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## Technical Report No. 21

# METHODOLOGY FOR ANALYSING THE SPACE-TIME DEVELOPMENT OF LARGE-SCALE FLOODS AT THE RIVER BASIN, REGIONAL AND CONTINENTAL SCALES



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Photo cover: Flood on the Thames, near Wallingford

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# 1 Introduction

Flooding can have many different causes: fluvial flooding is when the river discharge is very high, leading to high river levels and the water flowing outside the river channel and inundating adjacent areas; pluvial flooding relates to very large amount of water due to heavy rainfall runoff on the catchment's slopes outside any river channel network; costal flooding is due to high sea/lake water levels (due to high tide, surge or other combinations) causing the costal line to recede; groundwater flooding occurs when the water table reaches the ground surface in place it does not normally do so, causing the appearance of new springs. Some flood events result from a combination of causes, for example high tide and sea storm surge occurring simultaneous with heavy rainfall on the lowland catchment could result in severe flooding at the river mouth and upstream of the tidal limit. In WATCH WB4, only the discharge values of fluvial flooding are considered as flood events.

Fluvial flood events are exceptionally high river discharges, associated with water levels sometimes higher than the river bank and leading to inundations. Over-bank (outbank) flow can occur only on a part of a catchment, for example downstream of a confluence of two rivers experiencing high flows at the same time. Fluvial flooding can also occur during a very limited time, for example following a short but exceptionally heavy rainfall, generally localised as due to convective rainfall, or breach of reservoirs leading to a sudden increase in the discharge: the floods are then called flash-floods in reference to the speed at which they occur. In this report, large-scale floods can be understood as flood events of large magnitude (possibly *cum* large spatial extent) which can be complemented by a measure of regional synchronicity and coherence of flood-generating mechanisms. Flash flood events are not included within the analysis, unless otherwise specified.

When studying the variation of river stages (the water level in a river) it is possible to focus on the peak values, when the stage level and associated river discharge are at the highest. One definition of flood events refers to the highest recorded levels (and by extension, discharge values) and the days they occur. It is this definition of flood event and flood peak that will mostly be followed in this report, unless otherwise specified. Note that the spatial extent in terms of inundated area will not be studied in WATCH.

High river discharges can be caused by various combinations of extreme conditions. Fluvial floods may be caused by several mechanisms, such as: intense / long-lasting precipitation, snowmelt, flow obstruction (e.g. ice jam, landslide), dam failure, and storm surge. Heavy rainfall over short durations, deep snow cover rapidly melting and even moderate rainfall on ice, frozen ground or saturated soil can all contribute to a rapid and large runoff. From the records of peak discharge from major runoff events and complementary information such as rainfall measurements or atmospheric circulation patterns prior to a flood event, it is possible to better understand some of the main mechanisms leading to the generation of floods.

This report describes ways to conduct such analysis. After a definition of flood events and their quantification in terms of frequency under stationary (Section 2) and non-stationary (Section 3) conditions, methodologies to analyse the antecedent conditions (rainfall: Section 4 or weather types: Section 5) are suggested. Finally, a regional flood frequency index is developed and tested on two contrasting regions of the UK (Section 6) and two methodologies are suggested to compile flood catalogues (Section 7).

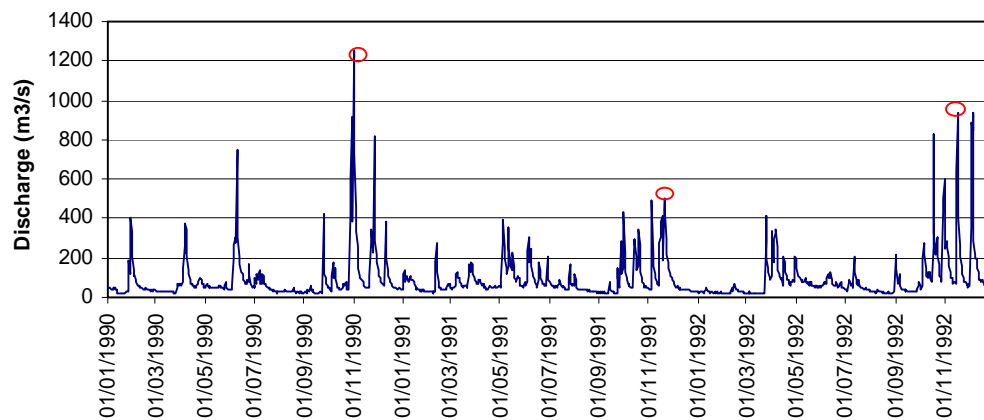
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## 2 Flood event definition

