A large-scale hydroclimatological perspective on western European river flow regimes
Donna Wilson, David M. Hannah and Glenn R. McGregor

ABSTRACT
A novel flow regime classification scheme was applied to 141 river basins across western Europe, providing more robust analysis of space–time variability in regimes and their driving hydroclimatological processes. Regime shape (timing) and magnitude (size) were classified to regionalise long-term average flow regimes and to quantify year-to-year variation in regimes for each basin. Six long-term regime shape regions identified differences in seasonality related to latitude and altitude. Five long-term magnitude regions were linked to location plus average annual rainfall. Spatial distribution of long-term regimes reflected dominant climate and runoff generation processes. Regions were used to structure analysis of (relative) inter-annual regime dynamics. Six shape and five magnitude inter-annual regimes were identified; and regime stability (switching) assessed at pan-European, regional and basin scales. In some years, certain regime types were more prevalent, but never totally dominant. Regime shape was more stable at higher altitude due to buffering by frozen water storage-release (cf. more variable rainfall-runoff at lower altitudes). The lower inter-annual magnitude regimes persisted across larger domains (cf. higher magnitude) due to the more widespread climatic conditions generating low flow. Notably, there was limited spatio-temporal correspondence between regime shape and magnitude, suggesting variations in one attribute cannot be used to infer the other.

Key words | classification, hydroclimatology, inter-annual variation, regionalisation, river flow regime, western Europe

INTRODUCTION
A river flow regime describes seasonal behaviour of runoff over the annual cycle (hydrological year). Hence, regimes provide a useful tool for monitoring spatial and temporal variations in flow seasonality and magnitude, which are important hydrological attributes for identifying and managing current and future water stresses (Krasovskaia 1997; Bower et al. 2004; Hannah et al. 2005). The importance of the whole river flow regime (i.e. annual hydrograph) for maintaining and protecting fluvial hydrosystems integrity, rather than managing to maximum, minimum or mean flow thresholds has been increasingly recognised (e.g. Evans 1997; Harris et al. 2000; Monk et al. 2008; Kennard et al. 2010). Poff et al. (1997) suggest the flow regime has five critical elements (i.e. magnitude, frequency, duration, timing and rate of change) that determine river ecological diversity. However, these flow components need to be accurately quantified to effectively establish hydrological management targets for both human water consumption and ecological purposes (Petts 2007).

At the global scale, several studies have considered variability of river flow regimes. Pardé (1953) used discriminating criteria to classify manually regimes based on the source and distribution of flow throughout the year and so identify three main groups of regimes: simple (with one high and one low flow season), complex I (multiple high and low flow seasons, generated by changing dominant hydroclimatological processes over the hydrological year) and complex II (multiple high and low flow seasons,
generated by overlap of different constituent flow regimes due to water draining from different hydroclimatological or physiographic zones. Beckinsale (1969) adapted a climatic classification for differentiating hydrological regions based on understanding of the linkages between intra-annual climatic and runoff patterns. This approach does not consider the role of basin characteristics. More recently, Haines et al. (1988) and Detttinger & Diaz (2000) clustered standardised mean monthly flows to identify regional differences in the timing of the flow regime on the basis of streamflow characteristics alone.

At the European scale, research into spatial variability of river flow regimes has focused largely on timing. Thirteen flow regime classes were identified by Arnell et al. (1993) for northern and western Europe as part of the Flow Regimes from International Experimental and Network Data (FRIEND) programme. The basic distinction of European regimes was between maritime and continental. In maritime areas, regime timing reflected seasonal patterns of rainfall (winter peak) and evaporation (summer trough); whereas, in the continental regions, glacier- and snow-melt was of increased importance and induced a spring/summer high flow season due to the annual compensation effect (Arnell et al. 1993; Krasovskaia et al. 1994). These regime classes were based on discriminating criteria that identified spatial variations in the timing of high and low flow periods, but neglect regime magnitude. The resultant groupings were very uneven in size, with the Atlantic regime type covering much of north-western Europe (including the UK, Ireland, Belgium, the Netherlands and Denmark, together with much of France and Germany). However, analysis of the flow regime seasonality has indicated a high degree of spatial variability at the UK scale (Ward 1968, 1981; Bower & Hannah 2002; Bower et al. 2004; Laizé & Hannah 2010). Krasovskaia et al. (1994) found a number of Atlantic sub-types could be defined for northern and western France, the Benelux countries, the British Isles, northern Germany, Denmark and parts of the Scandinavian Peninsula. Similarly, Shorthouse & Arnell (1998, 1999) and Shorthouse (1999) found it necessary to reorganise a number of regions in the Nordic countries due to their high intra-regional variability. These studies indicate the pan-European FRIEND river flow regime regionalisation could be further refined: (1) to characterise regime magnitude; and (2) to define the timing of seasonal flow variations more precisely.

