of the stations exhibit trends in at least two different flood series. Around 15% of the stations in total exhibit consistent trends in at least three different flood series.

The results are different when trends in flood frequency are considered (Fig. 11). In this case, a more consistent situation is detected across the different thresholds considered: more than 30% of the stations

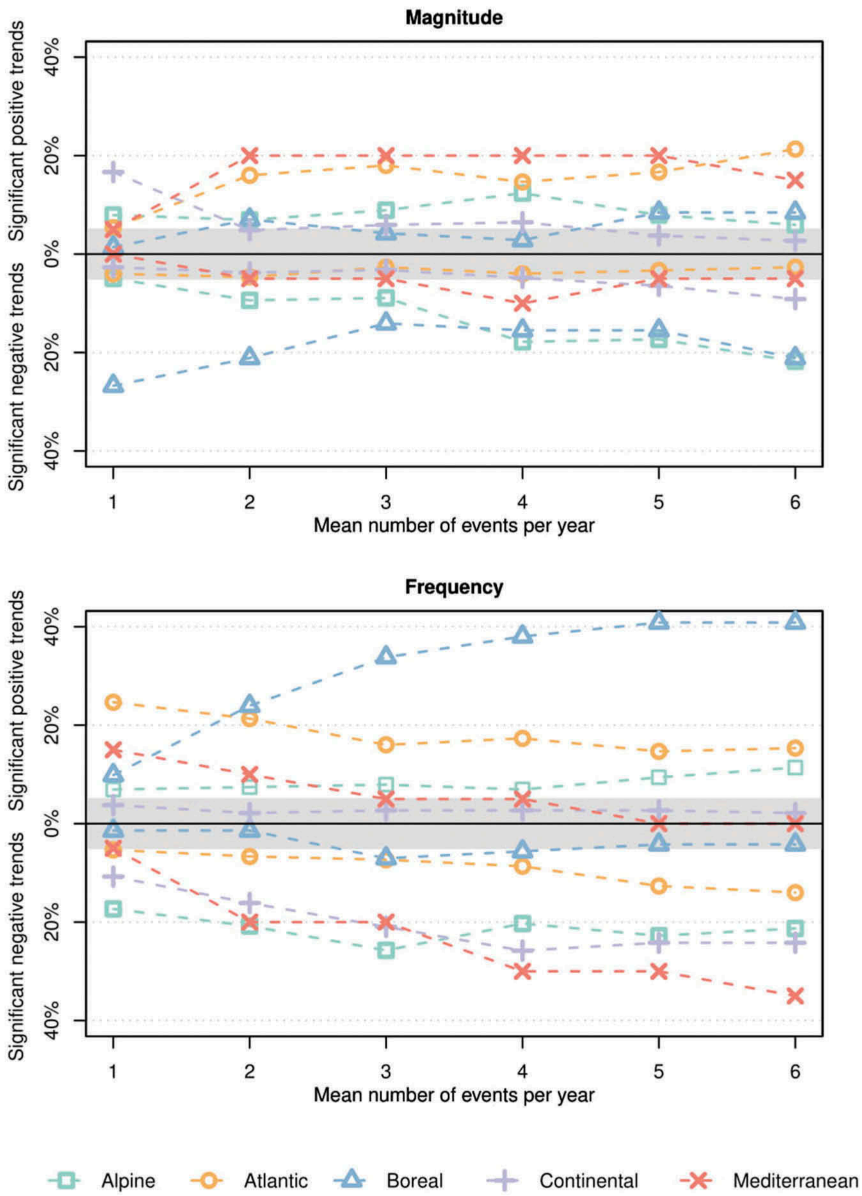

Figure 9. Percentage of stations exhibiting significant trends in magnitude and frequency at 10% level, with a threshold λ ranging from a mean of one to six events/year (POT1 to POT6). Top and bottom panels show the sensitivity analysis for flood magnitude and frequency, respectively. Different colours and symbols indicate the five hydro-climatic regions. The grey band represents the percentage of stations (5% in the positive semi-axis and 5% negative semi-axis) exhibiting a significant trend that is expected to be detected by chance, given the significance level of the test (see online for colour version).

in almost all the regions in Europe exhibit consistent trends in at least three different flood series.

