Journal of Hydrology 528 (2015) 341–360

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Identification of coherent flood regions across Europe by using the longest streamflow records

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ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form 29 May 2015
Accepted 8 June 2015
Available online 14 June 2015
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Floods
Peaks-over-threshold
Seasonality
Long streamflow series
Flood trends
Pan-European

SUMMARY

This study compiles a new dataset, consisting of the longest available flow series from across Europe, and uses it to study the spatial and temporal clustering of flood events across the continent. Hydrological series at 102 gauging stations were collected from 25 European countries. Five geographically distinct large-scale homogeneous regions are identified: (i) an Atlantic region, (ii) a Continental region, (iii) a Scandinavian region, (iv) an Alpine region, and (v) a Mediterranean region. The months with a higher likelihood of flooding were identified in each region. The analysis of the clustering of annual counts of floods revealed an over-dispersion in the Atlantic and Continental regions, forming flood-rich and flood-poor periods, as well as an under-dispersion in the Scandinavian region that points to a regular pattern of flood occurrences at the inter-annual scale. The detection of trends in flood series is attempted by basing it on the identified regions, interpreting the results at a regional scale and for various time periods: 1900–1999; 1920–1999; 1939–1998 and 1956–1995. The results indicate that a decreasing trend in the magnitude of floods was observed mainly in the Continental region in the period 1920–1999 with 22% of the catchments revealing such a trend, as well as a decreasing trend in the timing of floods in the Alpine region in the period 1900–1999 with 75% of the catchments revealing this trend. A mixed pattern of changes in the frequency of floods over a threshold and few significant changes in the timing of floods were detected.

1. Introduction

The seemingly endless reoccurrence of destructive and costly flood events across Europe reinforces the need for further research into all aspects of flood-risk management, especially in

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http://dx.doi.org/10.1016/j.jhydrol.2015.06.016
0022-1694/

understanding the risk of extreme events and in determining how the likelihood of such events might change because of drivers such as climate and land-use changes. Consequently, several studies of trends in observed series of flood events have been conducted at a national level in various European countries, from which the most recent studies involve the following: Austria (Blöschl et al., 2012; Villarini et al., 2012), Finland (Korhonen and Kuusisto, 2010), France (Renard et al., 2008; Giuntoli et al., 2012), Germany (Petrow and Merz, 2009; Bormann et al., 2011), Ireland (Murphy et al., 2013), Poland (Strupczewski et al., 2001; Kundzewicz et al., 2012), Portugal (Silva et al., 2012), Slovenia (Ulaga et al., 2008), Spain (Mediero et al., 2014), Sweden (Lindström and Bergström, 2004), Turkey (Cigizoglu et al., 2005) and the United Kingdom (Hannaford and Marsh, 2008; Prosdocimi et al., 2014). Reviews of the results obtained in these studies have been published by Hall et al. (2014) and Madsen et al. (2014).

However, the results of such studies at a national level are difficult to compare in order to derive a large-scale coherent picture, since they use different flood indicators, time periods and methods. Consequently, there is an increasing realisation of the benefits of considering the problem at a larger geographical scale, not confined within political and administrative boundaries. This applies both in terms of enlarging available datasets in time and space and a better consideration of large-scale climatic drivers (Kjeldsen, 2011; Kjeldsen et al., 2014; Hall et al., 2014). Examples of recent studies that consider changes in flood records at larger and trans-national scales include the Nordic countries (Wilson et al., 2010), Central Europe (Villarini et al., 2011), the Baltic States (Reihan et al., 2012; Sarauskiene et al., in press) and North America (Hodgkins and Dudley, 2006; Vogel et al., 2011).

Finally, some attempts have entailed a pan-European scale by using observed runoff data primarily from the Global Runoff Data Centre (GRDC) and the European Water Archive (EWA) of Flow Regimes from International Experimental and Network Data (FRIEND) (Hanna et al., 2011). Nevertheless, most of these studies have focused on monthly, seasonal and annual streamflows, as well as various streamflow indices (Gudmundsson et al., 2011; Hannaford et al., 2013; Stahl et al., 2010, 2012). Kundzewicz et al. (2005) focused on trends in long flood series from catchments located around the world. However, the European gauging stations included in Kundzewicz et al. (2005) were clustered in only seven countries in northern Europe, overlooking large areas in southern Europe. Consequently, there is a need for extending the availability of hydrological data from catchments spread more evenly throughout Europe to enable a holistic assessment of flood behaviour (trends and clustering) in a unified approach across the continent. This can unveil potential large-scale patterns, which may not be visible when comparing single studies on a national level. In addition, such patterns enable a sounder and more comprehensive connection with large-scale climatic drivers (Pires and Perdigão, 2007) and regional scale landscape–climate interactions (Perdigão and Blöschl, 2014).

Given the relatively short flow series available in practice, there will be an adverse impact on the statistical reliability of the trend estimates obtained from such series. Yue et al. (2012) recommended using records of at least 30 or even 50 years. Prosdocimi et al. (2014) found that the sample size needed to achieve a reasonable power level for a test on the regression coefficients in a linear trend model would require current streamflow records (typically initiated post-1960) to reach the end of the 21st century. In addition, it is necessary to consider the additional complications caused by long-term natural variability in flow series, such as those manifesting themselves in flood-rich and flood-poor periods (for example, Hall et al., 2014; Macdonald, 2006; Merz et al., 2012b). The findings of these studies should be contrasted with the record length typically available to researchers. For example, some countries have no records with a length in excess of 30 or 40 years, with the average length in the European gauging stations compiled by the GRDC database being 49.7 years (http://grdc.bafg.de). Clearly, a trade-off between a dataset consisting of a few sites with long records and a larger dataset with several shorter records is required.

Detected temporal trends in a region may be a result of various potential drivers that include the following: (i) climatic drivers, such as temperature, precipitation and related variables, such as evaporation and snow; (ii) drivers at the catchment scale that have an influence on rainfall-runoff transformation processes, such as land-use changes (deforestation, reforestation and urbanisation, among others) and climate-driven weathering and erosion; and, (iii) changes in rivers, such as river training and flood routing processes in reservoirs (Merz et al., 2012a). Drivers at the catchment scale (ii and iii) are expected to have a local influence on floods (Blöschl et al., 2007), though there has been some discussion on the potential role and influence of such drivers at differing flood magnitudes (Macdonald and Black, 2010) and on the propagation of influence, for example, of river training along the river network (Vorogushyn and Merz, 2013).

However, larger regional-scale trends in floods often result from changes in climatic variables. Consequently, the identification of flood regions that are under the influence of similar climatic variables is useful in enabling the interpretation of the results obtained from the statistical tests used for trend detection at a regional scale. Various approaches have been used to identify catchments with similar hydrological regimes. For example, in one study Hannaford et al. (2013) used clustering on standardised annual mean flow series to obtain homogeneous hydrological regions. In addition, Gudmundsson et al. (2011) identified seven regions in Europe in terms of cross-correlation between time series of a set of annual streamflow percentiles. In another study, Parajka et al. (2010) used cluster analysis to identify catchments with similar flood generation processes across the Alpine–Carpathian range in terms of flood and extreme precipitation regimes. Finally, Bard et al. (2012) classified catchments in Alpine regions of Europe according to mean inter-annual monthly streamflows.

The identification of homogeneous hydrological regions in terms of similar patterns in the flow response to climatic drivers may be further complemented by the characterisation of such climatic drivers. These provide the benefit of a deeper understanding of coherent large-scale atmospheric physical mechanisms that explain the patterns of precipitation, temperature, and related variables. Physical climatology references may be useful in such a sense, as they provide in-depth characterisations of such regions and their underlying physics (Peixoto and Oort, 1992; Salby, 2012).

In this study, a pan-European dataset of flow series established by the COST Action ES0901 on *European procedures for flood frequency estimation* is used, consisting of the longest flow records available in 25 European countries. This dataset combines the longest available flow series in Europe and a good spatial coverage in both northern and southern Europe. These data are used for identifying large-scale homogeneous regions in Europe in terms of flood regimes, including a hydrological characterisation of these regions in terms of flood seasonality, frequency and inter-annual clustering. Finally, detection of trends in flood series at a pan-European scale based on the identified regions is attempted. The longest records of the dataset provide a unique opportunity to study long-term trends in European flood data. Furthermore, these records can provide a more reliable and evidence-based foundation on which to detect large-scale changes in flood risk across Europe.

2. A pan-European dataset

The longest hydrological series from 25 European countries were collected, compiling a unique data set consisting of 102 gauging stations (Table 1). Data was supplied by 20 contributors involved in the COST Action ES0901 that tested the quality of the data series. The dataset was supplemented with flow series from the EWA-FRIEND for five additional countries. Flow series are classified as *long* when the record length exceeds 80 years. The longest available series were selected for each country, with a maximum of 10 stations for any country (Fig. 1).

The dataset consists of annual maximum (AM) series, as well as continuous records of mean daily flow (MDF). The longest AM series is from 1799 (River Vistula at Warsaw in Poland), with 29 daily data series that began in the late 19th century and several series digitised specifically for this analysis (for example, the Turkish sites). In this study, MDF series are considered, with a mean record length of 93 years, a minimum of 42 years (River Ayios Nikolaos at Kakopetria in Cyprus), a maximum of 196 years (River Nemunas at Smalininkai in Lithuania) and 58 *long* series (Table 2 and Fig. 2a). The catchment areas range from 19 to 576,232 km^2 (River Danube at Orşova in Romania) (Fig. 2b).

In this study, peaks-over-threshold (POT) series extracted from the MDF series were used rather than AM series, with the reason being primarily to avoid mixing data derived based on different hydrological years as defined across the countries. In addition, POT series overcome the restriction of AM series regarding the use of a single event per year, by identifying all floods that exceed a given threshold. A POT series is composed of the N largest floods in the record regardless of the date of occurrence. Consequently, several large floods that occur in flood-rich periods and which are overlooked in the AM series can be recovered in POT series, whereas some annual maxima (though relatively unimportant minor events below the threshold that usually occur in flood-poor periods) are ignored. In addition, POT series supply more information about floods, not only their magnitude and timing but also the waiting time between two successive peaks that exceed a given threshold and their clustering in time.

The main drawback of using POT series is that the extraction of events is more complex than the case of AM, in particular concerning the choice of the threshold. Stedinger et al. (1993) recommended a minimum mean number of peaks per year (λ) of 1.65 for a POT analysis to give more accurate estimates of extreme quantiles than an AM analysis, whereas Lang et al. (1999) recommended the average number of events per year to exceed two or three. In addition, POT series with $\lambda \geqslant 3$ were recommended to conduct a seasonality analysis by Cunderlik et al. (2004a).

In this study, a threshold value was adopted at each gauging station that results in an average of three exceedances per year, such as those used in previous trend studies (Svensson et al., 2005; Petrow and Merz, 2009). Consequently, the resulting POT series are denoted POT3. Two criteria were used to identify the independence between two successive peaks (USWRC, 1976): (i) the minimum lag time between two successive peaks (θ) is given by Eq. (1); and (ii) intermediate flows between two successive peaks must be below three quarters of the smallest peak (Eq. (2)).

$$\theta > 4.0483 + \log(A) \quad (1)$$

$$Q_{\min} < \frac{3}{4}\min(Q_1, Q_2) \quad (2)$$

where θ is measured in days, A is the catchment area in km^2 and $Q_{\min}$ is the minimum flow between two successive peaks Q_1 and Q_2.

Additionally, for the analysis of inter-annual clustering of floods over a threshold, the summer half-year from 1 April to 30 September (POT3su) and winter half-year from 1 October to 31 March (POT3wi) series were extracted from the annual POT3 series.

A trade-off between a small dataset with long records at a few sites compared with a larger dataset with shorter records at more sites is needed. Longer periods will lead to more robust trend results, though at the expense of spatial density. In addition, most flood trend studies conducted at national scales used shorter periods of time to obtain a better spatial distribution. The effect of this trade-off was examined by considering four periods of time: 1900–1999 (17 stations with a record length in excess of 100 years), 1920–1999 (41 stations with a length in excess of 80 years), 1939–1998 (58 stations with a length in excess of 60 years) and 1956–1995 (81 stations with a length in excess of 40 years) to cover combinations of temporal and spatial scales, with the first two including the *long* series and the last two reflecting timeframes over which most data are available. These periods maximise the number of gauging stations considered, accounting for the temporal availability of data in each country (Fig. 2c).

3. Identification of regions based on flood seasonality and hydrological regimes

Large-scale regions defined in terms of flood seasonality and hydrological regimes are identified by cluster analysis undertaken on the monthly frequency of floods observed in the POT3 series for the four time periods considered: 1900–1999, 1920–1999, 1939–1998 and 1956–1995.