In addition to understanding spatial patterns, it is important to characterise year-to-year variability in river flow regimes because knowledge of inter-annual regime dynamics (stability at a station) is fundamental to assessing and predicting possible alterations to hydrological regimes as a consequence of climate and/or land-use changes (PUB Science Steering Group 2003). In contrast to regionalisation work, the investigation of the inter-annual variability in European river flow regimes has focused on magnitude (e.g. Krasovskaia et al. 1993; Arnell 1994). A study by Krasovskaia et al. (1994) is an exception; this research examined inter-annual variability in the timing of flows for a subset of the FRIEND stations and found ‘rain-dominated’ regimes were particularly unstable due to year-to-year variations in seasonal precipitation and evaporation. Kingston et al. (2011) undertook a regional classification of monthly river flow for the northern North Atlantic rim (1968–1997); and, for regional mean monthly time series, analysed inter-annual variation and trends. This recent research considered regional composites for each monthly interval singularly; hence, a gap remains to consider the inter-annual regime variation.

To summarise, research into European river flow regimes has been predominantly concerned with spatial variations in the timing of flows but temporal investigations have focussed on magnitude of flow, thus yielding an inconsistent view. The following key issues can be identified that point toward the research gaps addressed herein: (1) the current classifications of the timing of flow are based on broad, subjective discriminating criteria, so subtle, but important, variations in flow may be masked; (2) pan-European study of spatial variation in regime magnitude has been neglected; (3) regions identified on the basis of the timing of flow have been used to structure analyses of temporal variations in flow magnitude (this assumes spatial variations in flow magnitude are the same as for the timing of flow, but this has not been established); and (4) research into inter-annual variability of the timing of flow regime is well advanced for the Nordic countries (Krasovskaia & Gottschalk 1992; Krasovskaia 1995, 1997) but the rest of Europe remains relatively poorly examined. This paper aims to address these research gaps by using a regime classification methodology (Bower
to examine spatial and temporal dynamics of the whole river flow regime (for both shape/timing and magnitude) across western Europe.

**DATA AND METHOD**

**Data**

Daily river flows for 141 western European basins (Figure 1) were obtained from two sources. The majority of data were extracted from the FRIEND European Water Archive (EWA) (Rees & Demuth 2000; Hannah et al. 2011) and augmented by daily flows from the Global Runoff Data Centre (GRDC, http://www.grdc.bafg.de) (Hannah et al. 2011). The latter source provided data for only two gauging stations: Le Tholon at Champvallon, France (station no. 6123550) and Taenndalssjoen at Taenndalen, Sweden (station no. 6233220).

The basins were selected from 4,933 contained within the FRIEND-EWA based on criteria devised to select a manageable but spatio-temporally representative sample of stations. These criteria included: (1) period of record; (2) temporal resolution of data; (3) location; (4) basin size; and (5) level of artificial (management) influence on flows. After exploratory analysis of the metadata catalogue (CEH 2000), it was decided to only select stations where daily data were available for a minimum period of 1974–91. Stations were then chosen to provide good spatial cover across western Europe, from a list of basins between 100 and 500 km² and with limited anthropogenic impact. Basins with flows approximating natural conditions have been included within the FRIEND-EWA (Roald et al. 1993). Visual screening of data was undertaken to check for signs of artificial influence on flows and ensure near-natural stations were used for analyses only. The GRDC data were used to patch data-sparse areas (of the FRIEND-EWA) and provide good pan-European coverage (Figure 1). The years of analysis and the temporal extent of the dataset are forfeited somewhat by a desire to optimise the spatial coverage of this study, but the spatio-temporal dimensions of the dataset and the methodology employed still enable a more holistic description of regimes than previously undertaken at the pan-European scale.

Since many chosen stations had short periods of missing data, three interpolation methods were used: (1) linear fill, (2) linear regression or (3) the long-term daily value. The technique employed was determined by the size of the gap to be replaced, the availability and strength of the relationship with neighbouring stations, as summarised by Figure 2. Approximately 0.01% of data across all station-years were estimated.

Monthly averages of daily flows (mm month⁻¹) were calculated to characterise annual regimes. The start of the hydrological year (timeframe for the regime classification, below) was defined as 1 month after the month of minimum flow (September). Hence, all time-series were divided into hydrological years commencing in October. Santos & Henriques (1999) used the same October–September period for analysis of European annual precipitation records. Throughout the paper, station-years are referred to by the calendar year in which they begin.

**Method**

When assessing spatial and temporal variations in river flow regimes, it is important to identify both the size (magnitude) and timing (shape) of discharges over the annual cycle. Hence, Bower et al. (2004) developed a multivariate methodology based on that originally devised by Hannah et al. (1999, 2000) and adapted by Harris et al. (2000) to separately
classify regimes according to their ‘shape’ and ‘magnitude’. This methodology is summarised in Figure 3 (refer to Bower et al. (2004) for a full description and evaluation).

The shape classification identifies stations (for regionalisation) or station-years (to assess inter-annual regime variability) with similar regime forms, regardless of magnitude; whereas the magnitude classification is based on four indices (i.e. the mean, minimum, maximum and standard deviation) derived from long-term mean monthly values or monthly mean values for each station or station-year, respectively, regardless of timing.

It is important to note that these methods (for both shape and magnitude) are applied to give two separate sets of regime classification results: (1) regionalisation groups stations based on long-term average values to examine spatial patterns; and (2) annual regimes for each station-year (based on monthly mean values) are grouped to identify temporal (between-year) variability.