The AMF series exhibit the highest decadal trends, with median values of 9 and 10% per decade for increasing and decreasing trends, respectively. The median intensity of decadal change in POT1-M series is 5% per decade for increasing trends and 4% per decade for decreasing trends, while lower median trend magnitudes are detected in the other POT-M series (POT2-M to POT6-M).

The magnitude of decadal changes in the flood frequency is small and decreases considerably with increasing exceedence threshold, λ, with similar values for increasing and decreasing trends. The median magnitude of change in POT1-F series is 0.3 events per decade and decreases to less than 0.14 events per decade in POT6-F series.

Interestingly, for trends in both flood magnitude and flood frequency, no inversions in sign of significant trends are found across the different thresholds. The results presented above focus on the spatial patterns of change and do not account for (a) the existence of nested catchments and (b) possible anthropogenic changes within the catchment, which might affect the overall conclusions of the analysis.

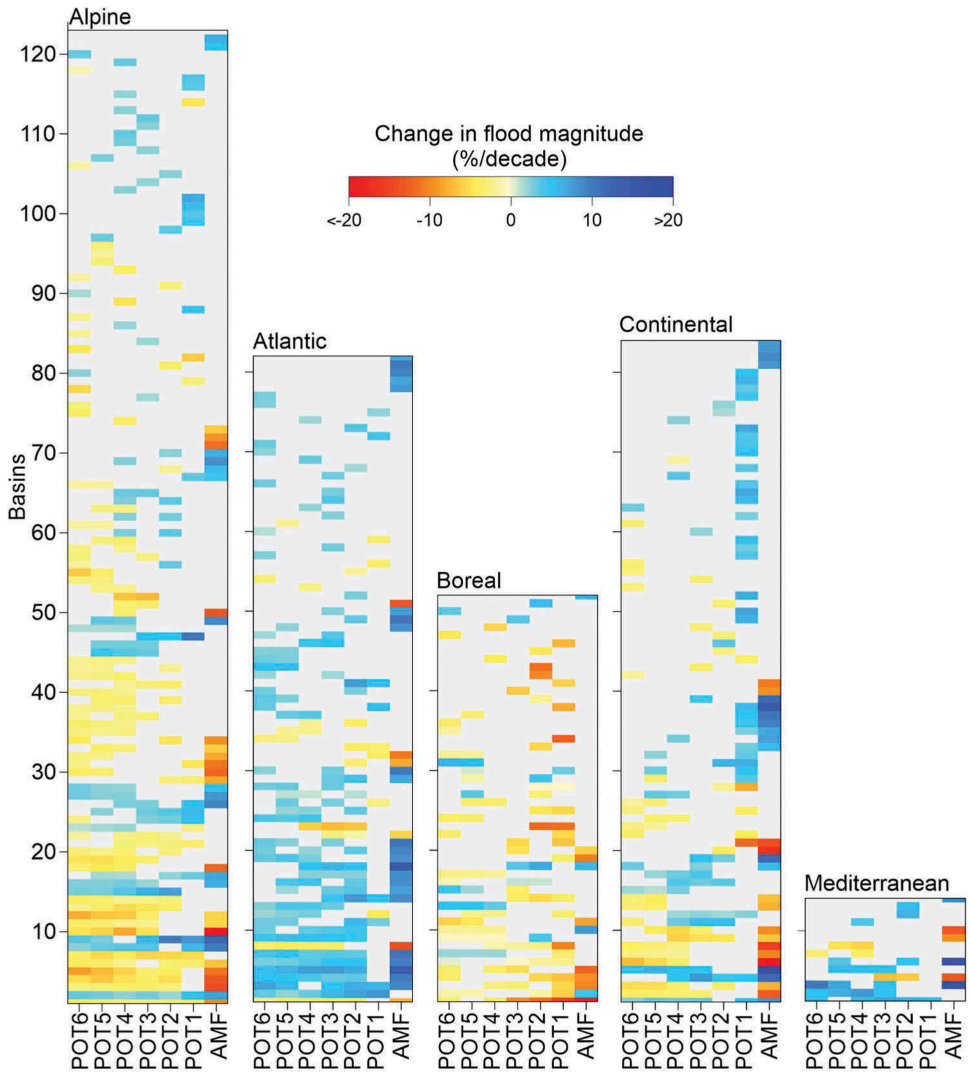

Figure 10. Summary of the significant trends detected at 10% level in the AMF and POT-M series. The POT-M series are compiled for a mean number of exceedences, λ, ranging from one to six. The colour scale indicates the magnitude of the decadal change detected for significant trends, in % per decade. Grey is used when no significant trend is detected. Catchments are grouped into the five hydro-climatic regions of Europe and are sorted in decreasing order (from the bottom) by the cumulative number significant trends detected in individual catchments over the different flood series (see online for colour version).