Cluster analysis of flood parameters is the most frequently used technique for identifying homogeneous groups of catchments to help infer spatio-temporal patterns of flood occurrence (for example, Burn, 1989; Lecce, 2000). Variants of this include the use of discriminating criteria and discriminant function analysis. Discriminating criteria are used to assign catchments to regions based on prior knowledge or commonly held beliefs about hydrological patterns and functioning. Gottschalk et al. (1979) used this approach to devise a manual classification technique. Discriminant function analysis is a method used by following cluster analysis to reorganise groups (among others, Mosley, 1981). While it may only be used to increase the homogeneity of the groups through reorganisation, it does not provide an initial classification. Alternative approaches used to infer hydrological regions include the use of geographical regions (among others, NERC, 1975) and the similarity of catchment characteristics (among others, Acreman and Sinclair, 1986).

Several clustering approaches may be considered in identifying the optimal clustering, including the partitioning around medoids (PAM) technique and hierarchical cluster analysis by using various agglomeration methods, such as Ward's (Ward, 1963) single, complete and average linkage and McQuitty's (McQuitty, 1966) median and centroid. For all four periods, Ward's hierarchical cluster analysis with five clusters was selected as the preferred method and the optimum number of clusters. This was determined via the use of cluster plots, together with the characteristics and interpretability of the clusters obtained (Fig. 3).

Five regions, based on the monthly frequency of flood occurrence, are identified across Europe (Fig. 4 and Table 3):

- Region 1. An *Atlantic region*, from the Iberian Peninsula to Denmark and central Germany in the east and Iceland in the north, where floods are mainly driven by persistent and intense rainfall associated with frontal storms caused by extra-tropical depressions advected from the North Atlantic into Europe by westerly atmospheric circulation. In addition, filamentary

Table 1
Summary of the streamflow dataset.

Country	Code	River	Location	Area (km^2)	Lat	Long	Record length
Austria	AUS1	Bregenzerach	Mellau	229	47.36	9.88	59
	AUS2	Inn	Innsbruck	5792	47.28	11.40	59
	AUS3	Antiesen	Haging	165	48.27	13.45	59
	AUS4	Donau	Kienstock	95,970	48.38	15.46	116
	AUS5	Krems	Imbach	306	48.45	15.57	59
Cyprus	CYP1	Ayios Nikolaos	Kakopetria	15,884	34.98	32.89	42
Czech Republic[a]	CZE1	Elbe River	Decin	51,123	50.79	14.23	120
	CZE2	Divoka Orlice	Nekor	182	50.07	16.55	101
	CZE3	Loucna	Dašice	624	50.04	15.91	97
Denmark	DEN1	Lindholm Å	Elkær Bro	104	57.16	9.91	93
	DEN2	Skjern Å	Alergård	1055	55.98	9.10	91
	DEN3	Århus Å	Ved Skibby	119	56.14	10.04	92
	DEN4	Odense Å	Nørre Broby	302	55.26	10.23	94
	DEN5	Tryggevælde Å	V. Ll. Linde	130	55.34	12.21	94
Finland	FIN1	Vuoksi	Vuoksi, Tainoinkoski	61,061	61.21	28.78	165
	FIN2	Kokemäenjoki	Muroleenkoski	6102	61.85	23.91	149
	FIN3	Kymijoki	Nilakka	2157	63.01	26.68	116
France	FRA1	La Loire	Montjean-sur-Loire	109,930	47.39	−0.86	141
	FRA2	L'armancon	Aisy-sur-Armancon	1350	47.67	4.23	108
	FRA3	Lariège	Foix	1340	42.97	1.61	104
	FRA4	L'ubaye	Barcelonnette	549	44.38	6.65	104
	FRA5	Le Tarn	Mostuejouls	925	44.21	3.22	97
	FRA6	La Maronne	Argentat	821	45.08	1.95	92
	FRA7	La Nive des Aldudes	Saint-Étienne-de-Baigorry	156	43.18	−1.34	90
Germany	GER1	Inn	Wasserburg	11,983	48.06	12.23	183
	GER2	Salzach	Burghausen	6649	48.16	12.83	183
	GER3	Elbe	Wittenberge	123,532	52.99	11.75	110
	GER4	Mosel	Cochem	27,088	50.15	7.17	111
	GER5	Elbe	Dresden	53,096	51.03	13.73	160
	GER6	Rhein	Koeln	144,232	50.96	6.98	195
	GER7	Weser	Vlotho	17,618	52.28	8.92	186
	GER8	Bode	Wegeleben	1215	51.53	11.03	118
Greece	GRE1[b]	Acheloos	Kremasta	3570	38.96	22.09	42
	GRE2[b]	Boeoticos Kephisos	Karditsa	1930	38.75	23.59	104
Hungary[a]	HUN1	Danube	Nagymaros	183,533	47.78	18.95	69
	HUN2	Sajo	Felsoezsolca	6440	48.11	20.84	65
Iceland	ICE1	Húseyjarkvísl	Varmahlíð	396	65.49	−19.38	80
	ICE2	Hvítá	Reykholt	1570	64.69	−21.41	61
	ICE3	Dynjandisá	–	38	65.74	−23.21	56
Ireland	IRE1	Ballysadare	Ballysadare	642	54.21	−8.51	57
	IRE2	Newport	Barrington's Bridge	223	52.64	−8.47	58
	IRE3	Fergus	Ballycorey	562	52.87	−8.97	55
	IRE4	Scarawalsh	Scarawalsh	1036	52.55	−6.55	56
	IRE5	Blackwater	Ballyduff	2338	52.15	−8.05	57
Italy	ITA1	Po	Pontelagoscuro	71,000	44.83	12.20	90
	ITA2	Po	Piacenza	42,030	45.05	9.70	86
Lithuania	LIT1	Nemunas	Smalininkai	81,200	55.08	22.58	196
The Netherlands[a]	NET1	Rhine River	Lobith	160,800	51.84	6.11	110
	NET2	Meuse	Lith	29,000	51.82	5.45	85
	NET3	Meuse	Borgharen	21,301	50.87	5.72	98
Norway	NOR1	Glomma	Sarpsfoss/Solbergfoss	41,806	59.28	11.13	166
	NOR2	Glomma	Elverum	15,447	60.88	11.56	141
	NOR3	Gudbrandsdalslågen	Skjenna	1834	61.81	9.55	134
	NOR4	Fusta	Fustvatn	526	65.91	13.31	104
	NOR5	Stjørdalselva	Høggås_bru	495	63.49	11.36	100
	NOR6	Tana	Polmak	14,158	70.07	28.06	100
Poland	POL1	Vistula	Warsaw	84,540	52.25	21.03	61
	POL2	Warta	Poznan	25,900	52.40	16.94	189
	POL3	Zagozdzonka	Plachty Stare	82.4	51.45	21.46	49
Portugal	POR1	Sorraia	Ponte Coruche	5847	38.96	−8.52	62
	POR4	Sabor	Quinta das Laranjeiras	3487	41.21	−7.06	64
	POR6	Ribeira do farelo	Vidigal	18.6	37.20	−8.61	53
Romania[a]	ROM1	Danube River	Orşova	576,232	44.70	22.42	151
	ROM2	Maros	Arad	27,280	46.16	21.32	57
Russia[a]	RUS1	Severnaya Dvina	Ust-Pinega	348,000	64.15	41.92	61
	RUS2	Kuban	Tikhovsky	48,100	45.19	38.23	58

Table 1 (*continued*)

Country	Code	River	Location	Area (km^2)	Lat	Long	Record length
	RUS3	Vitim	Bodaibo	186,000	57.82	114.17	57
Slovakia	SLK1	Danube	Bratislava	131,338	48.14	17.11	131
	SLK2	Morava	Moravsky Sv. Jan	24,129	48.58	17.02	84
	SLK3	Hron	Banska Bystrica	1766	48.73	19.15	78[b]
Slovenia	SLO1	Sava	Litija	4821	46.06	14.83	116
	SLO2	Sava	Radovljica I	908	46.34	14.17	101
	SLO3	Savinja	Laško I	1664	46.15	15.23	98
Spain	SPA1	Arlanza	Quintana del Puente	5256	42.03	−4.14	85
	SPA2	Ebro	Zaragoza	40,434	41.39	−0.52	77
	SPA3	Alfambra	Teruel	1396	40.21	−1.07	80
	SPA4	Miño	Lugo	2303	43.00	−7.33	78
	SPA5	Tajo	Trillo	3253	40.42	−2.35	62
	SPA6	Guardal	Huéscar	28	37.53	−2.40	61
	SPA7	Alcaucín	Viñuela	68.5	36.51	−4.08	58
Sweden	SWE1	Goeta Aelv	Vargoens Krv	46,886	58.36	12.37	72
	SWE2	Torneälven	Kukkolankoski Øvr	33,930	67.81	22.98	99
	SWE3	Kalixälven	Räktfors	23,103	66.17	22.82	74
	SWE4	Vindelälven	Sorsele	6056	65.54	17.51	102
	SWE5	Äcklingen	Äcklingen	157	63.74	13.01	72
	SWE6	Harkan	Rengen	1110	64.07	14.10	75
	SWE7	Ljusnan	Ljusnedal Övre	340	62.55	12.60	81
	SWE8	Västerdalälven	Ersbo	654	61.31	13.01	99
	SWE9	Alsterån	Getebro	1333	57.01	16.17	91
	SWE10	Fylleån	Simlången	260	56.72	13.13	84
Turkey	TUR1	Seyhan	Goksu	2597	37.86	36.07	67
	TUR2	Susurluk	Mustafakemalpasa	9629	39.96	28.51	65
	TUR3	Büyük Menderes	Cine	948	37.42	28.13	65
United Kingdom	UKE1	Ouse	York (Skelton)	3301	53.99	−1.13	42
	UKE2	Lee	Fielders Weir	1036	51.78	0.02	131
	UKE3	Thames	Teddington	9948	51.43	−0.32	128
	UKE4	Trent	Nottingham (Colwick)	7486	52.95	−1.08	53
	UKE5	Tyne	Bywell	2172	54.95	−1.92	55
	UKS1	Tay	Perth (Ballathie)	4587	56.49	−3.42	59
	UKS2	Findhorn	Forres	782	57.61	−3.64	53
	UKW1	Severn	Bewdley	4325	52.38	−2.32	90
	UKW2	Dee	Manley Hall	1019	52.96	−2.96	74

[a] Countries where flow series were collected from the EWA-FRIEND database.
[b] Gauging stations with only annual maximum flow series.

structures of air with a high moisture content moving fast from the west may cause extreme precipitation events in autumn and winter (Lavers and Villarini, 2013).

- Region 2. A *Continental region* in Central Europe, from eastern Germany to the Baltic states and from Slovakia and northern Austria to southern Sweden, where snowmelt, synoptic depressions and atmospheric blocking in winter and spring are occasionally complemented by Vb systems in summer, which are Central European cyclonic weather patterns embedded in mid-latitude synoptic depressions, linked to the large-scale atmospheric flow coming from the Atlantic and encircling the northern hemisphere, and further fed by local depressions of Mediterranean nature. These local depressions are cyclonically advected from the Mediterranean into Central Europe, feeding the main synoptic system (Blöschl et al., 2013).
- Region 3. A *Scandinavian region* that includes the Nordic countries, except Denmark and southern Sweden, where floods are often driven by snowmelt potentially in combination with rainfall mostly generated by synoptic systems.
- Region 4. An *Alpine region* that includes rivers with headwaters in the Alps, where most of the largest floods are summer floods resulting from blocking situations and more minor ones that may occur in winter associated with snowmelt and rain on snow (Blöschl et al., 2013).
- Region 5. A *Mediterranean region* identified mainly in the periods 1900–1999, 1920–1999 and 1939–1998 and included in Region 3 in 1956–1995, from eastern Spain to Romania, where floods are driven by multiple mechanisms of both continental and maritime nature, from which stratiform precipitation events in spring and intensive convective summer and autumn storms of less coherent synoptic nature should be highlighted (Llasat, 2001; Ruiz-Leo et al., 2013).

It should be noted that some issues that were encountered while identifying the regions require clarification. In the period 1956–1995 the Scandinavian (Region 3) and Mediterranean (Region 5) regions merge in Fig. 3d, exhibiting a similar monthly frequency pattern with a peak in May. Despite this similarity in flood seasonality, the dominating flood generating processes are somewhat different in the two regions. In Scandinavia, most large floods are recorded in spring, resulting from snowmelt often in combination with rainfall mostly driven by synoptic mechanisms. However, in the Mediterranean area convective storms, often embedded in larger and unstable synoptic structures, and slow-moving Atlantic storms tracking across the western Mediterranean region during spring, account for the most common flood generating mechanisms.