The regionalisation of long-term regimes provides a basis for structuring analyses of between and within region patterns in inter-annual regime variability. It is also important to note that regime classes are not interchangeable between long-term and station-year regime classifications, as analyses are performed on different input data matrices, and that magnitude classes for regionalisation identify absolute differences between stations whereas magnitude classes for regime stability identify relative inter-annual variations at a station. Together, the two classification modes characterise spatial and temporal regime dynamics.

Regionalisation

The long-term regime for a station was estimated from mean monthly values across all years. To classify regime shape independently of magnitude, the 12 monthly observations for each station are standardised separately using $z$-scores ($\text{mean} = 0$, standard deviation = 1). The four magnitude indices are derived for the long-term regime for each station; it is necessary to standardise ($z$-score) between indices to control for differences in their relative values.

For both shape and magnitude, classification is achieved using a two-stage procedure: hierarchical, agglomerative
cluster analysis followed by non-hierarchical, \( k \)-means cluster analysis. The selection of clusters was based on a clear break in the agglomeration schedule and the dendrogram. The comparison of solutions for seven hierarchical, agglomerative clustering algorithms (i.e. average linkage between and within groups, complete linkage, single linkage, centroid, median and Ward’s Method) revealed that different algorithms identify different groups. Ward’s Method produces the most robust clusters with fairly equal membership. Once clusters are formed by hierarchical, agglomerative cluster analysis outliers cannot be reassigned to a more appropriate cluster; therefore, non-hierarchical \( k \)-means clustering is used to realign cluster boundaries around cluster centroids defined using Ward’s Method. The refinement achieved using this two-stage clustering procedure is assessed by comparing results with those from discriminant function analysis (DFA). The 141 stations are grouped by regime shape and magnitude; the spatial distribution of classes allows identification of regions.

**Inter-annual regime classes**

Regimes for individual station-years were characterised using monthly mean values. To standardise for absolute magnitude differences between stations, the 12 monthly observations for each station-year are \( z \)-scored before shape classification. To classify the magnitude indices for all stations jointly, it is necessary to control for between-station differences in the indices. This is achieved by expressing each index as \( z \)-scores over the 17-year record for individual stations prior to amalgamating \( z \)-scores for all stations into the four indices. Regime shape and magnitude classes are identified for the 2,397 station-years using the same statistical procedures as for regionalisation.
WESTERN EUROPEAN REGIME REGIONS

Regime shape

To understand the spatial structure of western European river flows, regime shape and magnitude were classified using long-term (1974–91) mean monthly runoff for 141 stations. No attempt is made to spatially interpolate results or draw regional limits. The emergent regional patterns are discussed in relation to findings of previous regionalisation studies.

Six shape classes were identified with differences in flow seasonality (Figure 4). The six long-term shape regimes are as follows:

- Region A: January peak and secondary March peak, with gradual rising and recession limbs (17 stations);
- Region B: December–March broad peak (59 stations);
- Region C: December–April broad peak (42 stations);
- Region D: April peak with gradual rising and steeper recession limb (16 stations);
- Region E: April–May peak with sharp rising and recession limbs (7 stations);
- Region F: May–June peak with sharp rising and recession limbs (20 stations).

Figure 5 shows the location of stations within each of the six regime regions. A summary of the geographical characteristics of these regions is presented in Table 1. Broadly, regions appear to be associated with different latitudinal and altitudinal environments. Spatial variation in average annual rainfall (AAR) seems to have limited influence on the regional expression of long-term shape classes (Table 1). Figure 5 and Table 1 show the six classes group in particular geographical areas, with a progressive delay in the timing of flow peaks towards the southeast (i.e. January peak in the north–west, to June peak for higher altitude Austrian basins). This gradient is likely to reflect change in the dominant processes affecting streamflow generation from precipitation-led processes in the north and west to snowmelt-led processes in the south and east. Many upland Scandinavian basins have the same long-term regime (i.e. May–June peak) as the Austrian basins most likely due to the increased dominance of snow/ice-melt-led processes.

All 141 stations may be classed as having Pardé’s (1955) ‘simple’ regime type, because one distinct period of high flow and one distinct period of low flow can be identified. Regions A, B and C could be considered as Pardé’s (simple) ‘oceanic rainfall-evapotranspiration’ regime type, indicating rainfall is well distributed over the whole year but higher summer temperatures result in increased evapotranspiration and summer low flows. Regions E and F are akin (but peak earlier) to Pardé’s ‘mountain snowmelt’ regime type. The regime classification presented herein adds detail of sub-seasonal variations to Pardé’s early classification scheme. Some similarity exists between these results and Beckinsale’s (1969) World regime map based on Köppen climate divisions (Köppen 1936); however, limited comparisons are possible since Beckinsale (1969) described very broad seasonal patterns, with shape and magnitude undifferentiated.