A flood event can be defined as a high river flow, exceeding a pre-defined threshold, possibly related to a damage. There are two essential approaches for automatic sampling of flood events from discharge time series. They are briefly exposed in this section.

### 2.1 Annual Maxima

The Annual Maxima (AM) technique consists in sampling, for every single year (calendar or water year) of the discharge time series, the largest event as illustrated in Figure 1. AM can be selected from the original daily flow data (Kundzewicz et al., 2005). When river discharge time series with high temporal resolution are available, the samples are close to real flood peaks (generally called ‘instantaneous flood peaks’). However, more often discharge is provided at a daily time step, representing the discharge observed in particular time instant (regular sampling hour, once a day, possibly more frequently, when alarm level is exceeded), the AM daily series are considered as proxy for flood events series. Some relationships can be established between daily flood events and instantaneous flood peaks.



**Figure 1. Illustration of the definition of an Annual Maxima (AM) flood series for the River Soca at Streda nad Bodogrom (Slovakia).**

The main disadvantage of this technique is that it can sample events which are not major floods, for example during relative dry year (e.g. the year 1991 in Figure 1), while other events of greater magnitude can be disregarded when occurring during a relatively wet year, when an even greater flood had occurred (e.g. the year 1990 in Figure 1). However, AM series are common in hydrological databases and the AM technique is very widely used (Robson and Reed, 1999), the approach being straightforward and based on a well established concept.

Analysing statistically the AM series allows to identify relationships between flood magnitude and frequency using the extreme value theory and probability distribution function of the AM as defined by:

$$F_x(Q) = \text{Prob}(X^* < Q) = 1 - \frac{1}{T_{QAM}} \quad \text{and} \quad T_{QAM} = \frac{1}{1 - F_x(Q)}$$

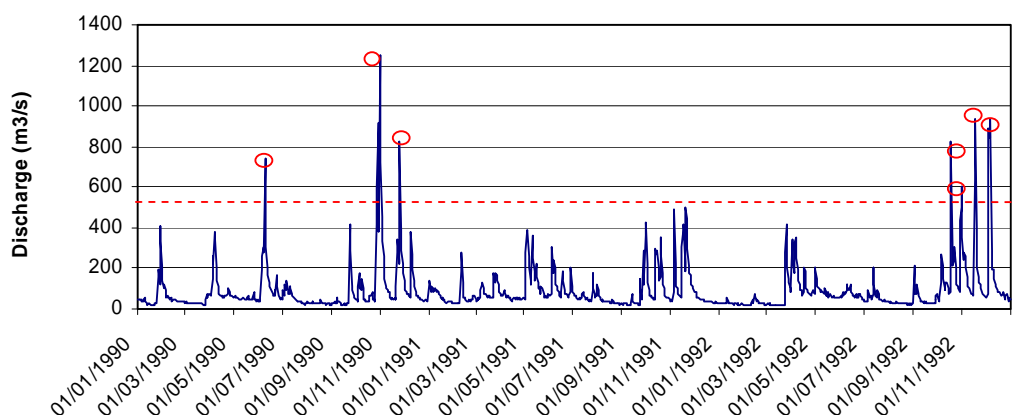
where  $X^*$  is the AM of the random variable  $Q$ , and  $T_{QAM}$  is the return period of the value  $Q$ .

For AM series,  $T_{QAM}$  is the average interval (in years) containing one or more flows exceeding  $Q$ . According to the theory of extremes,  $F_x(Q)$  can be described by the Generalised Extreme Value (GEV) distribution.