In the case of the Slovenian gauging stations, there is a common pattern caused by the presence of large karst areas and a number of lakes in their catchments that smooth spring and autumn floods, which are driven by either cold fronts that pass over central Europe or Mediterranean cyclones formed in the Bay of Genoa; these stations were included in the Mediterranean region.

In addition, the Turkish gauging stations show a complex set of flood generating mechanisms dominated by winter precipitation,

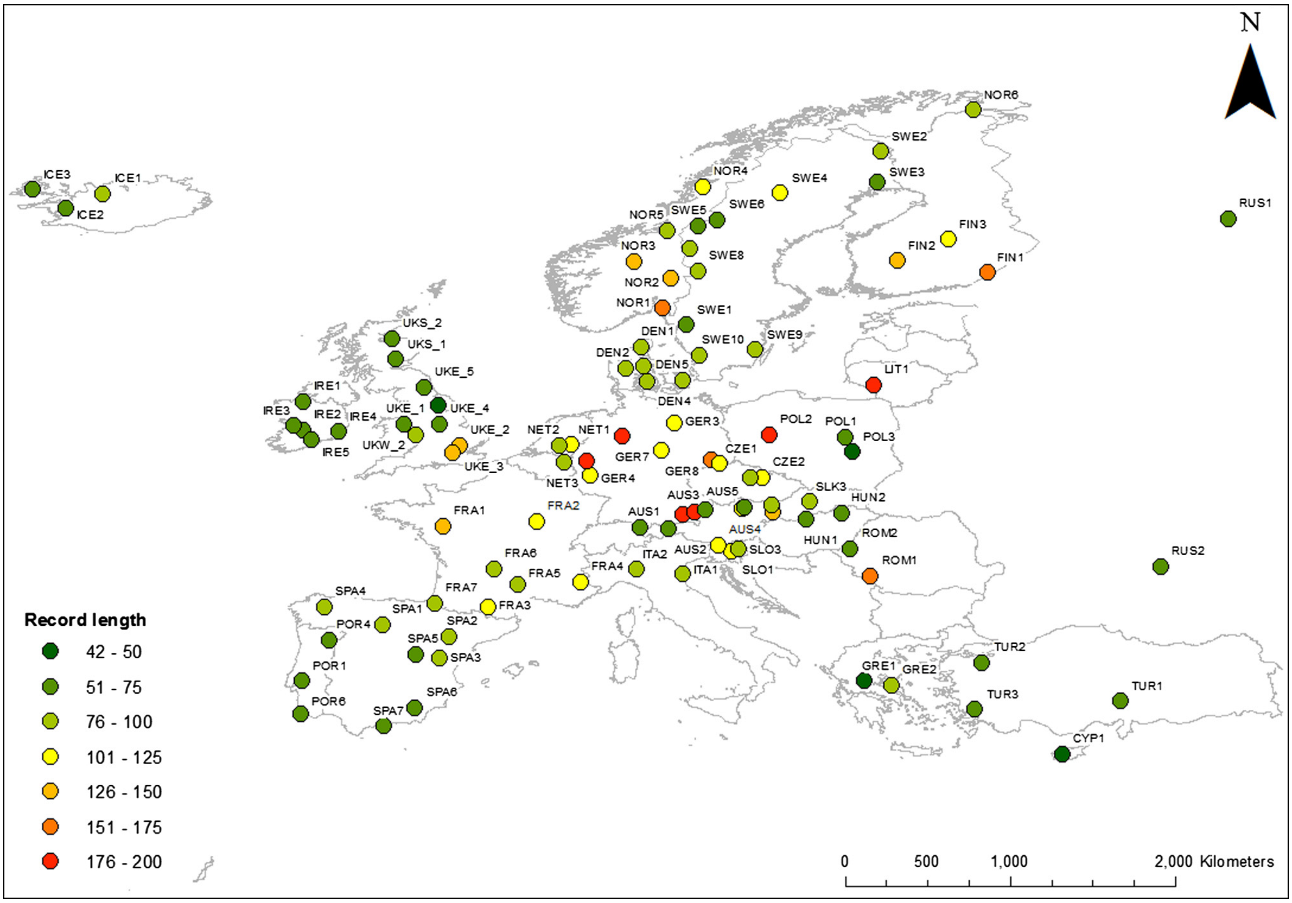

Fig. 1. Spatial distribution of the collected dataset.

Table 2
Summary of record lengths of the mean daily flow dataset.

Record length (years)	Gauging stations
⩾175	6
⩾150	10
⩾125	17
⩾100	34
⩾80	58

snowmelt and seasonal Atlantic frontal storms. These different flood-generating mechanisms reflect its position at the juncture between the Atlantic–Mediterranean and Asian atmospheric systems (notably continental polar air masses and occasional systems from the Persian Gulf in eastern Turkey). In terms of monthly flood frequency patterns, western Turkish gauging sites were included in the Atlantic region (winter dominated Atlantic systems) and the eastern site was included in the Continental region (April/May flooding generated by convective storm systems and associated heavy and intense rainfall events). These findings concur with the principal findings of Sariş et al. (2010) about spatial patterns and associated controlling factors in precipitation behaviour, and Türkeş and Erlat (2003) about the controls of the North Atlantic oscillation on the weather and climate conditions and the extremes with regard to precipitation across Turkey.

Apart from their hydrological specificities, these regions are ultimately under the influence of similar large-scale atmospheric mechanisms, with sources of atmospheric moisture from either the northern Atlantic Ocean or the Mediterranean Sea (Gimeno et al., 2012). Synoptic systems of westerly Atlantic nature ultimately drive the entire European climate, albeit with important modulations from orographic and continental features. For instance, mountain ranges usually mark the transition, from windward to leeward of the large-scale atmospheric flow, between marine-dominated and continental-dominated climate types. Moreover, the high elevations in mountain ranges in the mid-latitudes and the continental areas at higher latitudes are associated with higher snowfall and thus snowmelt-driven runoff as warmer seasons ensue. In addition, the Mediterranean Sea plays an important role in the generation of heavy rainfall events, mainly caused by cyclonic centres in the western Mediterranean (Jansa et al., 2001).

4. Hydrological characteristics of the regions

The hydrological characteristics of the five regions identified based on the monthly frequency of flood occurrence in the previous section are examined based on the information contained in the extracted POT3 series. Flood events included in POT series are characterised by several variables (Fig. 5): (i) the magnitude of the flood peak (Q) above the threshold, enabling the identification of flood frequency distribution characteristics; (ii) the time of occurrence (t), enabling characterisation of flood seasonality and determination of the number of flood occurrences per year; and, (iii) the waiting time between two successive floods (w) that allows characterisation of the clustering behaviour of flood occurrences.

In the following, the five regions are characterised by: (i) the identification of flood-poor and flood-rich seasons based on the

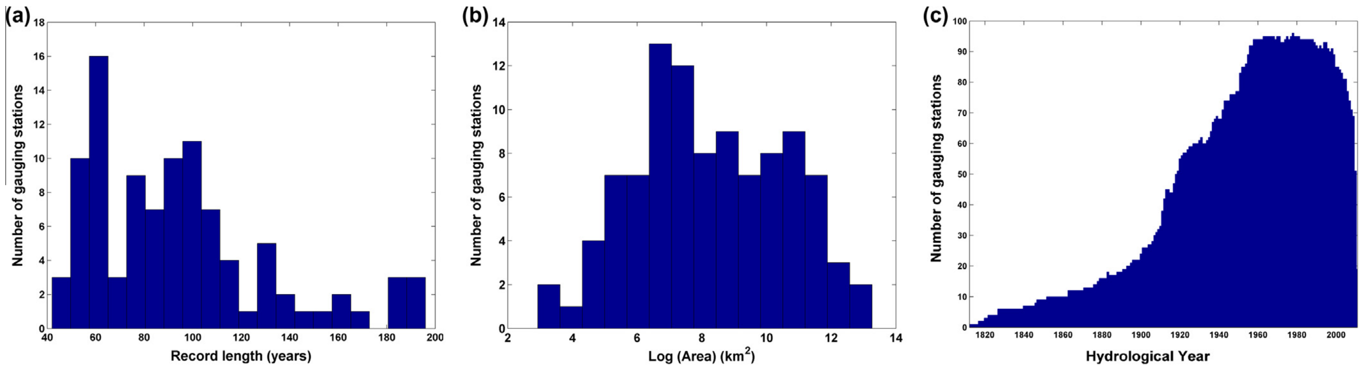

Fig. 2. Summary of the mean daily flow dataset: (a) Histogram of record lengths; (b) Histogram of logarithmic values of catchment areas in km^2; (c) Number of available gauging stations per year.

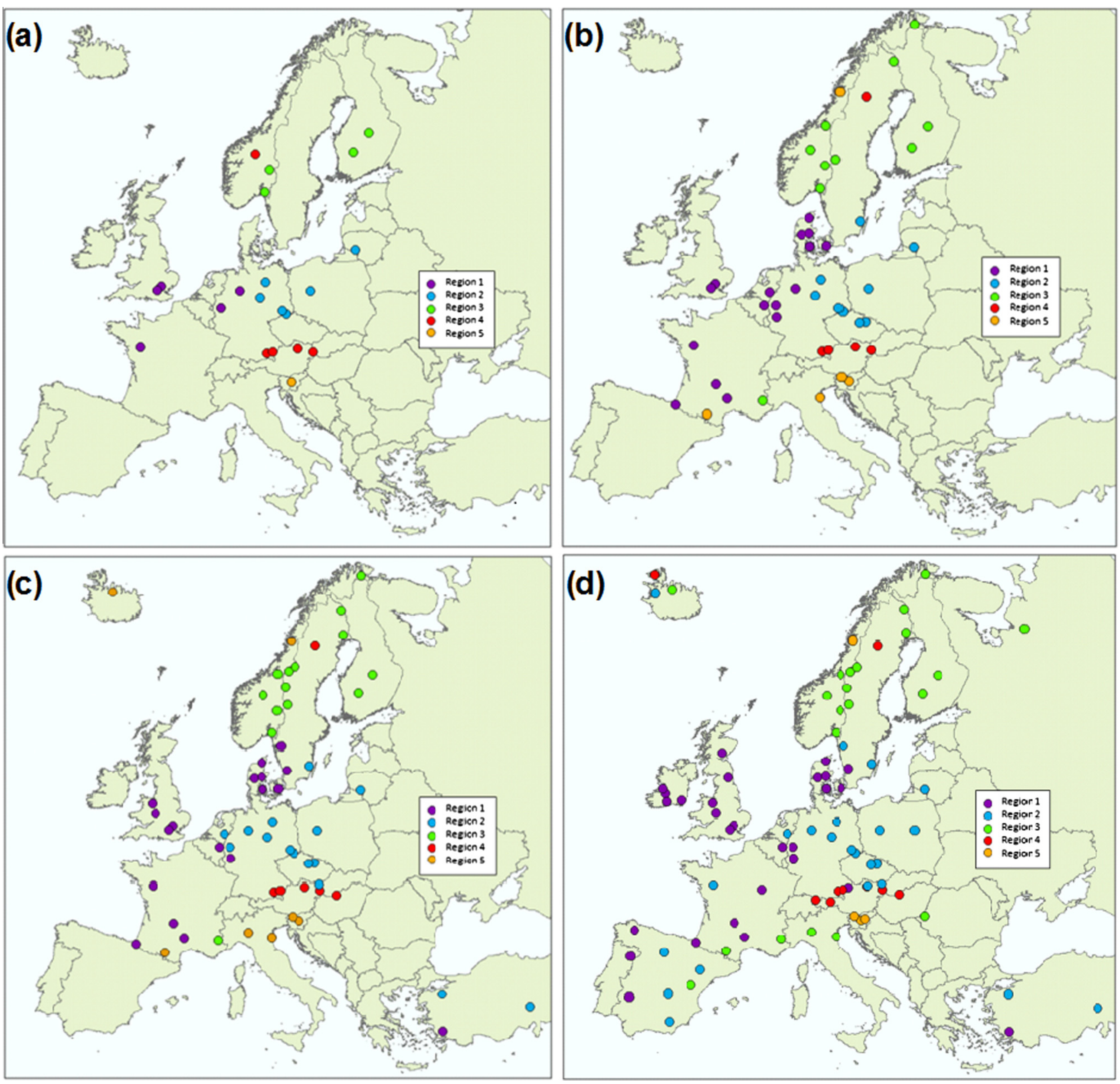

Fig. 3. Regions based on clustering of the monthly frequency of flood occurrences in POT3 series: (a) 1900–99; (b) 1920–99; (c) 1939–98; (d) 1956–95.