More recently, Arnell et al. (1993) identified 13 European river flow regime types reflecting variations in the timing of high and low flows. This is the only other contemporary, quantitative study of the timing of the river flow regime at the European-scale. Their classification concluded that most of western Europe has the same long-term Atlantic regime type (i.e. winter maxima and late summer minima). In contrast, Figures 4 and 5 show a 4-month lag in the timing of peak river flows from the UK to central Europe, illustrating clearly variation within the Arnell et al. (1993) Atlantic group. Arnell et al. (1993) showed Scandinavian flow regimes to have high spatial variability due to diverse interactions between maritime, continental and topographical influences. This study supports this finding, in part, by objectively identifying three different regime types for Scandinavia, but results also suggest that there are other mountain areas within Europe (e.g. Austria) where regimes show a similar high level of variability (Figure 5). Nonetheless, identifying geographical regions which contain the greatest spatial variability depends on the representativeness of selected stations; therefore it is perhaps only possible to conclude that the areas with the most varied topography, hence potential for a wide range of hydrological processes (e.g. snow/glacier melt, rainfall or evaporation-dominated) show greatest spatial variation in regimes (Kingston et al. 2009).

Arnell et al. (1993) found that east of the Elbe basin (northeast Germany) flow regimes were increasingly...
controlled by spring snowmelt, with just one maxima occurring in the spring on both the plains and at altitude. Haines et al. (1998) present similar findings with flow regimes changing to an early spring peak to the east of this point, as spring rainfall and snowmelt become increasingly important. However, spatial patterns presented within Figure 5 suggest a northwest–southeast transition across continental Europe, rather than a simple west–east switch as suggested by these earlier studies. The number of stations considered by Arnell et al. (1995) is not stated; but the resolution of Haines et al.’s (1988) study is lower than that presented here, which may explain the apparent
differences. However, results may also differ due to different analytical methods. Haines et al. (1992) analysed regime shape and magnitude together, possibly masking some variations in these individual regime components, whereas the classification used by Arnell et al. (1993) allows stations to be grouped in the same broad region despite the maximum and minimum flow varying by several months.

**Regime magnitude**

Five magnitude regimes were identified and described using the indices presented in Figure 6:

- **Regime 1** Low mean and seasonality with the lowest values for all indices (77 stations);
- **Regime 2** Low-intermediate mean and seasonality with second lowest values for all indices (33 stations);
- **Regime 3** Intermediate mean and high seasonality with high maximum and standard deviation and low minimum (10 stations);
- **Regime 4** Intermediate-high mean and intermediate seasonality with intermediate minimum, maximum and standard deviation (16 stations);
- **Regime 5** High mean and seasonality with the highest values for all indices (5 stations).

Figure 7 illustrates the spatial distribution of stations within each of the magnitude regime classes. The geographical characteristics of each region are summarised in Table 2. It is not possible to describe further these spatial patterns in relation to specific basin geology or land use due to paucity of ancillary data (CEH 2000); however, discernable patterns are emergent. Notably, there appears relatively strong commonality between AAR and regime magnitude classes (Table 2). The stations in Region 1 (low) are the most dispersed, being located across a wide latitudinal area. Region 1 stations are predominantly found at low altitudes (<543 m), with the exception of the Spanish stations (630–1,278 m). The low AAR rainfall at these stations (Table 2) is likely to yield low flow magnitudes throughout the year. The low-intermediate (Region 2) and intermediate-high

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**Table 1** Geographical characteristics of six shape regime regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Latitude (N)</th>
<th>River gauge altitude (m)</th>
<th>Average annual rainfall (mm)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region A</td>
<td>51–59</td>
<td>4–211</td>
<td>995–3,350</td>
<td>Predominantly western UK. One station in southern Norway</td>
</tr>
<tr>
<td>Region B</td>
<td>46–58</td>
<td>3–284</td>
<td>592–1,497</td>
<td>Basins with very low altitudes, situated in the British Isles, Belgium, northern Germany, Denmark and Poland</td>
</tr>
<tr>
<td>Region C</td>
<td>42–53</td>
<td>4–927</td>
<td>528–1,718</td>
<td>Low altitude basins in the UK, low-intermediate altitude catchments on the European mainland (28–927 m)</td>
</tr>
<tr>
<td>Region D</td>
<td>38–56</td>
<td>58–1,278</td>
<td>596–1,791</td>
<td>Zonal swathe from Spain, France, Switzerland, Germany, Austria, Czech Republic to Belarus</td>
</tr>
<tr>
<td>Region E</td>
<td>46–64</td>
<td>15–655</td>
<td>510–2,380</td>
<td>Small number of stations in Norway, Finland, Austria and Slovakia</td>
</tr>
<tr>
<td>Region F</td>
<td>44–71</td>
<td>15–1,097</td>
<td>525–3,300</td>
<td>Predominantly Austria and Norway. Single stations in France, Sweden and Finland</td>
</tr>
</tbody>
</table>

*Characteristics provided only for basins within FRIEND-EWA metadata catalogue (CEH 2000).
(Region 4) magnitude regimes are characteristic of the western UK, Austrian and Swiss basins in particular. These stations are located at similar latitudes and altitudes, but the higher magnitude and more seasonal flows of Region 4 stations are associated with higher AAR (Table 2). Region 3 (intermediate mean and high seasonality) covers a limited geographical area: Norway, Sweden and Finland. These stations are located at relatively low altitudes (<700 m) with AAR ranging from 525 to 1,690 mm. This magnitude regime is most likely caused by the high latitude of these stations, at which low winter temperatures result in snow/ice storage in winter resulting in low flows, but high flows during the spring/summer melt, hence high flow seasonality. High magnitude Region 5 includes one Austrian, three Norwegian and one Scottish station. These few basins are predominantly low-lying, with high AAR (2,060–3,300 mm) producing relatively high flows year-round. These findings are considered in relation to the few previous studies of the spatiality of European river flow magnitude.