(a) If nested catchments are considered, the detected trends can propagate downstream resulting in the same significant flood trend being counted multiple times, inflating the percentage of significant trends detected within a region. Therefore, all gauging stations except one station on the same river are randomly removed (22% of the total number of stations are removed) and the entire analysis described above is repeated.

(b) Anthropogenic impact might also influence the number and the spatial pattern of significant trends detected. In order to test the sensitivity of the results, all gauging stations in which an anthropogenic impact can be suspected are removed (41% of the stations are removed). The existence of an anthropogenic impact is estimated by testing time series of the flashiness index (FI; Baker *et al.* 2004, Holko *et al.* 2011) for step changes using the Pettitt test (Pettitt 1979) at the 10% significance level. A step change in the FI time series indicates a considerable change in the hydrological response of a catchment and can therefore be associated with anthropogenic changes (Aich *et al.* 2014)

In both of the above-mentioned cases, the spatial patterns of detected flood trends do not change considerably (see Supplementary material, Figs S1 and S2 for a comparison with Fig. 9). Therefore, the general conclusions obtained in the previous sections can be considered representative, even in the presence of confounding factors.

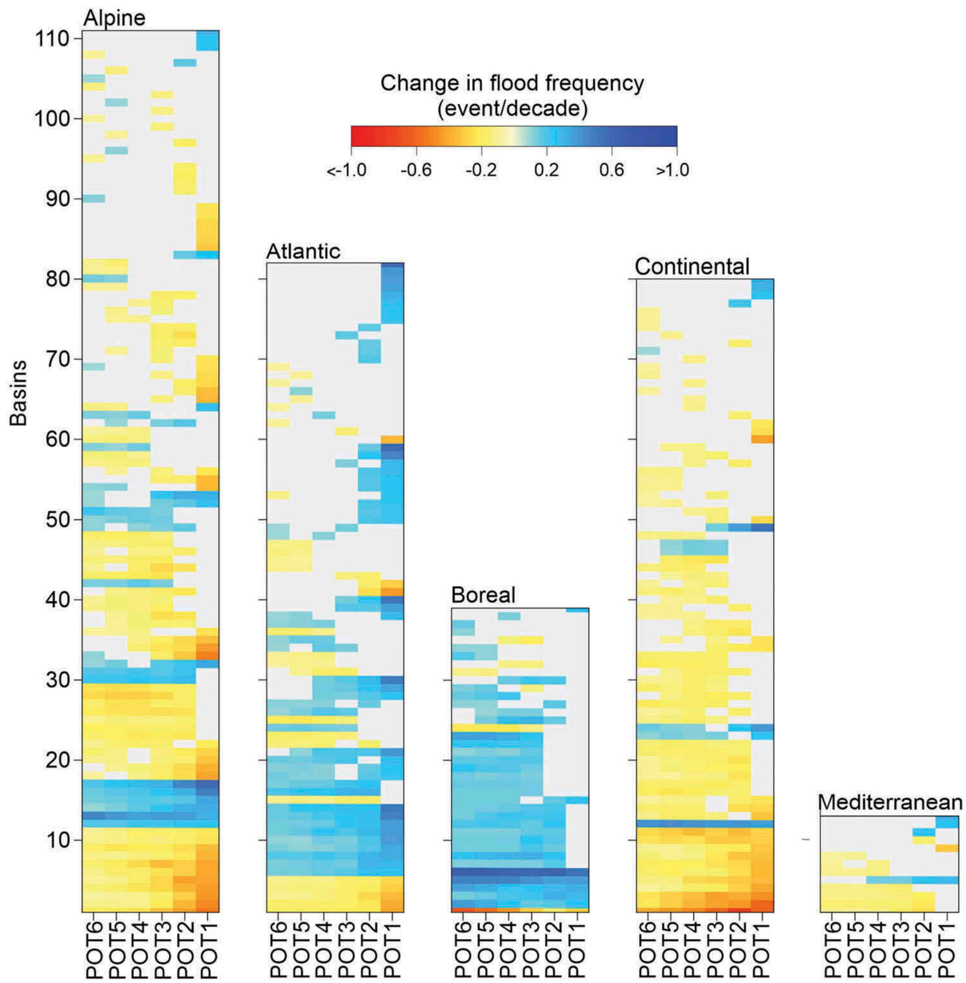

Figure 11. Same as Figure 10, but for the POT-F series.