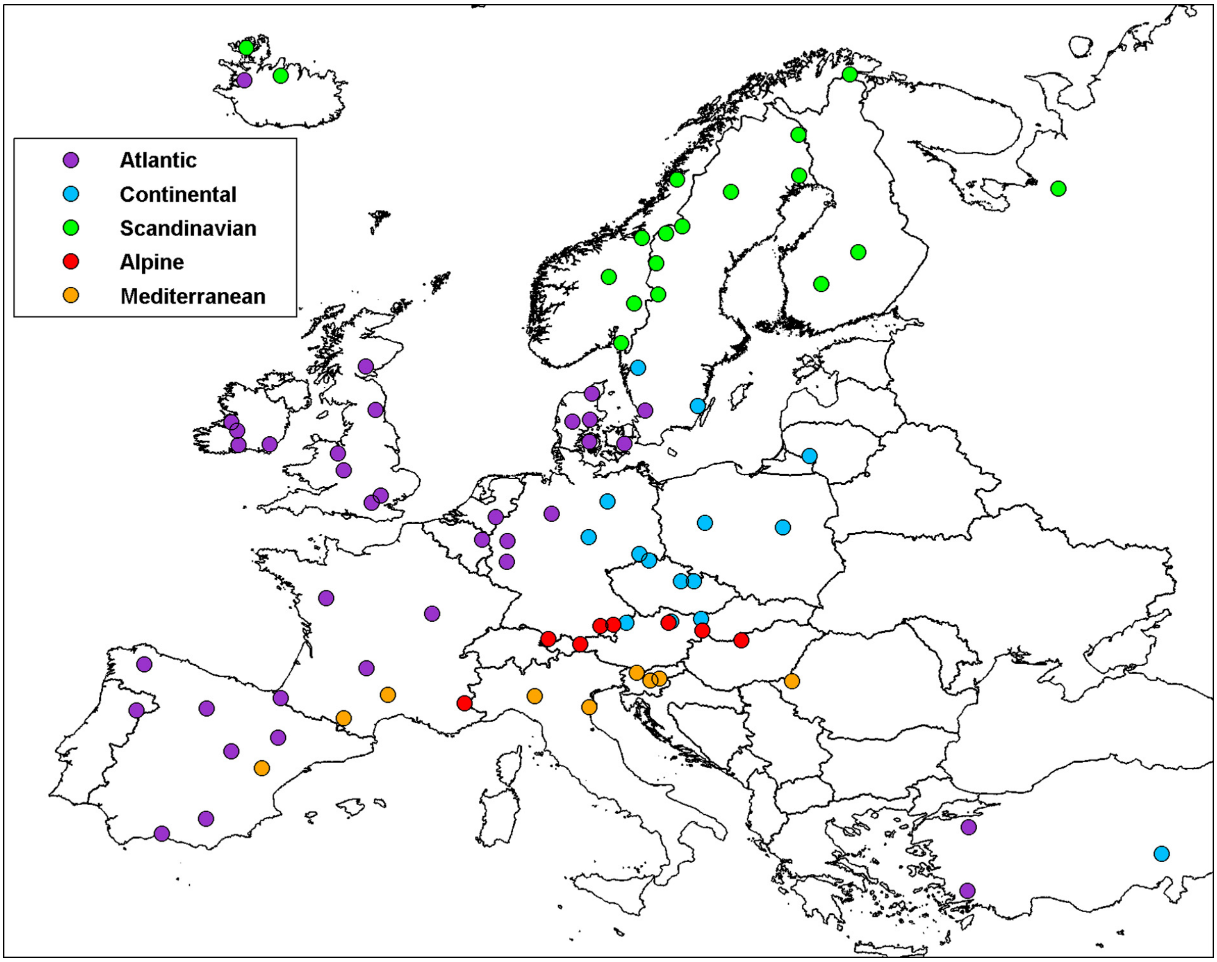

Fig. 4. Regions identified across Europe in terms of flood regimes.

Table 3
Hydrological characteristics of the large-scale regions identified in Europe.

Region	Flood-rich months	Flood-poor months	Dominating flood generation mechanism	Frequency distribution
Atlantic	December–March	May–September	Rainfall from Atlantic frontal systems	GP
Continental	March–April	September–October	Synoptic depressions; snowmelt coupled with rainfall; atmospheric blocking and Vb storms	EXP
Scandinavian	May–June	November–April	Snowmelt coupled with rainfall	GP
Alpine	May–July	September–March	Frontal systems and Vb storms; snowmelt	GP
Mediterranean	May	July–August	Convective storms; snowmelt at high elevations	EXP

seasonality of floods, (ii) the regional frequency distribution of the magnitude of floods, and (iii) the clustering of flood occurrences in time.

4.1. Identification of flood-poor and flood-rich seasons

The frequency of flood occurrence changes during a hydrological year with flood-rich and flood-poor months depending on the generating mechanisms of floods. For instance, in a snowmelt-dominated catchment, most floods occur in spring and early summer when temperatures rise and snowmelt reaches a peak, while in the case of Atlantic catchments, most floods are observed in winter, when persistent frontal storms discharge over soils with an already high level of saturation. Consequently, a seasonality analysis is valuable in identifying seasons with a higher likelihood of flooding. Several methods exist for characterising flood seasonality, from which the most commonly used are those based on either directional statistics or monthly frequencies of flood occurrences (Macdonald et al., 2010).

Significant flood-poor and flood-rich months can be identified by comparing the expected sampling variability of monthly flood occurrences when no seasonality is assumed with the sampling variability of the observed monthly flood occurrences in a given record. In a non-seasonal model floods have the same probability of occurrence in all months, while in a seasonal model they are more likely to occur in given months. First, observed monthly flood frequencies (FF_m) are corrected to account for months with a different number of days (Eq. (3)). Then, if no seasonality is assumed, the probability of occurrence of a flood in a given month is 1/12. Consequently, in a non-seasonal model FF_m equals 1/12 for any month with upper and lower bounds given by Eqs. (4) and (5) for a significance level of 5%. If a monthly frequency is out of these

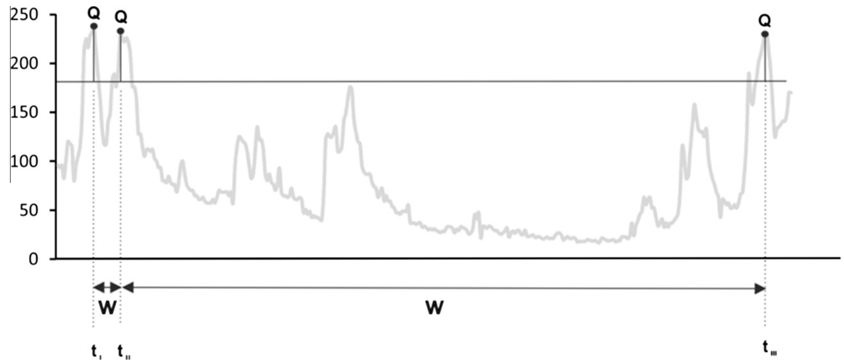

Fig. 5. Flood characteristics in a POT series. Q is the magnitude over the threshold, *t* is the time of occurrence and *w* is the waiting time between consecutive occurrences.

bounds, floods do not follow an annual uniform distribution and a seasonal pattern exists at the 5% significance level (Cunderlik et al., 2004b).

$$FF_m = \frac{F_m}{N}\frac{30}{n_m} \quad (3)$$

$$L_U^N = \frac{N + 11.491}{0.048N^{1.131}} \quad (4)$$

$$L_L^N = \frac{N - 27.832}{0.199N^{0.964}} \quad (5)$$

where FF_m is the frequency of floods in the month m, F_m is the number of floods observed in the month m, N is the number of floods observed in the POT3 series, n_m is the number of days of month m that, in the case of February, is 28.25 to account for leap years, L_U^N and L_L^N are the upper and lower bounds, respectively, for a non-seasonal population of N floods that follows a uniform distribution along the year at a significance level of 5%.

The seasonality pattern of the monthly frequency of floods in each region is analysed from their mean values in the period 1956–1995 (black solid lines in Fig. 6 and Table 3). In the Atlantic region (Fig. 6a), a long flood-rich season was identified in winter from December to March, when persistent storms generated by Atlantic frontal systems from the west occur most frequently, supporting previous findings for Germany (Beurton and Thieken, 2009) and the United Kingdom (Black and Werritty, 1997). A flood-poor season was identified in late-spring and summer between May and September, agreeing with the dry season in this region.

In the Continental region (Fig. 6b), two flood-rich months were identified in March and April, when synoptic depressions, in the western part of the region, and snowmelt coupled with rainfall, in the eastern part, usually generate large floods. Two flood-poor months were identified in September and October with a low frequency of floods, when Atlantic frontal systems are less pronounced. It should be noted that a longer flood-poor season could be expected including July and August too, as these months are also relatively flood-poor compared to spring months (Beurton and Thieken, 2009; Reihan et al., 2012). However, heavy floods triggered by persistent rainfall stemming from stationary depressions (atmospheric low-pressure blocking) and regional Vb weather patterns may sometimes occur. Low-pressure blockings are often a consequence of storms being nested between blocked high-pressure systems, for example when stationary depressions in central Europe are nested between high-pressure blocking in the Azores and Scandinavian anticyclones (Blöschl et al., 2013), or during a resonant atmospheric flow (Pires and Perdigão, 2015). Also, in the Alpine–Carpathian catchments located at high elevations, snow and glacier melt together with warm advection and rain being important flood-producing processes in June and July (Parajka et al., 2010). Consequently, these months were not identified as flood-poor through the regional mean monthly frequency, though some sites showed a longer flood-poor season including them.

In the Scandinavian region (Fig. 6c), two flood-rich months were identified in May and June when increasing temperatures cause snowmelt, often in combination with rainfall. In addition, a flood-poor season was identified between November and April, when snow accumulates in the catchment and floods occur less frequently, as low temperatures prevent snowmelt and often result in ice and snowpack accumulation.

In the Alpine region (Fig. 6d) consisting of the Inn and Upper Danube, the seasonality pattern differs from that observed in the Scandinavian region. A slightly longer flood-rich season extends from May to July, mainly as a result of large-scale precipitation originating from Atlantic cyclonic activity. A typical storm track includes Vb patterns from the Adriatic that push north, though other atmospheric conditions such as large-scale depressions may also result in major floods (Blöschl et al., 2013). A long flood-poor season is observed from September to March, when cyclones are less common and low temperatures prevent snowmelt.

Finally, in the Mediterranean region (Fig. 6e) a mixture in flood generating mechanisms leads to a similar monthly frequency of floods throughout the hydrological year. However, a flood-rich month was identified in May, caused by stratiform precipitation events, occasional intense convective rainfall events and snowmelt in catchments located at high elevations. In addition, two flood-poor months were identified in July and August, though local flash-flood events in steep gradient catchments usually occur in summer and are caused by intensive convective storms. It should be noted that flood-rich months could be expected in autumn (October and November) when intense convective rainfall events occur over the western Mediterranean coast, though they were not identified in the regional mean monthly frequency, reflecting the generally localised impact of these intense precipitation events (though some individual sites showed a peak in this season).