The Assessment of the Regional Impacts of Droughts in Europe (ARIDE) project identified 19 groups of European basins with simultaneous periods of streamflow below a daily varying \( Q_{90} \) threshold of water deficit (Stahl & Demuth 2000). The regions identified in this paper and the ARIDE classifications show little similarity, emphasising that streamflow deficiency is only one aspect of regime
magnitude. The results presented herein show many similarities with global classification of river flow regimes of Haines et al. (1998) since Germany, southeast France, Switzerland and part of Austria are all described by Haines et al. (1998) as having non-seasonal regimes, with all months lying in the range 5–12% of annual flow. Similarly, Figures 6 and 7 suggest a range of 2–17% at stations within these countries. Long-term regime magnitude (Figure 7) is more spatially stable than long-term regime shape (Figure 5) due to differences in the driving processes. Long-term regime shape appears responsive to a greater number of factors (notably basin geology, presence of snow/glaciers and precipitation and evaporation regimes); whereas, long-term regime magnitude is dependent largely upon AAR, which shows less spatial variation.

INTER-ANNUAL REGIME VARIABILITY (STABILITY)

Regime shape and magnitude were classified using monthly mean flow across 17 years at 141 stations (i.e. 2,597 station-years). These regime classes provide the basis for assessing inter-annual regime stability at the pan-European scale. The regionalisation results structure analyses of between-and within-region inter-annual regime variability. As stated in the ‘Data and method’ section, the long-term and inter-annual regime classes are not the same; it must be noted that magnitude classes for regionalisation are absolute (between-stations) whereas magnitude classes for annual regimes are relative (between-years at a station). Therefore, summary statistics for the annual regime magnitude classification are presented for objectively selected examplar stations within each region. To avoid confusion with long-term regimes (regions), the prefix ‘I’ is added to denote inter-annual regime classes (IA, IB etc.; I1, I2).

Regime shape

Six inter-annual regimes were identified with differences in flow seasonality (Figure 8):

Regime IA November–January broad peak (504 station years);
Regime IB January peak with sharp rising and recession limbs (321 station years);
Regime IC February peak with sharp rising and recession limbs (421 station years);
Regime ID March peak with sharp rising and recession limbs (279 station years);
Regime IE April peak with gentle rising and recession limbs (463 station years);
Regime IF May–June peak with sharp rising limb and gentle recession limb (409 station years).

Figure 9 illustrates inter-annual variability of regime shape across Western Europe. In individual years, certain regime types are more prevalent, but are never totally dominant. For example, many stations in the UK, Belgium,
Denmark, Germany and Czech Republic show similar shape regimes in 1975 (IB), 1976 and 1979 (IC) and 1982 (IE). Studies which report year-to-year variations in the timing of seasonal rainfall and river flows are limited, making it difficult to cross-reference these results with the literature. However, a distinct onset to the 1975 hydrological year drought, in late January 1976 was identified (Zaidman et al. 2001), which corresponds with the timing of the peak and sharp recession limb of Regime IB.

There is some evidence that stations from the same region show similar patterns of inter-annual variability, for example Region A in the years 1977–82, 1984, 1986–87;
Figure 9 | Spatial distribution of inter-annual shape regime classes for each hydrological year from (a) 1974 to (q) 1990. (Continued.)
Figure 9 | Continued.
Figure 9 | Continued.

- (m) 1986
- (n) 1987
- (o) 1988
- (p) 1989
- (q) 1990

Key:
- □ Regime IA
- ■ Regime IB
- ○ Regime IC
- ● Regime ID
- △ Regime IE
- ▲ Regime IF
Region D in 1977–78, 1984 and 1986–87; Region E in 1984; and Region F in all years (Figure 10). Inter-annual regimes are less spatially coherent within Regions B and C. This greater regime variability within Regions B and C may be explained by the wider, more diverse geographical area over which these stations are spread (Figure 5). This suggests the long-term regime of these regions maybe equifinite: that is the long-term average (composite) response may be similar but the underlying driving processes may differ. Alternatively, this may be a consequence of the long-term averaging procedure masking spatially variable year-to-year regime dynamics.