4.4 Morpho-climatic characteristics of catchments exhibiting significant changes in flood magnitude and frequency

Figure 12 shows the distribution of the mean elevation (top left), area (top right), mean annual precipitation (bottom left) and mean annual air temperature (bottom right) of the catchments that exhibit significant increasing (left box plot) or decreasing (right box plot) trends in flood magnitude. Categories along the x-axes indicate the different flood series considered, i.e. the AMF and the POT-M series (POT1-M to POT6-M).

The results indicate that the significant increasing trends in flood magnitudes detected in the AMF series and the POT-M series for high λ values (i.e. POT3-M, POT5-M and POT6-M) tend to occur in low-elevation watersheds, with a mean elevation below 400 m a.s.l. The flood series of the highest floods (POT1-M) have the opposite tendency (decreasing flood magnitude is mainly detected in catchments having a low mean elevation). In addition, there is a clear tendency towards increasing flood magnitudes in catchments having a high mean annual air temperature and a high mean annual precipitation rate. A relationship between catchment size and the number of significant trends is not apparent.

Figure 13 shows a clear pattern of increasing flood frequency in catchments having a low mean catchment elevation and a low mean annual air temperature, particularly for the POT2-F series and higher λ values. Positive trends in flood frequency are usually associated with catchments having a low mean annual precipitation. Higher mean annual precipitation is associated with decreasing trends in flood frequency. Similarly to the trends detected in flood magnitude, no clear relationship between the catchment size and the number of significant trends is found.

5 Discussion and conclusions

The overall aim of this study is to contribute to the assessment of flood trends in Europe. Compared to previous works, three novel aspects have been investigated.

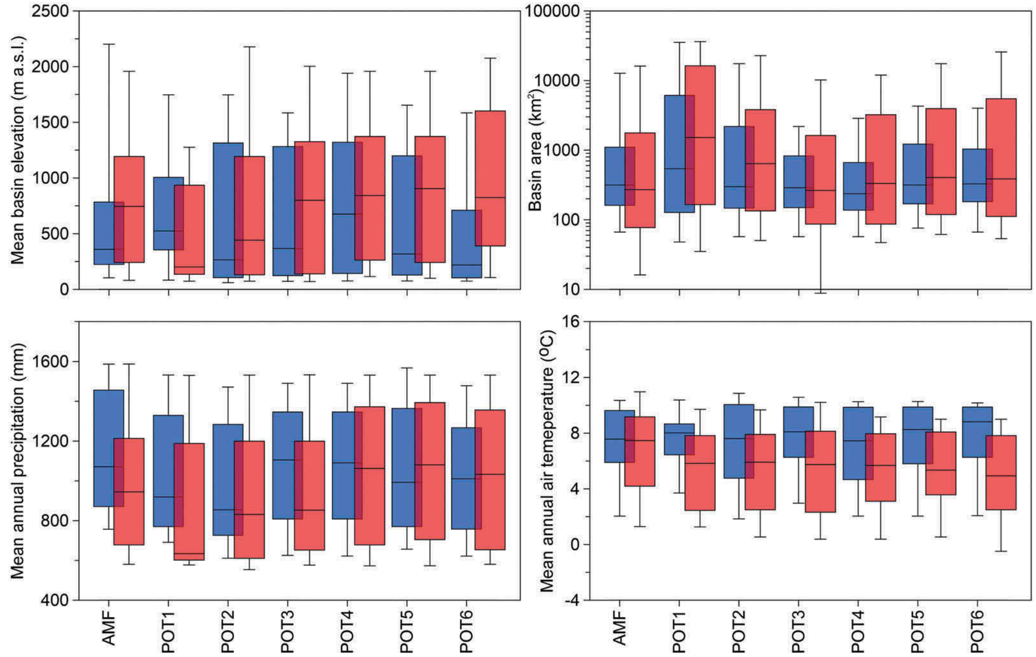

Figure 12. Distribution of selected physiographic characteristics of the catchments exhibiting significant trends in flood magnitude at 10% level. Increasing and decreasing trends in flood magnitude are presented in blue (left box plot) and red (right box plot), respectively. Bold lines represent the 50% percentile; boxes and whiskers indicate the 10, 25, 75 and 90% percentiles (see online for colour version).