4.2. Frequency distribution of the magnitude of floods

Considering flood magnitude, exceedances in a POT series are usually assumed to follow either an exponential distribution (EXP) (Eq. (6)) or a generalised Pareto distribution (GP) (Eq. (7)) (Madsen et al., 1997).

$$F(x) = 1 - \exp\left[-\frac{1}{\alpha}(x - q_0)\right] \quad (6)$$

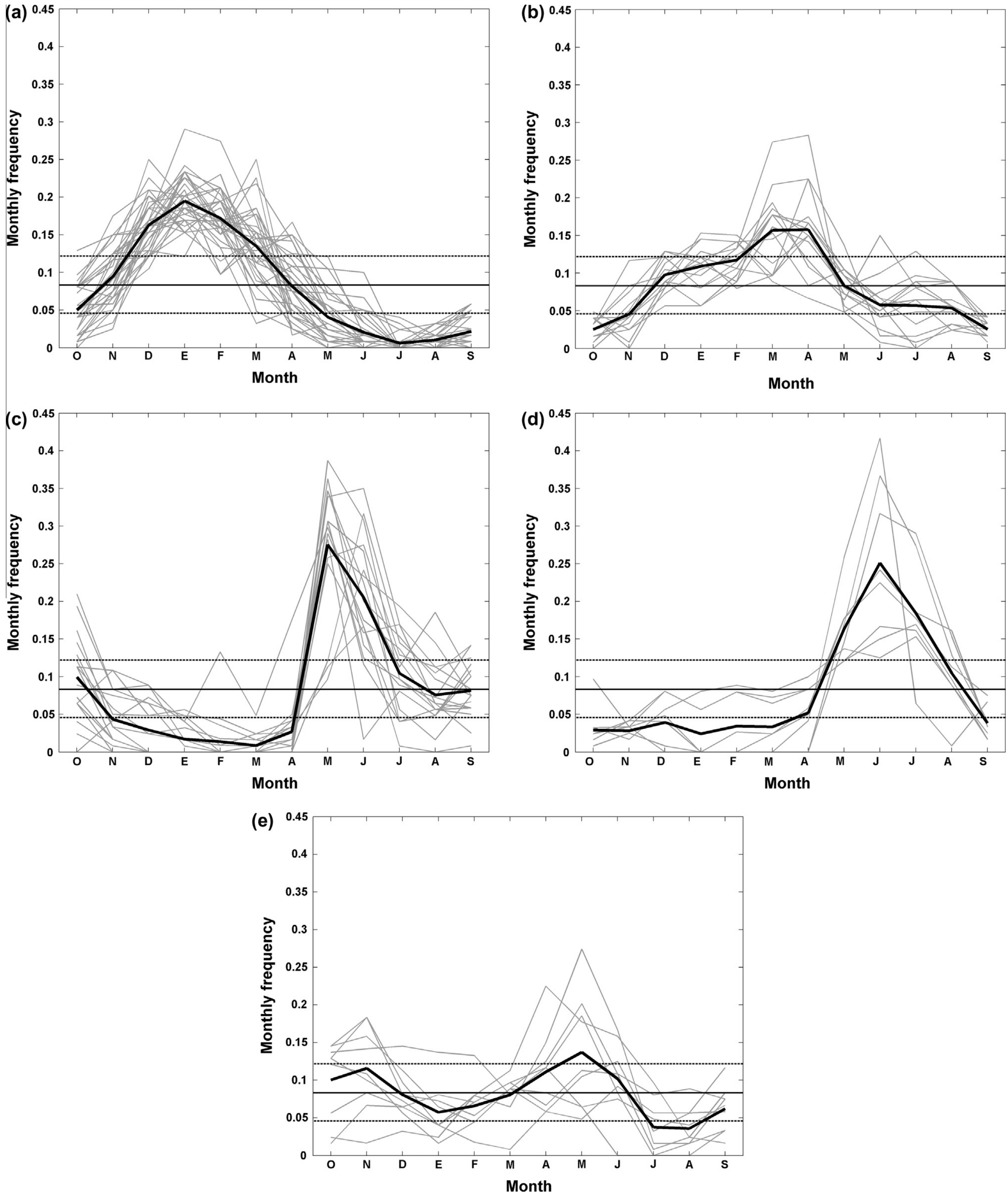

Fig. 6. Monthly frequency of flood occurrences by regions: (a) Atlantic; (b) Continental; (c) Scandinavian; (d) Alpine; (e) Mediterranean. While grey lines show monthly frequencies at each site, solid black lines show the regional mean. Horizontal lines show the mean and boundaries for a confidence interval of 5%, in the case of a non-seasonality pattern.

$$F(x) = 1 - \left[1 - \frac{k}{\alpha}(x - q_0)\right]^{1/k} \quad (7)$$

where q_0 is the threshold of a POT series above which floods are identified, α is the scale parameter and k is the shape parameter.

The L-moment ratio diagram introduced by Hosking and Wallis (1997) was used to examine the limiting distribution of flood exceedance magnitude for each region, assuming the flood series are stationary. This diagram plots the L-coefficient of skewness (L-CS) against the L-coefficient of kurtosis (L-CK) of each sample, as well as the average L-CS and L-CK of each region. The sample

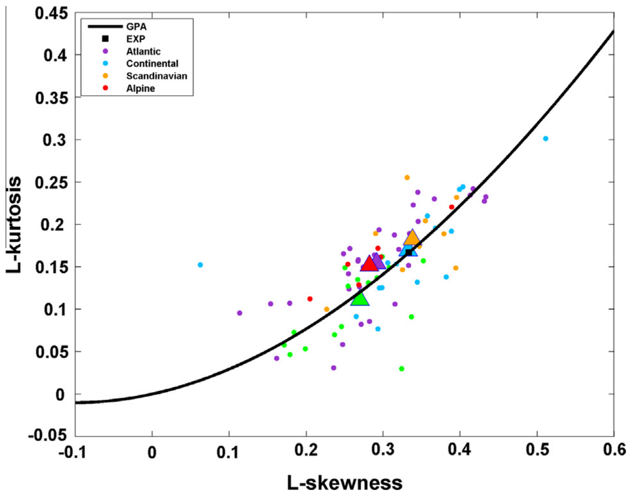

Fig. 7. L-moment ratio diagram by regions. Triangles show mean values in each region.

points are compared with the corresponding theoretical relationships for a selection of two- and three-parameter distributions. For a suitable distribution, the regional average L-moment ratios should be located close to the theoretical line or point and the at-site points scattered around consistently.

The characteristics of the frequency distribution of the magnitude of floods in the POT3 series are studied. In particular, the L-moment diagram was used to test if the common distribution functions used for POT series could represent the behaviour of floods in the identified regions in Europe. From Fig. 7 it may be seen that the mean regional values of L-CS and L-CK are located close to the theoretical curve representing the GP distribution, suggesting that this distribution can be used to describe the magnitude of the events in the POT3 series from all five regions. Furthermore, both the Continental and Mediterranean regions show mean values that are quite close to the two-parameter EXP distribution function, suggesting that in these cases this distribution could be preferred to the three-parameter GP, as the former is a special case of the latter with the k parameter equal to one and, consequently, a lower uncertainty in estimates (Table 3).

4.3. Inter-annual clustering of floods

The annual number of flood occurrences in a POT series is often assumed to follow a Poisson distribution (Eq. (8)), as floods above a given threshold can be interpreted as a realisation of a point process (for example, Cunnane, 1979).

$$P(m) = e^{-\lambda}\frac{\lambda^m}{m!}. \quad (8)$$

where $P(m)$ is the probability of exceeding m times the threshold q_0 in a given year, and λ is the mean number of peaks per year.

The waiting time, w, between two events in a Poisson process follows an exponential distribution, assuming that the number of occurrences in different years is identically and independently distributed. However, the presence of flood-rich and flood-poor periods at the inter-annual scale is widely acknowledged (Mudelsee et al., 2004; Schmocker-Fackel and Naef, 2010), which jeopardises the assumption of the realisation of a homogeneous Poissonian process. For example, Villarini et al. (2013) demonstrated the influence of the Atlantic and Pacific Oceans as well as the antecedent rainfall on the occurrence of floods in the Midwestern United States.

The degree of flood clustering and departure from a Poisson process can be characterised by the index of dispersion (D) that relates the variability in an observed series of annual number of flood occurrences to its expectation value (Eastoe and Tawn, 2010). This measure was previously used for instance to detect clustering of extratropical cyclones (Mailier et al., 2006). A modified version of D as applied by Vitolo et al. (2009) is used in this study to characterise flood clustering behaviour (Eq. (9)).

$$D = \frac{\mathbb{V}ar(Z(T))}{\mathbb{E}(Z(T))} - 1. \quad (9)$$

where $Z(T)$ is the series of annual flood occurrences for a time window T.

For a Poisson process, D is equal to zero. A negative value of D represents under-dispersion, characterising a more regular pattern of flood occurrences than would be expected in a Poisson process, that is to say most years have a similar number of flood occurrences. A positive value of D indicates over-dispersion, pointing to the existence of temporal clusters of flood events that produce flood-rich and flood-poor periods. For example, Robson and Reed (1999) found that the POT data for rivers in the United Kingdom are generally over-dispersed, indicating a tendency for flood events to cluster in time.

The statistical significance of D was tested under a 5% significance level by using the Lagrange multiplier (LM) statistic (Eq. (10)) (Greene, 2003). The limiting distribution of the LM statistic is chi-squared with one degree of freedom.

$$LM = 0.5 * \frac{\left(\sum_{i=1}^{k}\left[(z_i - \hat{\lambda})^2 - z_i\right]\right)}{k\hat{\lambda}^2} \quad (10)$$

where $\hat{\lambda}$ is the estimated mean of the Poisson distribution fitted to the Z series of flood occurrences of length k. A time window, T, equal to one year was applied to examine the clustering at the annual time scale.

POT3 series were randomly permuted 10,000 times, with each event being assigned to arbitrary days within the length of record. The value of D for the original POT3 series was compared with the empirical distribution of D computed for the bootstrapped series to check the null-hypothesis.

Different patterns in the clustering of flood occurrences in time were found for the period 1956–1995 in the annual POT3 data

Table 4
Mean values of the modified index of dispersion, D, in each region for four time periods. The column "Clustering" characterises clustering in time of POT3 series for each region as follows: number of gauges with positive D/number of gauges with statistically significant positive D/number of gauges with negative D/number of gauges with statistically significant negative D. Acronyms indicate the following "OD" – over-dispersion, "UD" – under-dispersion, "NCP" – no clear pattern.

Region	$\overline{D}_{1956-1995}$	Clustering (1956–1995)	$\overline{D}_{1939-1998}$	Clustering (1939–1998)	$\overline{D}_{1920-1999}$	Clustering (1920–1999)	$\overline{D}_{1900-1999}$	Clustering (1900–1999)
Atlantic	0.133	OD (21/7/12/0)	0.165	OD (14/3/5/0)	0.332	OD (13/9/2/0)	0.255	OD (5/2/0/0)
Continental	0.36	OD (14/9/1/0)	0.566	OD (11/7/1/0)	0.51	OD (8/5/1/0)	0.34	OD (5/5/1/0)
Scandinavian	−0.298	UD (4/2/14/6)	−0.158	UD (4/2/12/7)	−0.069	UD (3/2/8/4)	0.032	NCP (2/2/3/2)
Alpine	−0.201	NCP (4/0/4/1)	0.44	NCP (3/0/3/2)	0.08	NCP (3/1/2/0)	0.074	NCP (3/0/1/0)
Mediterranean	0.273	NCP (6/2/3/0)	0.136	NCP (4/0/2/0)	0.184	NCP (4/2/1/0)	0.089	NCP (1/0/0/0)

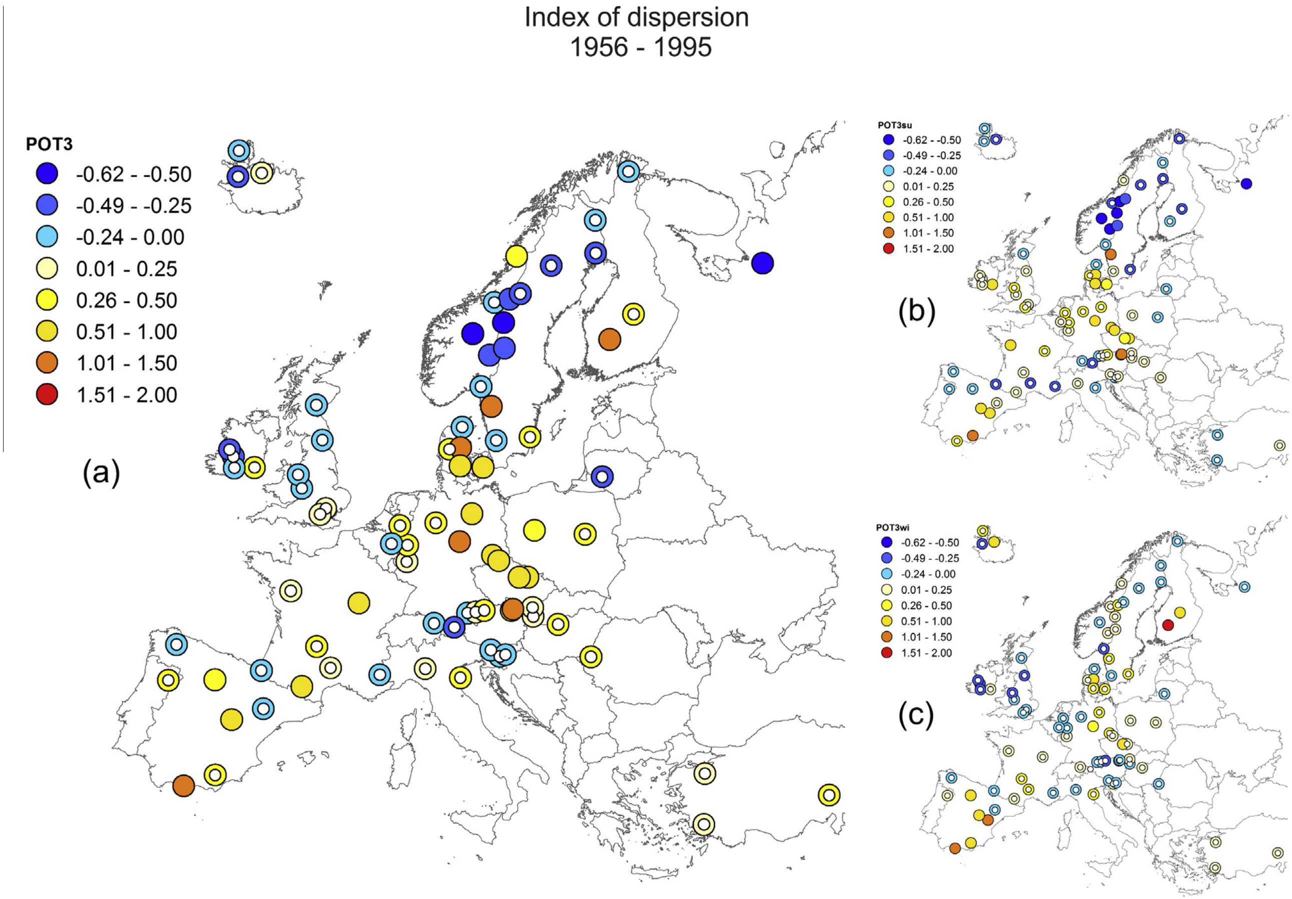

Fig. 8. Index of dispersion for (a) annual, (b) summer half-year (1 April to 30 September) and (c) winter half-year (1 October to 31 March) POT3 series for the period 1956–1995. Negative indices indicate clustering of floods, while positive indicate a more regular inter-annual occurrence. White holes indicate non-significant indices of dispersion under a 5% significance level.