The results also indicate that most regions tend to be dominated by particular inter-annual regimes and that the dominant regimes vary between regions (e.g. Regime IA in Region A; Regime IE in Region D; Regimes IE and IF in

![Figure 10](https://iwaponline.com/hr/article-pdf/44/5/809/370519/809.pdf) | Regional frequencies of flow regime shape.
Region E; Regime IF in Region F; Figure 10). In Region B, Regimes IA, IB, IC and ID all occur with high frequencies, as do Regimes IB, IC, ID and IE within Region C (Figure 10). The frequencies and equitability of regimes occurring at each station were calculated to quantify inter-annual regime dynamics each within regions (for details of methods refer to Bower et al. (2004)). Equitability is measured on a scale from 0 to 1; higher values indicate greater equitability (evenness). The number and equitability of regimes for each station are grouped by region and presented in Table 3. In Regions A and E, equitability is at an intermediate level (0.38 ≤ E ≤ 0.75) compared with other regions. For Region E the equitability distribution is skewed by one station having a relatively high equitability at the upper limit of this range. This indicates that the regime at stations in these regions do vary, but not to the extent of that observed at some of the stations in other regions, particularly Regions B and C (0.58 ≤ E ≤ 0.97). Within Regions A and E year-to-year variations in inter-annual regime type are likely to be caused by year-to-year variations in the timing of seasonal rainfall and the timing of snow/ice-melt, respectively. Region D has a high range of equitability (0.12 ≤ E ≤ 0.96) due to some stations in this region having stable regimes, whereas the regime at other stations are very unstable. However, although many stations in Region D have the same long-term regime (Figure 10), for some stations this will represent the regularity of snow/ice-melt, while at others the long-term an regime simply masks high year-to-year variability. Regime frequency and equitability are lowest at stations in Region F (0 ≤ E ≤ 0.69) due to the persistence of Regime IF. Stations in Region F are mainly located at high altitudes within Austria and Norway (Table 1), suggesting the regularity of seasonal snow/ice storage and melt yield year-to-year regime stability. Similarly, Krasovskaia et al. (1993) found snow-dominated basins show greater stability than rain-dominated basins. However, even within this otherwise stable region regime equitability is relatively high at two stations in this region: the Etneelv at Stordalsvatn (Norway) and the Raab at Takern II (Austria) with equitability values of $E = 0.53$ and $E = 0.69$, respectively. At these stations, Regime IF dominates but several of the earlier peaking regimes also occur (for 6 out of 17 and 10 out of 17 of the years, respectively). Only 11% of stations experience the full suite of six inter-annual regime types. These stations are found in Regions B, C, D and E. This instability is shown by the higher regime frequency and equitability at the upper limits of the range for stations within these regions (Table 3), possibly caused by the more variable timing of seasonal rainfall.

The dominance of particular inter-annual regimes and evidence for similar patterns of inter-annual variability within regions, both on a regional basis, suggest that the regions are a good basis for investigating and understanding inter-annual regime dynamics. Nevertheless, the regimes observed at stations within these regions do vary, and the differences are greater in some regions than others.

### Regime magnitude

Five inter-annual regimes were evident, which may be described using the indices (Figure 11):  

Regime I1 Low mean and seasonality with low values for all four indices (677 station years);
Regime I2 Low-intermediate mean and seasonality with low-intermediate values for all four indices (650 station years);

Regime I3 Intermediate mean and high seasonality with high maximum and standard deviation and low minimum (414 station years);

Figure 11 | Box and whisker plots of (a) mean, (b) standard deviation, (c) minimum and (d) maximum monthly mean values for inter-annual magnitude classes at centroid stations for Regions 1 (Stepenitz at Boerzow, Germany) and 5 (Nordelva at Krinsvatn, Norway).
Regime I4 Intermediate-high mean and intermediate seasonality with intermediate minimum, maximum and standard deviation (457 station years);
Regime I5 High mean and intermediate-high seasonality, with high minimum and maximum and intermediate-high standard deviation (199 station years).

The centroid station from each magnitude region was selected as being representative of each long-term region. Equation 1 was used to identify the centroid station from each magnitude class. (i.e. lowest $d$-value).

$$d = \left| \frac{\text{Zmean}(Rn)}{-} - \frac{\text{Zmean}(Rn)}{-} \right| + \left| \frac{\text{Zstddev}(Rn)}{-} - \frac{\text{Zstddev}(Rn)}{-} \right| + \left| \frac{\text{Zmin}(Rn)}{-} - \frac{\text{Zmin}(Rn)}{-} \right| + \left| \frac{\text{Zmax}(Rn)}{-} - \frac{\text{Zmax}(Rn)}{-} \right|$$

(1)

where $d$ is the standardised distance from cluster centroid, $\text{Zmean}(Rn)$ is the mean index value for each region ($Rn$; e.g. $\text{Zmean} = z$-score of mean value) and $\text{Zmean}(Rn)$ is the observed index value for each region ($Rn$).

Due to space limitations, the centroid station for Regions 1 and 5 only are presented in Figure 11. As the absolute magnitude of flow at a station increases (from Region 1 to 5) so does the absolute magnitude of each inter-annual regime. For example, the mean of the monthly runoff for Regime I1 at Stepnitz at Boerzow, Germany (Region 1) is 18.2 mm month$^{-1}$ compared to 129.6 mm month$^{-1}$ at the Nordelva at Krisvatn, Norway (Region 5).