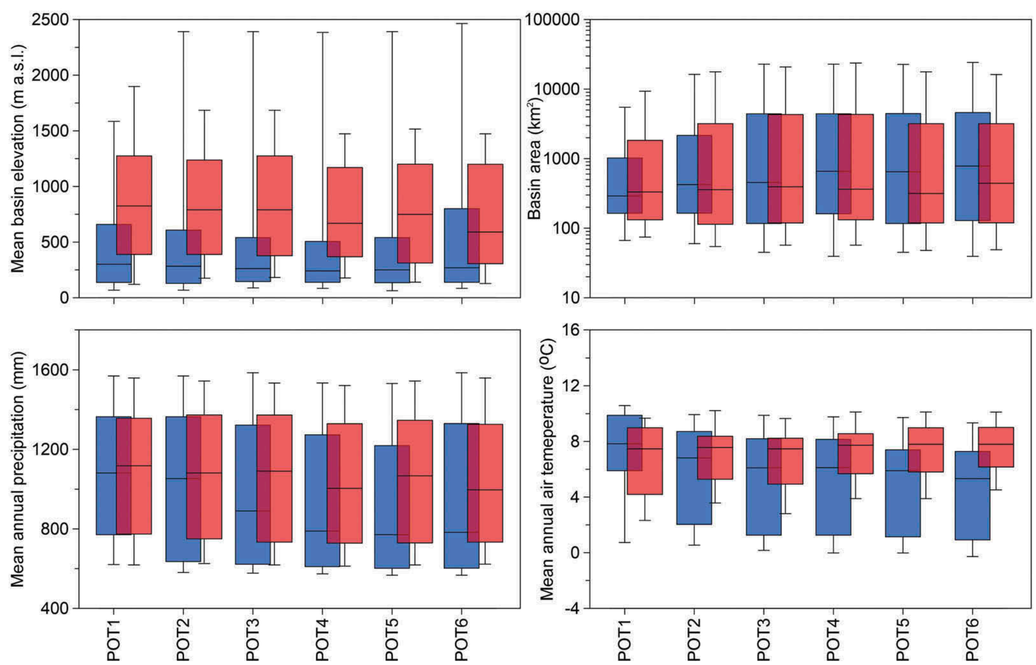

Figure 13. Same as Figure 12, but for trends in flood frequency.

First, the comparison of significant trends detected in different flood series derived through two widely used methods: the annual maximum flood (AMF) and the peak over threshold (POT) approaches. Second, the sensitivity of flood trends to the selection of different exceedence thresholds in the POT approach. Third, the use of large-scale morpho-climatic characteristics of the catchments to describe the detected trends. In addition, this study supports the value of open data and tools for the advancement of hydrological science, providing open access to the derived time series and enabling full reproducibility of the analyses.

Previous regional or continental studies in Europe have analysed the spatial pattern of flood trends either by considering some predefined regions, as shown in Kundzewicz (2012) and Hall *et al.* (2014), or by considering regions exhibiting similar flood regimes identified by clustering techniques (Parajka *et al.* 2010, Mediero *et al.* 2015). In this study, regional patterns of statistically significant flood trends are stratified across five predefined regions based on a biogeographical classification of Europe (EEA 2016b): the Alpine, Atlantic, Boreal, Continental and Mediterranean regions. Although these regions have been identified without a specific hydrological application in mind, the regions can be used for stratification as they correspond approximately to the three main regions (Atlantic western Europe and northern Europe, Continental central Europe and eastern Europe, and the European Mediterranean) identified in Hall *et al.* (2014) and to the five regions derived by Mediero *et al.* (2015).

Trends are detected in the AMF and POT flood series using two-sided tests at 10% significance level. When considering Europe as a whole, this study demonstrates that the percentage of stations exhibiting statistically significant trends, across all flood series, is higher than what is expected to be detected by chance. However, the trend significance of the AMF and POT1-M series is not always consistent at the level of individual stations. For this reason, trend results are further interpreted within larger scale hydro-climatic regions, as the trend signal within a region can be considered less sensitive.