The QMED is the median annual maximum flood, and is the flood that is exceeded on average “every other year” (Robson and Reed, 1999). It is derived from the flood maximum series by ordering the annual maxima and taking the middle ranking value (or the arithmetic mean of the two central values in case of even number of annual maxima). The QMED is the flood index recommended by the UK Flood Estimation Handbook (Robson and Reed, 1999).

## 2.2 Peak-Over-Threshold

The second main automatic sampling technique aims to select all the highest independent flood events recorded (Svensson et al., 2005). The *Peak-Over-Threshold* (POT) series (also called ‘Partial Duration Series’, PDS) consists in all flood peaks above a certain threshold (i.e. possibly several events in one year and none in another year), and provides a more complete description of flood behaviour than AM series described above. In generating a POT sample, it is important to insure that the selected flood peaks are all independent, i.e. the sampling does not select two peaks which relate to the same larger flood mechanism. An example of the sampling of a POT series is illustrated in Figure 2. By contrast with the AM sampling from the same daily discharge series (Figure 1), no POT is sampled in 1991, while three independent flood events are selected in 1990. Note that for 1992, additional criteria of independence might be necessary to avoid selecting flood peaks which might result from the same event.



**Figure 2. Illustration of the definition of a Peak Over Threshold (POT) flood series for the River Soca at Streda nad Bodogrom (Slovakia).**

The main disadvantage of the POT series is the absence of many long records in hydrological databases, while some flood records of the form of AM are sometimes accessible. Its main advantage is that it allows to capture all major events much more efficiently than the AM sampling. In particular, the use of POT series allows an estimate of the trend in the frequency (counts) of floods rather than just their magnitude, by calculating the number of POTs that occur each year and investigating the tendency in this series.

The POT series are associated with return period  $T_{QPOT}$  which is the average interval between floods exceeding the value  $Q$ .  $T_{QPOT}$  is the true and rigorous return period (as opposed to  $T_{QAM}$ ) and the links between return periods of both series is given by:

$$\frac{1}{T_{QAM}} = 1 - \exp\left(-\frac{1}{T_{QPOT}}\right)$$

The probability distribution of a POT series follows a Generalised Pareto Distribution (e.g. Bayliss and Jones, 1993; Naden, 1992).

### 2.3 Different POT samples

Depending on the value chosen for the sampling threshold, it is possible to select more POT values than number of years of the original time series. When the threshold is such that exactly N peaks are selected for N years of record (often called POT1 sample) the sample is called *Annual Exceedance Series*, which is a special case of the POT series (Shaw, 1983).

There is a direct link between the chosen threshold and the size of the flood sample: a high threshold will insure that only the very extreme events are selected, but will lead to reduced sample size. This can be critical in particular for those catchments where the hydrological record length is short. On the other hand, lowering the threshold has the advantage of increasing the sample size and thus, allowing more confidence in the statistical analysis undertaken, but may also include events that would otherwise be considered as 'middle-size floods'.

### 3 A non-stationary index flood model for extreme distribution analysis

#### 3.1 Methodology

In this section we describe a relatively simple tool to assess the regional distribution of extreme precipitation and discharge. The method was originally proposed by (Hanel et al., 2009) for analysis of precipitation extremes in transient regional climate model simulations. The climate change assessment (cf. Solomon et al., 2007) often relies on assumptions of stationarity within a fixed time-slice periods, e.g. of 30-year length (interval called *climatological standard normal*) and considers only changes between such (stationary) periods for present and future climate. However, non-stationarity was reported to be an important factor in observed runoff time series (Cunderlik and Burn, 2003) and will be also essential for the assessment of future hydrological extremes in transient climate model data or in situations when the trend within the time-slice cannot be simply ignored.