Figure 12 maps the inter-annual regime magnitude for each hydrological year of analysis (1972-1990). As for regime shape, in individual years certain regime types are more prevalent but never totally dominant (e.g. Regime I1 in 1975, 1989–1990; Regime I2 in 1977–1978, 1985; and Regime I4 in 1980). Interestingly, lower magnitude regimes (i.e. Regimes I1 and I2) more frequently persist over larger geographical areas than higher magnitude regimes (i.e. Regimes I4 and I5; Figure 12). This is possibly due to the nature of the climatological conditions leading to the development of low flows, that is, dry high pressure anticyclone conditions tend to persist over larger geographical domains than the low pressure, cyclonic systems associated with wetter conditions. Results indicate that magnitude regimes show less spatial coherence than shape, with a single regime only dominating 75% of stations within a single region on average 1 out of 17 years, compared with 5 out of 17 years for regime shape (Figures 10 and 13). However, for individual years stations with the same magnitude regime often span across regions (Figure 13). This suggests relative variations in regime magnitude at a station may occur irrespective of spatial variations in the absolute regime magnitude (i.e. regions). In 1974, 1976, 1980–1982, 1986–1987 and 1989, the high flow inter-annual class (15) magnitude regime occurred within limited geographical areas spanning several regions (Figure 12). Nevertheless, for low flow inter-annual class (11), there is greater regional consistency (e.g. Regions 1, 2 and 4 during years 1975 and 1988–1991; Figure 13). The drought event which occurred in the 1975 hydrological year was highly spatially and temporally coherent, with the most intense streamflow droughts occurring in southern England and northern France (Jones & Conway 1997; Zaidman et al. 2001). Central parts of Europe experienced only severe streamflow droughts during June, July and August 1976 when there was negligible precipitation across large parts of Europe. The 1988–1991 drought was much less spatially and temporally coherent compared to the 1975 drought (Figure 12), being characterised by a series of shorter and less severe droughts (Zaidman et al. 2001). Regions 3 and 5 (stations mainly located in Norway, but with single stations in Sweden, Finland, Scotland and Austria; Figures 7 and 13) display different regimes in these years. On closer inspection, there appears to be further evidence for different patterns of variation in Regions 3 and 5 compared with 1, 2 and 4. For instance, in 1976–1977, and 1979 the relative frequency of Regime I1 is higher in Regions 3 and 5, whereas in 1983 and 1988 the frequency of Regime I1 is lower; in 1975 the relative frequency of Regime I5 is higher, whereas in 1987 the frequency of Regime I5 is lower (Figure 13). These findings are largely consistent with those of Krasovskia et al. (1995) and Arnell (1994) who found that seasonal (3 monthly averages) river flows within the Nordic countries tend to follow a different pattern of variability to the rest of Europe. However, this is a broad generalisation since the variability displayed at individual Nordic stations in 1976–1977 in some cases is similar to stations in the rest of Europe. For
Figure 12 | Spatial distribution of inter-annual magnitude regime classes for hydrological year from (a) 1974 to (q) 1990. (Continued.)
Figure 12 | Continued.
Figure 12 | Continued.
instance, in 1976–1977 the low magnitude Regime I1 is not only evident in the Nordic countries, but also much of Germany and the British Isles (Figure 12). In addition, Figure 12 provides some evidence that years with high and low magnitude regimes have a tendency to cluster temporally (e.g. I1 from 1988 to 1990; I4 from 1979 to 1980).

**CONCLUSIONS**

This paper has examined spatio-temporal variations of river flow regimes across western Europe. The analyses and interpretation allow several conclusions to be drawn relating to (i) long-term flow regime regions and (ii) inter-annual flow regime dynamics.

When assessing spatial and temporal variations in river flow regimes, it is important to identify both the size (magnitude) and timing (shape) of discharges over the annual cycle. Previous studies have been predominantly concerned with spatial variations in the timing of flows, but temporal investigations have focussed on the magnitude of flow, yielding an inconsistent view. In this paper, a multivariate methodology was used to separately classify regimes according to their 'shape' and 'magnitude'. The shape classification identifies stations (for regionalisation) or station-years (to assess inter-annual regime variability) with similar regime forms,
regardless of magnitude; whereas the magnitude classification identifies stations or station-years with similar regime magnitude regardless of timing. However, two important points to note are: (1) regime classes are not interchangeable between long-term and station-year classifications, as analyses are performed on different input data matrices; and (2) magnitude classes for regionalisation identify absolute differences between stations while magnitude classes for regime stability identify relative inter-annual variations at a station. Together, these two classification modes characterise spatial and temporal regime dynamics.

The classification method is particularly useful for identifying large-scale patterns in regimes and their between-year stability. Interpreting these results in relation to large-scale variations in climate variables and/or physiographical characteristics is necessary to understand and predict possible alterations to hydrological regimes as a consequence of climate and/or land-use changes. Analysing linkages where one or more parameters are described as a nominal classification presents a challenge; but approaches have been developed to quantify the relationship between nominal classifications such as the sensitivity index of Bower et al. (2004) or multiple DFA (Hannah et al. 2006).