For example, a general tendency towards increasing flood magnitude and flood frequency is found in the Atlantic region. The percentage of stations exhibiting significant trends in flood magnitude is high for AMF and POT-M series with more than one event per year on average, while for $\lambda = 1$ only a few significant positive trends are detected. Trends in flood frequency are apparent across all the thresholds. Increasing trends detected in the AMF series are consistent with the main findings of Hannaford and Buys (2012) and Murphy *et al.* (2013) for the UK and Ireland, respectively, although these studies considered slightly different time periods.

In the Boreal region, a clear tendency towards increasing flood frequency and decreasing flood magnitude is detected across all the POT series. This is in line with the main findings presented in Hall *et al.* (2014), for the northern part of Eastern Europe and Scandinavia. However, for the AMS series, no apparent spatial pattern of change in flood magnitude is detected (Fig. 6). This finding agrees with the results from Arheimer and Lindström (2015) for Swedish catchments, in which no widespread evidence of flood trends in 69 AMF series was detected.

The Central region presents the highest percentage of stations (17%) exhibiting significant positive trends in magnitude in the POT1-M series. Similarly, Kundzewicz *et al.* (2013) found that positive trends can be detected in that region with respect to two metrics (flood severity, related to flood frequency, and flood magnitude) when analysing the main flood events over the time period 1985–2009. However, this study shows that, when lowering the threshold a higher number of decreasing trends in flood magnitude and flood frequency can be detected, especially on the Elbe River. This is in accordance with the negative trends detected in Brázdil *et al.* (2006, 2012) within the Czech Republic boundaries.

The Alpine region, including the Alps and the other main mountain areas of Europe, exhibits here a similar spatial pattern of flood changes as that described in Blöschl *et al.* (2011) for the Austrian parts of the Alps. In the northern part of the main alpine ridge, a general tendency towards increasing flood magnitude is detected, while a clear pattern towards decreasing flood magnitude is detected in the southern part of the Alps, particularly for the POT series compiled considering high λ values (i.e. smaller floods included). These decreasing trends are also found in southeastern France and in the alpine rivers originating in the Tatra Mountains as well. The overall spatial pattern of decreasing flood trends in the POT3 series corresponds to the main findings of Mediero *et al.* (2015).

The Mediterranean region shows a general tendency towards increasing flood magnitude and decreasing flood frequency, especially in series compiled considering low λ values. This is in line with the results presented in Giuntoli *et al.* (2012) in France.

From a methodological point of view, this study shows that the number of catchments exhibiting significant changes within a region is rather consistent across all flood series (flat lines in Fig. 9), with a few exceptions, such as the trends in flood frequency in the Mediterranean and Boreal regions. However, although trends are regionally consistent across the different thresholds, Figures 10 and 11 show that the number of catchments exhibiting significant trends consistently across a large range of exceedence threshold (more than three thresholds) is rather small. This is particularly evident when analysing trends in flood magnitude.

Thus, similarly to the main findings of Archfield *et al.* (2016) for the USA, the picture of flood change in Europe is strongly heterogeneous and no general statements about uniform trends across the entire continent can be made. However, regional patterns of significant flood trends do exist and are not an artefact of the methods used. Areas where consistent flood trends are detected can serve as prime locations for future studies aimed at attributing the causes of the trends at a regional scale using a scaling fingerprint approach (Viglione *et al.* 2016) or other appropriate methods.

Data, tools and results used in the study are openly accessible. A table listing the station name, geographical coordinates, selected physiographic attributes and the results of trend analysis is provided on the SWITCH-ON website (http://www.water-switch-on.eu/sip-webclient/byod/#/resource/12069) (see also the Supplementary material). Mean daily runoff time series can be obtained from the Global Runoff Data Centre on request, while the derived catalogue of flood peak events is accessible on the SWITCH-ON website under the name "Pan-European catalogue of flood events" in the Spatial Information Platform (http://www.water-switch-on.eu/sip-webclient/byod/#/resource/12056). Appreciating the recommendation of Ceola *et al.* (2015), the authors believe that the availability of data, tools and results will allow advancing flood change research, facilitating the comparison and extension of the present study.

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