Regional frequency analysis is a well established approach for reducing uncertainty related to inference on distribution of extreme rainfall and river discharge. A very important method of regional frequency analysis is the index flood method. The idea behind this method is that the variables within a homogeneous region are identically distributed after they are scaled with a site-specific factor, the index flood. As a consequence, the index flood method can be used to assess the regional distribution of extremes and their changes (Hosking and Wallis, 1997).

Various probability models have been used to describe the distribution of precipitation and runoff extremes. The suggested non-stationary index flood model employs the generalized extreme value (GEV) distribution, defined by the distribution function

$$F(x) = \exp\left\{-\left[1 + \kappa\left(\frac{x - \xi}{\alpha}\right)\right]^{-\frac{1}{\kappa}}\right\}, \quad \kappa \neq 0,$$
$$F(x) = \exp\left\{-\exp\left[-\left(\frac{x - \xi}{\alpha}\right)\right]\right\}, \quad \kappa = 0,$$

with  $\xi$ ,  $\alpha$  and  $\kappa$  being the location, scale and shape parameter, respectively. In the index flood method, the dispersion coefficient  $\gamma = \alpha/\xi$  is considered. This parameter is comparable with the coefficient of variation. The GEV distribution has been shown to be appropriate for analysis of the observed and RCM simulated precipitation Annual Maxima (AM) (Ekström et al., 2005; Kyselý and Pícek, 2007) and observed AM discharges (Merz and Blöschl, 2004; Stedinger and Lu, 1995). Note, that the index flood model can incorporate other probability models, such as the Generalized Pareto distribution (GPD) for the analysis of the Peak-Over-Threshold series (Coelho et al., 2008).

Let  $X(s)$  be the annual or seasonal maxima (of precipitation or discharge) at site  $s$ . The  $T$ -year quantile  $Q_T(s)$  of the variable  $X(s)$  can be expressed as

$$Q_T(s) = \mu(s)q_T$$

where  $\mu(s)$  is the at-site scaling factor (the index flood) and  $q_T$  is a regional dimensionless quantile function. In the standard index flood procedure, the mean or median of  $X(s)$  is usually used as the index flood. For the non-stationary index flood model, it is convenient to use the location parameter  $\xi$  of the GEV distribution instead to avoid the dependency of the index flood on the GEV scale and shape

parameters. Adding the time-dependency and using the location parameter  $\xi(s,t)$  as the index flood, the  $T$ -year quantile at site  $s$  in year  $t$  can be written as

$$Q_T(s,t) = \xi(s,t)q_T(t).$$

Scaling the distribution of  $X(s,t)$  by  $\xi(s,t)$  results in a (regional) GEV distribution with  $\xi(s,t) = 1$ ,  $\alpha(s,t) = \gamma(t)$  and  $\kappa(s,t) = \kappa(t)$ , i.e. the distribution is constant over the region but time-dependent. Then  $q_T(t)$  follows from GEV distribution function by setting  $F(q_T(t)) = 1-1/T$ :

$$q_T(t) = 1 - \frac{\gamma(t)}{\kappa(t)} \left\{ 1 - \left[ -\log\left(1 - \frac{1}{T}\right) \right]^{-\kappa(t)} \right\}, \quad \kappa(t) \neq 0$$

$$q_T(t) = 1 - \gamma(t) \log \left[ -\log\left(1 - \frac{1}{T}\right) \right], \quad \kappa(t) = 0.$$

The temporal variation of the GEV parameters can be described by the following equations:

$$\xi(s,t) = \xi_0(s) \exp[\xi_1 I(t)],$$

$$\gamma(t) = \exp[\gamma_0 + \gamma_1 I(t)],$$

$$\kappa(t) = \kappa_0 + \kappa_1 I(t).$$

with  $I(t)$  being the time indicator. The exponential relation in the case of the location parameter implies that the relative changes of quantiles of the distribution are constant over the region. The model for the time-dependence may be extended to consider e.g. quadratic terms, when necessary. The time indicator can simply be the year  $t$ , i.e.,  $I(t) = t$ , or other time-dependent covariate representative of enhanced greenhouse effect, e.g., global or local temperature anomaly. More generally, the non-stationary index flood model provides a conditional frequency distribution of extremes dependent on key relevant non-stationary factor.