**Long-term flow regime regions (shape and magnitude)**

To understand the spatial structure of western European river flows, regime shape and magnitude were classified using long-term (1974–1991) mean monthly runoff for 141 stations. Six long-term shape regime regions were classified. These classes identify a clear lag in the timing of the flow regime peaks in a south-easterly direction across western Europe (from a January peak with a secondary March peak in the west of the UK, to a May–June peak in the highest Austrian basins). This gradient reflects a change in the dominant processes affecting streamflow generation from precipitation-led processes in the north and west to snow/ice-melt-led processes in the south and east. Many of the Scandinavian basins have the same long-term regime (i.e. May–June peak) as the Austrian basins also likely due to the increased dominance of frozen water storage-release processes. The classification approach used has been able to more precisely characterise the timing of seasonal flow variations, when compared with broad discriminating criteria often used in previous studies which may mask subtle, but important, flow variations. The six shape regions identified are more even in size than the thirteen identified by Arnell et al. (1993), where their Atlantic regime type covers much of north-western Europe. Results presented herein show a 4-month lag in the timing of peak river flows from the UK to central Europe, which clearly illustrates the variation within the Atlantic group of Arnell et al. (1993). The areas with the most varied topography, and hence the potential for a wide range of hydrological processes (e.g. snow/glacier melt, rainfall or evaporation-dominated) show the greatest spatial variation in regimes.

Five long-term magnitude regime regions were identified, related to differences in altitude, latitude and AAR. Stations with low magnitude regimes are most dispersed, occurring across a wide latitudinal range, but tend to be located at low altitudes with low AAR. Low-intermediate and intermediate-high magnitude regimes are characteristic of western UK, Austrian and Swiss basins. Intermediate regimes with high seasonality are found in a limited geographical area: Norway, Sweden and Finland, due to the frozen water stores annual compensation effect (winter snow/ice accumulation and spring/summer melt water generation). High magnitude regimes are characteristic of one Austrian, three Norwegian and one Scottish station. These few basins are predominantly low-lying with high AAR producing relatively high flows year round.

**Inter-annual flow regime (shape and magnitude)**

Regime shape and magnitude were classified using monthly mean flow across 17 years at 141 stations (i.e. 2,397 station-years). These regime classes provide the basis for assessing inter-annual regime stability at the pan-European scale, rather than considering only regime magnitude which has tended to be the focus of previous studies. The regionalisation results structure analyses of between- and within-region inter-annual regime variability.

Six inter-annual shape regimes were identified. In individual years, certain regime types are more prevalent, but never totally dominant. There is also some evidence that stations from the same region show similar patterns of inter-annual variability. Most regions (A, D, E and F) tend to be dominated by particular inter-annual regimes and the dominant regime varies between regions. Regime
frequency and equitability are lowest at stations in Region F. Stations in Region F are mainly located at high altitudes within Austria and Norway, suggesting the regularity of seasonal snow/ice storage and melt yield year-to-year regime stability. Flow regime shape at lower altitudes shows greater year-to-year variability, likely due to greater year-to-year variability in the timing of seasonal rainfall (cf. meltwater generation). However, in addition to the consistent regional patterns identified, there are also some within regional differences. Thus, although the long-term average regime response at stations (particularly within Regions B, C and D) may be similar, it must be recognised that the driving processes at individual stations may differ. These findings advance understanding of the inter-annual variability of the timing of the flow regime at the European scale, which previously was only relatively well advanced for the Nordic countries.

Five inter-annual magnitude regime types were identified to describe the regime magnitude during individual years. As for regime shape, in individual years certain regime types are more prevalent but never totally dominant. The lowest magnitude regimes more frequently persist over larger geographical areas than the highest magnitude regimes. This is possibly due to the nature of the climatological conditions leading to their development because dry, high pressure anticyclone conditions tend to persist over a wider area than low pressure, cyclonic systems which can generate high rainfall totals and higher magnitude regimes. Inter-annual regime magnitude shows less spatial coherence than regime shape. However, for individual years stations with the same magnitude regime often span across regions, suggesting relative variations in regime magnitude at a station may occur irrespective of spatial variations in absolute regime magnitude. Results indicate that Regions 1, 2 and 4 display different patterns of variation to Regions 3 and 5, and there is evidence that years with high and low magnitude regimes have a tendency to cluster.

These shape and magnitude regimes together yield a more holistic description of the spatial and temporal variability of regimes than previously undertaken at the pan-European scale. They also inform that spatial and temporal variations in flow shape do not follow the same patterns as for the magnitude of flow, and vice versa. This implies that both aspects of the regime need to be considered when investigating current and potential future water stress.

ACKNOWLEDGEMENTS

D. Wilson (née Bower) was funded by NERC studentship GTNER/S/A/2000/03956. This research is a contribution to the UNESCO-IHP FRIEND-Water (Flow Regimes from Experimental and Network Data) crosscutting theme. G. Rees and I. Akram at the Centre for Ecology and Hydrology (CEH), Wallingford extracted daily river flow time-series from the UNESCO-IHP FRIEND European Water Archive. Additional river flow time-series were supplied by the Global Runoff Data Centre.

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First received 23 December 2011; accepted in revised form 18 May 2012. Available online 9 November 2012.