(Table 4 and Fig. 8). Although the majority of gauging stations show statistically non-significant results of D, a clear dipole pattern between the Scandinavian region and other regions is visible. Mainly positive values of D were found in the Atlantic and Continental regions, leading to a larger variability in the annual number of flood occurrences with respect to a Poissonian process (Table 4). Floods in these regions are mainly driven by different types of rainfall and occasional snowmelt events, which occur depending on atmospheric circulation patterns subject to wet and dry years. Consequently, wet years will have more flood occurrences over a given threshold than dry years. The strongly negative indices in the Scandinavian region may be related to the significant regular clustering of peaks, as a result of snow accumulation over several months leading to one major snowmelt event in a year associated with a number of large (above threshold) flood discharges. In the Alpine and Mediterranean regions, no clear under- or over-dispersion was found. In addition, most of the results are statistically not significant. For example, an undetermined pattern of flood clustering in the Alpine region can result from a mixture of driving mechanisms, such as more regular snowmelt and irregular/clustered rainfall events.

Remarkably, the characteristic over-dispersion in the Atlantic and Continental regions persists in the other three longer time periods examined, 1939–1998, 1920–1999 and 1900–1999 (Table 4 and Supplement Figs. S1–S3). The dipole between the Scandinavian region that exhibited under-dispersion and the other regions is evident for all the periods except the longest one, 1900–1999, for which only a few gauging stations are available. In this period, no clear pattern could be identified for the Scandinavian region (Table 4). For the Alpine and Mediterranean regions, no clear pattern emerged in any period, mainly due to the small number of available gauging stations.

The magnitude of the dispersion changes depending on the region. Larger values of D up to 1.5 (statistically significant) were obtained in the Continental region, meaning that on average floods occur 1.5 times more often in flood-rich years than would be expected from the Poisson distribution. However, the Atlantic region showed a smaller variability in the annual number of flood occurrences, as floods are mainly driven by Atlantic frontal storms that would seem to have a more regular temporal pattern among years.

The clustering pattern in summer inferred from the POT3su series was similar to the one for the annual POT3 with even fewer statistically significant indices, which would be expected for shorter seasonal series. Nevertheless, though not as pronounced the dipole between the Scandinavian region and the rest of the regions remained visible in the summer half-year. These patterns are also persistent in the longer time periods 1939–1998 and 1920–1999 (Supplement Figs. S1–S3). In the winter period, the gradient in clustering was smaller with the majority of indices being non-significant. It would appear, as with annual POT3, that summer floods showed regularity in the Scandinavian region and some clustering remained in the Atlantic and Continental regions. In the latter two regions the clustering in the annual POT3 series was constituted from clustering in summer and winter floods. These regions appear to be driven by large-scale variability of wet and dry years.

The analysis of the index of dispersion emphasised the high variability of flood clustering behaviour across Europe with systematic over-dispersion in the Atlantic and Continental regions and under-dispersion in the Scandinavian region. With extension of the period length, while the share of statistically significant indices of dispersion mainly increases, the spatial coverage naturally shrinks. Remarkably, the dispersion behaviour in the regions remains predominantly the same in the four periods of different length.

5. Detection of flood trends

In this section, the method used to detect trends in flood series based on the Mann–Kendall (MK) test is presented. Flood trends are analysed in the five large-scale regions identified. Trends in characteristics of floods in the POT3 series are tested: (i) the magnitude of flood exceedances, (ii) the frequency of floods in terms of the annual number of flood occurrences, and (iii) the timing of floods in terms of changes in the day of the year of flood occurrences. Trends are tested in the four periods selected: 1900–1999, 1920–1999, 1939–1998 and 1956–1995.

5.1. Method to detect trends based on the MK test

In this study, the MK test was selected to detect trends in magnitude, frequency and timing of POT3 series (Eqs. (11) and (12)).

Table 5
Number (percentage) of gauges with upward/downward trends in the magnitude of floods. Field-significant trends are indicated in bold.

Region	1900–1999		1920–1999		1939–1998		1956–1995	
	Up	Down	Up	Down	Up	Down	Up	Down
All Europe	0 (0%)	2 (10%)	1 (2%)	**5 (11%)**	2 (3%)	**8 (14%)**	2 (2%)	4 (5%)
Atlantic	0 (0%)	0 (0%)	1 (7%)	**2 (13%)**	1 (5%)	**2 (10%)**	2 (6%)	**3 (9%)**
Continental	0 (0%)	**2 (33%)**	0 (0%)	**2 (22%)**	0 (0%)	**4 (33%)**	0 (0%)	1 (7%)
Scandinavian	0 (0%)	0 (0%)	0 (0%)	0 (0%)	**1 (7%)**	**2 (13%)**	0 (0%)	0 (0%)
Alpine	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Mediterranean	0 (0%)	0 (0%)	0 (0%)	**1 (20%)**	0 (0%)	0 (0%)	0 (0%)	0 (0%)

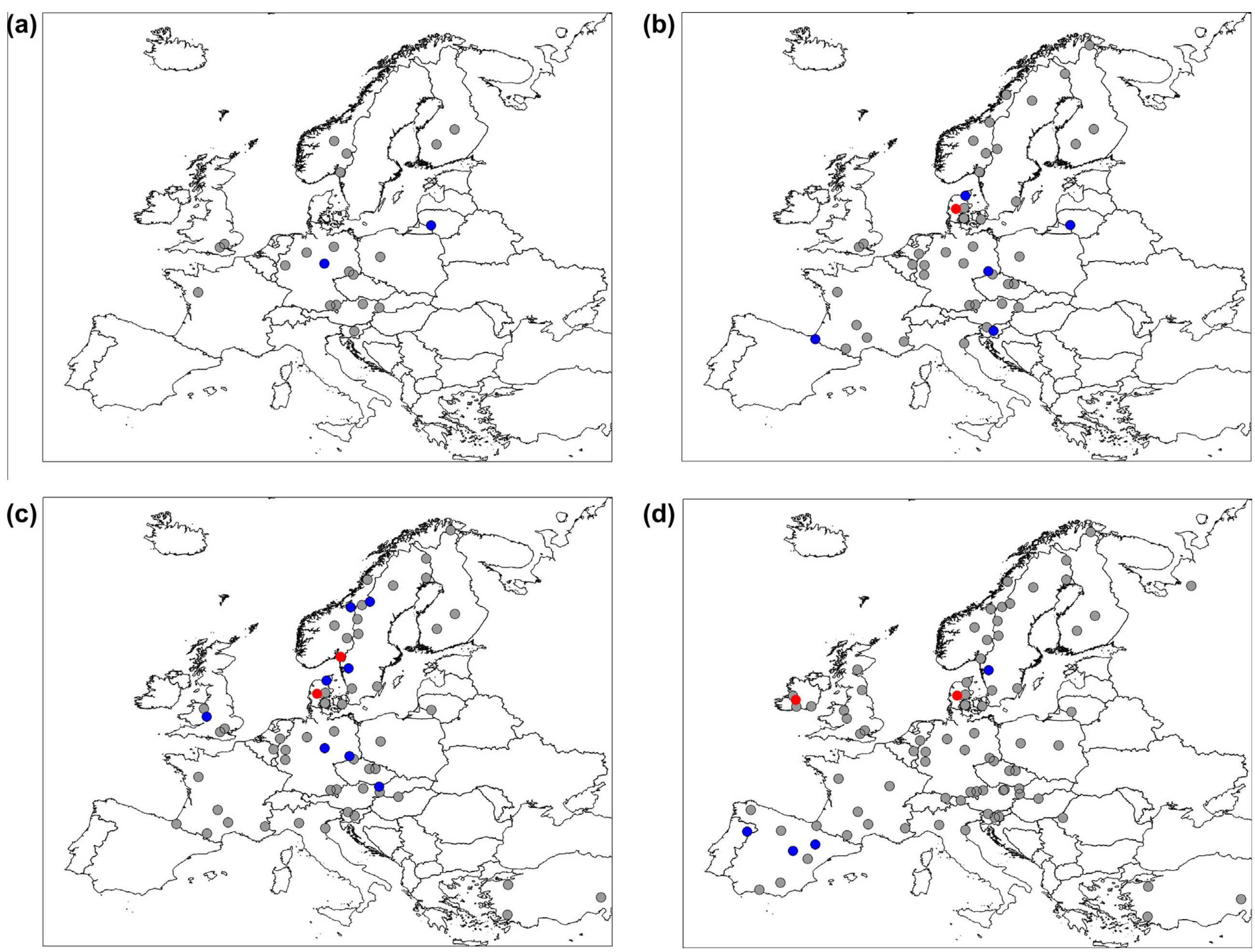

Fig. 9. Trends in the magnitude of floods in POT3 series through the Mann–Kendall test for the periods: (a) 1900–1999; (b) 1920–1999; (c) 1939–1998; (d) 1956–1995. Blue, red and grey circles show significant decreasing, significant increasing and insignificant trends, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Number (percentage) of gauges with upward/downward trends in the frequency of floods. Field-significant trends are indicated in bold.

Region	1900–1999		1920–1999		1939–1998		1956–1995	
	Up	Down	Up	Down	Up	Down	Up	Down
All Europe	1 (5%)	**3 (14%)**	3 (7%)	**7 (16%)**	**5 (8%)**	4 (7%)	3 (4%)	**8 (10%)**
Atlantic	0 (0%)	0 (0%)	0 (0%)	1 (7%)	2 (10%)	**2 (10%)**	**3 (9%)**	**4 (12%)**
Continental	0 (0%)	**1 (17%)**	0 (0%)	1 (11%)	**2 (17%)**	**1 (8%)**	0 (0%)	1 (7%)
Scandinavian	**1 (20%)**	0 (0%)	**2 (18%)**	**2 (18%)**	1 (7%)	0 (0%)	0 (0%)	0 (0%)
Alpine	0 (0%)	**1 (25%)**	0 (0%)	**1 (20%)**	0 (0%)	**1 (17%)**	0 (0%)	**1 (13%)**
Mediterranean	0 (0%)	1 (100%)	**1 (20%)**	**2 (40%)**	0 (0%)	0 (0%)	0 (0%)	**2 (22%)**