Since the estimation of the at-site index floods also involves the parameters of the regional distribution and their changes, the estimation of parameters  $\xi_0(s)$ ,  $\xi_1$ ,  $\gamma_0$ ,  $\gamma_1$ ,  $\kappa_0$  and  $\kappa_1$  is done at once in two-step procedure by maximizing the log-likelihood

$$L = \sum_{s=1}^S \sum_{t=1}^N L_{s,t}(\xi_0(s), \xi_1, \gamma_0, \gamma_1, \kappa_0, \kappa_1)$$

where  $L_{s,t}(\xi_0(s), \xi_1, \gamma_0, \gamma_1, \kappa_0, \kappa_1)$  is the log-likelihood for the annual (or seasonal) maxima at site  $s$  in year  $t$ ,  $S$  is the number of sites in the region and  $N$  is the number of years in the record. The initial values of  $\xi_0(s)$ ,  $\gamma_0$ , and  $\kappa_0$  are found by the method of L-moments, the other parameters are initially set to 0. Then, in the first step the at-site  $\xi_0(s)$  are determined keeping the other parameters fixed. In the second step the regional parameters  $\xi_1$ ,  $\gamma_0$ ,  $\gamma_1$ ,  $\kappa_0$ ,  $\kappa_1$  are estimated keeping the  $\xi_0(s)$  fixed. These two steps are repeated until convergence.

### 3.2 Evaluation of uncertainty

Since the maxima at different sites are often dependent, the log-likelihood cannot be used to derive standard errors of the parameter estimates. The bootstrap resampling can be used instead. The procedure can be summarized as follows:

1. The parameters  $\xi_0(s)$ ,  $\xi_1$ ,  $\gamma_0$ ,  $\gamma_1$ ,  $\kappa_0$ ,  $\kappa_1$  are estimated by maximum likelihood using original series

2. The trend is removed from the original series  $X(s,t)$  using the estimates from previous step by transformation

$$\tilde{X}(s,t) = \frac{1}{\hat{\kappa}(t)} \log \left[ 1 + \frac{\hat{\kappa}(t)}{\hat{\gamma}(t)} \left( \frac{X(s,t)}{\hat{\xi}(s,t)} - 1 \right) \right],$$

where  $\hat{\xi}(s,t), \hat{\gamma}(t)$  and  $\hat{\kappa}(t)$  are the maximum likelihood estimates of the GEV parameters and  $\tilde{X}(s,t)$  is the detrended series - residuals

3. A sample is drawn from years 1 ...  $N$ , where  $N$  is the length of the sample (same for all stations)
4. To retain the spatial dependence, the series of resampled residuals are formed by selecting the records corresponding to the sample of years (step 3) from the residuals (step 2) for all stations simultaneously.
5. Finally, the resampled residuals are transformed back to their original scale using the estimates from step 1 by transformation

$$X(s,u) = \hat{\xi}(s,u) \left\{ 1 + \hat{\gamma}(u) \frac{\exp[\hat{\kappa}(u) \tilde{X}(s,t_u)] - 1}{\hat{\kappa}(u)} \right\},$$

where  $u$  is the ordinate of the resampled year ( $u = 1 \dots N$ ) and  $t_u$  is the resampled year corresponding to the ordinate  $u$

6. The parameters are re-estimated

The steps 3–6 are repeated until required number of estimates is obtained. Further details on uncertainty assessment and goodness-of-fit testing can be found in (Hanel et al., 2009).

### 3.3 Example of application

As an illustration, we show the result of the analysis of the 5-day day winter (DJF) precipitation extremes from the simulation of the RACMO regional climate model (part of the ENSEMBLES project outputs (Hewitt and Griggs, 2004)) over the Rhine basin (Hanel et al., 2009). The Rhine basin was divided into five homogeneous regions (Figure 3a). The basin-average relative changes of quantiles of 5-day winter precipitation extremes between the periods 1961–1990 and 2070–2099 are given in Figure 3b. Note the largest changes are found for the 2-year quantile with an increase of about 20% (ratio equal to 1.2), while changes are of lower magnitude for lower frequency events.