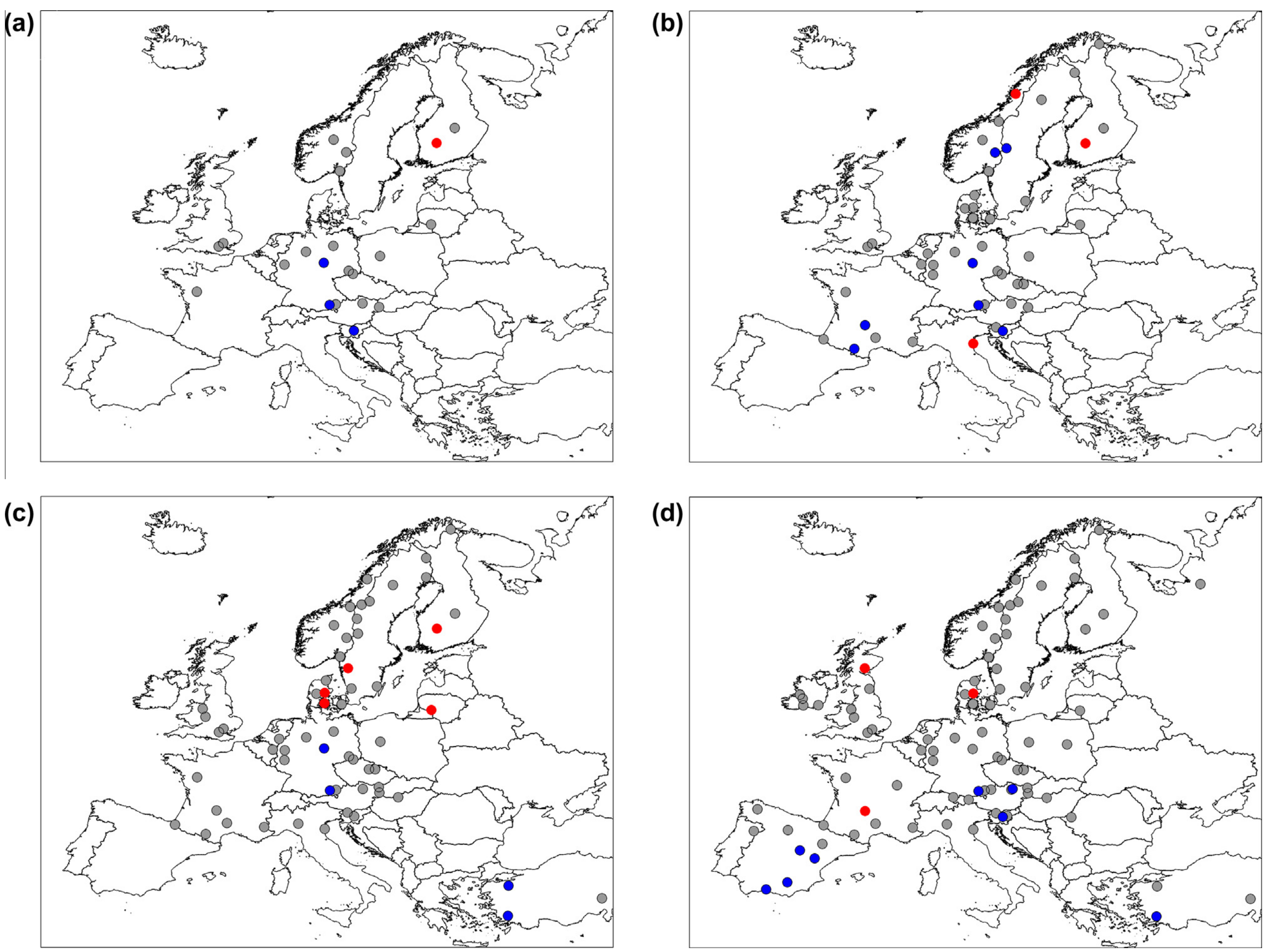

Fig. 10. Trends in the annual frequency of floods in POT3 series through the Mann–Kendall test for the periods: (a) 1900–1999; (b) 1920–1999; (c) 1939–1998; (d) 1956–1995. Blue, red and grey circles show significant decreasing, significant increasing and insignificant trends, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$S = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} sgn(X_j - X_i) \quad (11)$$

$$sgn(X_j - X_i) = \begin{cases} 1 & \text{for } X_j - X_i > 0 \\ 0 & \text{for } X_j - X_i = 0 \\ -1 & \text{for } X_j - X_i < 0 \end{cases} \quad (12)$$

where X_i and X_j are the ith and jth data values, respectively, arranged in temporal order, and N is the record-length. Significant trends were detected for p-values smaller than a significance level of 5%.

The magnitude of a trend was estimated by the Sen slope (Sen, 1968) (Eq. (13)).

$$\beta = median\left(\frac{X_j - X_i}{j - i}\right) \quad \forall i < j \quad (13)$$

Spatial correlation among sites may lead to a greater probability of detecting significant trends. As such, those trends detected at several sites could be transformed into an insignificant trend at the regional scale when accounting for spatial correlation. Therefore, a field significance test should be applied to detect significant trends in a region where cross-correlation among sites exists. In this study, the bootstrap test proposed by Yue et al. (2003) has been applied by using a significance level of 5%:

1. A bootstrap procedure is applied, resampling (with replacement) observations across all the m gauging sites in a given region for individual years. A set of M series of randomly

Table 7
Number (percentage) of gauges with upward/downward trends in the timing of floods (later/earlier occurrence). Field-significant trends are indicated in bold.

Region	1900–1999		1920–1999		1939–1998		1956–1995	
	Up	Down	Up	Down	Up	Down	Up	Down
All Europe	2 (10%)	**3 (14%)**	0 (0%)	**2 (4%)**	1 (2%)	0 (0%)	1 (1%)	0 (0%)
Atlantic	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Continental	**2 (33%)**	0 (0%)	0 (0%)	0 (0%)	1 (8%)	0 (0%)	0 (0%)	0 (0%)
Scandinavian	0 (0%)	0 (0%)	0 (0%)	**1 (9%)**	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Alpine	0 (0%)	**3 (75%)**	0 (0%)	**1 (20%)**	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Mediterranean	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (11%)	0 (0%)

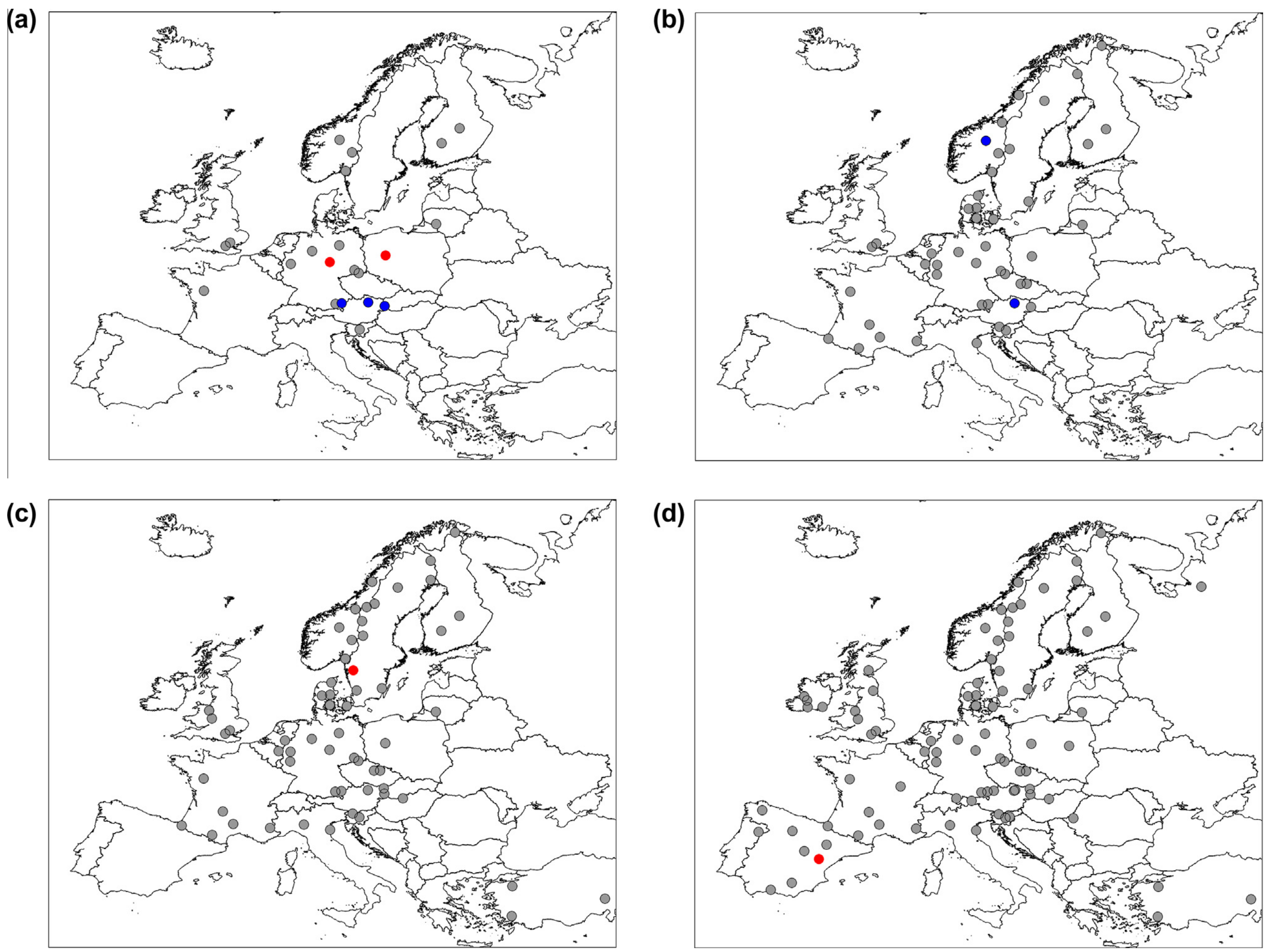

Fig. 11. Trends in the timing of floods in POT3 series through the Mann–Kendall test for the periods: (a) 1900–1999; (b) 1920–1999; (c) 1939–1998; (d) 1956–1995. Blue, red and grey circles show significant decreasing (trend to earlier occurrence), significant increasing (trend to later occurrence) and insignificant trends, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

selected years is obtained with the same length as the original series, though with different year orders. Therefore, M synthetic regions of m sites are obtained, resulting in a total of $M \times m$ synthetic series of floods. Consequently, spatial correlation among sites is preserved, while the temporal order is randomised. In the case of POT series, the number of flood occurrences in a given year may differ among sites. Consequently, the $M \times m$ synthetic series can have different record lengths, despite all having the same number of years.

2. The MK test and its corresponding p-value are obtained for each synthetic series obtained in step 1. The number of sites with a significant upward (N^*_{up}) and downward (N^*_{down}) trends are counted in each synthetic region. A series of N^*_{up} and N^*_{down} of length M are obtained.
3. The bootstrap empirical cumulative distribution (ECD) of the series of N^*_{up} and N^*_{down} obtained in step two are calculated. The probability (p_{obs}) of the observed number of significant upward (N_{up}) and downward (N_{down}) trends in the real region are calculated from the ECD of N^*_{up} and N^*_{down} by Eqs. (14) and (15). Their corresponding p-value (p_F) is given by Eq. (16). If p_F is smaller than the significance level, the trend is considered as field-significant.

$$p_{obs}^{up} = P(N_{up} \leqslant N_{up}^*) \quad (14)$$

$$p_{obs}^{down} = P(N_{down} \leqslant N_{down}^*) \quad (15)$$

$$p_f = \begin{cases} p_{obs} & \text{if } p_{obs} \leqslant 0.5 \\ 1 - p_{obs} & \text{if } p_{obs} > 0.5 \end{cases} \quad (16)$$

5.2. Trends in the magnitude of floods

Trends in the magnitude of floods in POT3 series for the four periods selected were tested (Table 5 and Fig. 9). In the period 1900–1999, only two gauging stations showed significant at-site decreasing trends, both located in the Continental region and field-significant. In the period 1920–1999, most of the at-site detected trends were decreasing and field-significant in the Atlantic, Continental and Mediterranean regions. In addition, one at-site increasing trend was found in the Atlantic region (Denmark).

In the period 1939–1998, most of the detected at-site trends were also decreasing and field-significant in the Atlantic, Continental and Scandinavian regions. In addition, two increasing trends were detected in the Atlantic (Denmark) and Scandinavian (Norway) regions. Finally, in the period 1956–1995, a smaller number of at-site trends was detected, with most of them being located in the Atlantic region with a mixture of increasing and decreasing tendencies. However, only the decreasing trends were found to be field-significant.

5.3. Trends in the frequency of floods

Trends in the frequency of floods in POT3 series were tested by the aforementioned MK test (Table 6 and Fig. 10) and Poisson regression (Supplement Fig. S4), with similar results being obtained. This section is focussed on discussing the results obtained through such a test. In the period 1900–1999, field-significant decreasing trends were found in the Alpine and Continental regions, in addition to a field-significant increasing trend in the Scandinavian region. In the period 1920–1999, while at-site decreasing trends were detected in all the regions, increasing field-significant trends were only found in the north-eastern part of the Scandinavian region. The at-site decreasing trends in the southern part of the Scandinavian region and in the Alpine and Mediterranean regions were field-significant. In the period 1939–1998, at-site increasing trends were detected in the north-eastern part of Europe, though they were only field-significant in the Continental region (clustered in the northern part). At-site decreasing trends were found in the south-eastern part of Europe, with field-significant ones being obtained in the Atlantic, Continental (located in its eastern part) and Alpine regions. Finally, in the period 1956–1995, while field-significant increasing trends were found in the Atlantic region (located in the northern part), field-significant decreasing trends were detected in the Atlantic (clustered in the southern part), as well as in the Alpine and Mediterranean regions.

5.4. Trends in the timing of floods

Trends in the timing of floods in POT3 series were also tested (Table 7 and Fig. 11). In this case, a small number of trends was found. In the period 1900–1999, two at-site increasing trends (floods occurring later in the hydrological year) were detected in the Continental region and three decreasing trends (floods occurring earlier in the hydrological year) in the Alpine region, with both being field-significant. In the period 1920–1999, two at-site decreasing trends (trend to floods occurring earlier in the hydrological year) were found in the Scandinavian and Alpine regions, with both again being field-significant. In the rest of the periods, few trends were detected (being scattered with an unclear spatial pattern).

5.5. Summary of trend results

In the Atlantic region, decreasing trends in flood magnitudes were detected in the periods 1920–1999, 1939–1998 and 1956–1995, as well as in the annual count of floods in the periods 1939–1998 and 1956–1995. However, in the period 1956–1995 increasing trends in the annual frequency of floods were found in the northern part. No trends in the timing of floods were detected.

In the Continental region, decreasing trends in flood magnitudes were detected in the periods 1900–1999, 1920–1999 and 1939–1998, though only in the periods 1900–1999 and 1939–1998 in terms of annual flood frequency. In addition, a trend of later-occurring floods was found in the period 1900–1999.

In the Scandinavian region, a mixture pattern of trends was detected. In the period 1939–1998, while increasing trends in the flood magnitude were found in the southern part, decreasing trends were detected in the northern part. In terms of annual frequency of floods, increasing trends were found in the periods 1900–1999 and 1920–1999, as well as decreasing trends in the period 1920–1999 in its southern part. A decreasing trend in the timing of floods was also found in the period 1920–1999.

In the Alpine region, decreasing trends in all the periods were detected in terms of flood frequency. Furthermore, decreasing trends in the timing of floods (a trend of floods occurring earlier in the hydrological year) were found in the periods 1900–1999 and 1920–1999. No trends in flood magnitude were detected.

Finally, in the Mediterranean region, decreasing trends in the flood magnitude were detected in the period 1900–1999, as well as decreasing trends in the annual frequency of floods in the periods 1920–1999 and 1956–1995. No trends in the timing of floods were found.

6. Discussion

In this study, Europe has been divided into five regions in terms of flood seasonality: Atlantic, Continental, Scandinavian, Alpine and Mediterranean. Gudmundsson et al. (2011) found six regions in Europe in terms of the 5th and 95th annual streamflow percentiles: Alpine, Central France, Iberian, Central Europe, North Sea and Scandinavian. Their Scandinavian and Alpine regions present good agreement with the findings of the present study in terms of the regions identified. However, the Continental region identified by Gudmundsson et al. (2011) moves to the west, covering Belgium, western Germany, the Netherlands and southern parts of the United Kingdom, with this perhaps being due to the lack of data available from eastern Europe and the different indicators used. The Atlantic region identified in the present study is split in a North Sea region, covering north-western British Isles, Denmark, southern Sweden and the west coast of Norway, and the central France region. Finally, an Iberian region was identified that merges the Atlantic and Mediterranean parts of Spain into a separate region. Differences between the studies may emerge because of large blank areas in southern and eastern Europe in the Gudmundsson et al. (2011) study and the variables used to determine regions.

Regarding flood trends, the overall patterns for the analysed periods generally agree with the pan-European summary on flood changes compiled by Hall et al. (2014). The review of flood trend studies in Europe in Madsen et al. (2014) revealed no clear signals of significant trends at large-scale regional or national level. However, a number of studies from regions dominated by snowmelt-induced floods showed decreasing flood magnitude and earlier spring floods, probably caused by increasing temperatures.

In the Atlantic region, in Ireland Murphy et al. (2013) found significant increasing magnitudes of annual maximum floods in the south and west of Ireland for the period 1976–2009, which is in agreement with the increasing trend detected in Ireland for the period 1956–1995 in this study. In the United Kingdom, Macdonald et al. (2010) found a significant increase in flooding in Wales, probably reflecting the timeframe within which the study was undertaken (1973–2002), as Hannaford and Marsh (2008) identified the early period as relatively quiescent. Dixon et al. (2006) also provided findings through some significant single stations trends, though they did not discern any regional pattern for the period 1962–2001. Robson et al. (1998) identified similar findings: while they failed to determine any significant trends for the United Kingdom, they identified regional variability with some systematic behaviour attributed to climatic fluctuations over the period 1941–1990. More recently, in their study Prosdocimi et al. (2014) did not identify any trends in annual and winter flood series in the United Kingdom, though they did identify a downward trend in summer maximum peak flow in the southeast of the country. These results agree with the trends detected for the United Kingdom in the present study.

In France, Renard et al. (2008) found inconclusive signals of a significant trend either at a national scale or regional level based on hydro-climatic factors, though they did detect a decreasing trend in high flows in the Pyrenees, which was also found by Giuntoli et al. (2012). This agrees with the decreasing trends detected in southern France in the period 1920–1999 in the present study. In the Iberian Peninsula, Mediero et al. (2014) found generalised decreasing trends in the magnitude and frequency of floods in the period 1959–2009 in Spain, which are in agreement with the decreasing trends detected in the present study in the period 1956–1995. And in Portugal, Silva et al. (2012) identified a peak in flood occurrence rates in the 1960s that could be in agreement with the decreasing trend in flood magnitude detected in Portugal in the period 1956–1995.

In Germany, trends in the magnitude of POT3 floods in the period 1951–2002 obtained by Petrow and Merz (2009) appear to confirm the trend pattern of POT3 magnitudes obtained in the present study with no significant changes in the period 1956–1995. In contrast, primarily increasing trends were found in the magnitude of floods at the German gauges belonging to the Atlantic and Continental regions based on annual maximum and POT1 series, although using a 10% significance level. Nevertheless, Petrow and Merz (2009) detected a strong increase in the frequency of winter floods in the Rhine (Atlantic region) and winter and summer floods in the Danube catchment (Alpine/Continental region) in POT3 series. They explained this pattern with an increasing frequency of flood generating large-scale circulation patterns (Petrow et al., 2009). The difference from the present study can partly be explained by the selected time periods, a lower significance level and a significantly lower density of gauging stations in the present study.

In the Continental region, Villarini et al. (2011) found neither monotonic increasing nor decreasing trends in a set of 55 gauging stations in Central Europe. However, the results are incomparable, as a common period was not used (they utilised complete series at each gauging site with different beginning and ending years). In Slovakia, statistically significant decreasing trends were detected in annual maximum series for the period 1950–2010 in catchments of east and central parts of the country (Jeneiova et al., 2014), which are consistent with the findings of this study. In the Baltic states, the largest floods ever recorded were observed in the period 1926–1970, leading to a decreasing trend in the magnitude of spring floods in the long periods of 1922–2008, 1941–2008 and 1961–2008 (Reihan et al., 2012), as well as in the period 1922–2010 (Sarauskiene et al., in press). These findings are in agreement with the decreasing trends found in the Lithuanian gauging station in the periods 1900–1999 and 1920–1999.

In the Scandinavian region, Wilson et al. (2010) analysed trends in both the timing and magnitude of floods over three periods (1920–2005, 1941–2005, 1961–2000) in the Nordic countries. In all three periods, a signal towards earlier snowmelt floods was evident, though the magnitude of the spring flood showed no systematic trend. In addition, Wilson et al. (2014) analysed trends in both the magnitude and frequency of floods in small catchments in Norway. Results suggest that trends in the frequency of flood events are stronger than the trend in the magnitude of annual maxima flood events. In Finland, Korhonen and Kuusisto (2010) found few significant trends in magnitudes of high flows, though over one third of the studied sites showed earlier occurence of the spring peak, related to earlier snowmelt.

In the Mediterranean region, in Slovenia, the results are similar to those achieved by national analyses in this country, showing mostly decreasing trends with a greater statistical significance at gauging stations in predominantly high-mountain and karstic catchments (Ulaga et al., 2008). The finding of insignificant trends in the magnitude of floods in Turkey is in accordance with the earlier studies by Onuşluel Gül et al. (2014) and Cigizoglu et al. (2005), which also indicate agreement with the detection of insignificant trends in annual precipitation series recorded in neighbouring rain gauges found by Türkeş et al. (2009). In Spain, the results also agree with the findings of Mediero et al. (2014).

7. Conclusion

This study has provided a pan-European dataset with the longest available flow series recorded at 102 gauging stations in 25 European countries. Mean daily flow series have a mean record length of 93 years and 58 series a record length in excess of 80 years. Peaks-over-threshold series with an average number of three peaks per year were extracted. Four periods were considered: 1900–1999, 1920–1999, 1939–1998 and 1956–1995 to cover a set of combinations of temporal and spatial scales.

Five large-scale homogeneous regions were identified in Europe in terms of flood regimes. An Atlantic region from the Iberian Peninsula to Denmark in the east and Iceland in the north, a Continental region from east Germany to the Baltic states and from Slovakia and northern Austria to southern Sweden, a Scandinavian region that includes the Nordic countries, except Denmark and southern Sweden, an Alpine region that includes rivers with heads in the northern face of the Alps, and a Mediterranean region from eastern Spain to Romania.

The five large-scale regions were characterised hydrologically, studying their flood seasonality to identify regional flood-poor and flood-rich seasons from the mean regional monthly flood frequencies, the regional frequency distribution of the magnitude of floods through the L-moment ratio diagram, and the regional clustering of flood occurrences in time through a modified version of the index of dispersion.

In the Atlantic region, a flood-rich season was identified from December to March, while a flood-poor season from May to September. In the Continental region, two flood-rich months were identified in March and April, and two flood-poor months in September and October. In the Scandinavian region, two flood-rich months were identified in May and June, while a flood-poor season between November and April. In the Alpine region, a flood-rich season extends from May to July, and a flood-poor season is detected from September to March. Finally, in the Mediterranean region, a mixture in flood generating mechanisms leads to a similar monthly frequency of floods throughout the hydrological year. A flood-rich month was identified in May and two flood-poor months in July and August.

The generalised Pareto distribution was identified as the most suitable for describing the magnitude of the events in the peaks-over-threshold series from all the five regions. However, the exponential distribution could be adopted in both the Continental and Mediterranean regions, as each distribution leads to similar results. However, it should be noted that as the exponential has one parameter less, it provides a lower uncertainty of estimates.

A larger variability in the annual number of flood occurrences with regard to a Poissonian process was observed in the Atlantic and Continental regions because of differences in flood generation processes between wet and dry years. In the Alpine and Mediterranean regions, no clear pattern could be found. In the Scandinavian region, a smaller variability was observed, pointing to a similar annual number of floods along the record. This pattern is consistent for nearly all four investigated time periods of different length.

Flood trends were analysed in the five large-scale regions through the Mann–Kendall test and a field significance test based on a bootstrap method. Trends in the magnitude, frequency and timing of floods were analysed. Regarding flood magnitudes, stronger field-significant decreasing trends were found in the Atlantic region from 1920–1999 to 1956–1995 and in the Continental region from 1900–1999 to 1939–1998. An unclear pattern of trends was found in terms of annual count of floods over a threshold, apart from a decreasing trend in the Alpine region for all the periods. Finally, in terms of timing of floods, no clear patterns of trends were found, apart from field-significant increasing trends in the Continental region in the period 1900–1999 and decreasing trends in the Alpine region in the periods 1900–1999 and 1920–1999.

This study has provided an insight into flood behaviour at a pan-European scale by using the longest streamflow records available with a good spatial coverage throughout the continent. In addition, it has derived a large-scale coherent picture that builds on the current studies mostly confined within political and administrative boundaries at a national level.

Acknowledgements

The authors thank the financial contribution made by the COST Office grant ES0901 *European procedures for flood frequency estimation (FloodFreq)*. The Austrian team would like to acknowledge the support of the ERC Advanced Grant *FloodChange* project no. 291 152. L. Mediero also acknowledge funding from the project CGL2014-52570 of the Spanish Ministry of Economy and Competitiveness. S. Kohnova would like to thank the Slovak VEGA Grant Agency for supporting the contract no. 1/0776/13. The authors also thank the Hydrographic Service (Austria), the Danish Centre for Environment and Energy (Denmark), the Finnish Environment Institute (Finland), the Office of Public Works (OPW) in Ireland, the Hydro-Meteorological Service of the Emilia-Romagna Regional Agency for Environmental Protection (ARPA-SIM-Italy), the Lithuanian Hydro-meteorological Service under Ministry of Environment (Lithuania), the Norwegian Water Resources and Energy Directorate (NVE-Norway), the National Information System for water resources (SNIRH-Portugal), the Slovenian Environment Agency (ARSO-Slovenia), the Centre for Hydrographic Studies of CEDEX (Spain), the General Directorate of Electrical Power Resources Survey and Development Administration (EIE-Turkey), the National River Flow Archive (UK), and the Global Runoff Data Centre (Germany) for providing the flow data used in this paper.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2015.06.016.

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