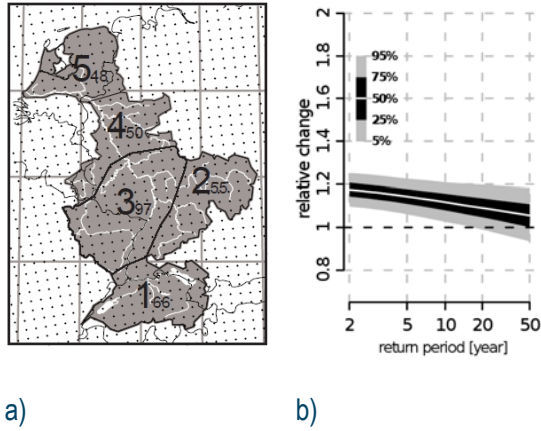


Figure 3. a) The subdivision of the Rhine basin into five homogeneous regions. The numbers in subscript give the number of grid boxes of the RACMO regional climate model in each region. b) The basin average relative changes of the 5-day winter precipitation extremes between the periods 1961–1990 and 2070–2099 as simulated by the RACMO model. The sampling uncertainty (shaded area) was estimated by the bootstrap procedure.

## 4 Extreme floods and preceding rainfall

Rainfall is the main driving process in fluvial floods which are not affected by snowmelt. However, the relationship between rainfall and severity of a river flood is not straightforward, being rather an interplay between many combining factors. The objective of this research is to determine the dominant temporal characteristics of the rainfall which caused the highest floods in catchments across Europe and to place these within the overall frequency of the occurrence of the rainfall. This information will provide a measure of the vulnerability of a catchment to future flooding, considering both natural variability within the current time frame and future changes in rainfall characteristics.

For each catchment, average daily catchment rainfall is calculated using all available rainfall time series and then cumulated over a number of n-day periods. The averaging technique of (Jones, 1983) is recommended here.

Extreme rainfalls are extracted for each n-day time period using a POT method. Extraction of flood events also uses a POT method and the n-day catchment rainfalls preceding the dates of each of the top flood peaks are determined. In order to consider the most extreme event, a POT1 series (where the number of episodes with flow above threshold is equal to the number of years, i.e. on average, one episode in one year) is recommended. A comparison of flood-generating peak rainfall with overall rainfall frequency shows the severity of rainfall which resulted in floods and whether more extreme rainfall has occurred which did not cause floods. This latter occurrence indicates the potential for the generation of more extreme floods, without more extreme daily rainfall, if the combination of causative factors had been different.

### 4.1 Definition of rainfall and flood extremes

Rainfall is a climatic factor which is highly variable both spatially and temporally. To quantify and analyse rainfall, both of these dimensions must be defined. When considering river flow and floods, the spatial dimension of rainfall is defined by the catchment area contributing to a discharge in a river cross-section of interest, with the smallest time dimension used in this study being one day. Sub-daily rainfall intensity is obviously important in the generation of floods, particularly over small catchments, but sufficient data are not available for this to be considered here.

Catchment rainfall is determined either from a number of point measurements averaged using an appropriate weighting technique e.g. Thiessen polygons or from gridded rainfall. For all but the smallest catchments, rainfall over more than one day is important for flood potential with the length of the preceding period depending on the size and physical properties of the catchment. Average daily catchment rainfall is calculated and then cumulated over a multi-day period. Extreme rainfalls are extracted for each n-day time period using a POT method.

### 4.2 Statistical analysis

An example of POT analysis of overall catchment daily rainfall and rainfall preceding extreme flood peaks is given in Figure 4 for a 325 km<sup>2</sup> catchment in Great Britain. The black lines are frequency curves for 1, 2, 3, 5 and 10-day cumulative rainfall. The superimposed coloured lines show the highest 1, 2, 3, 5 and 10-day rainfalls during the 10 days preceding the nine highest flood peaks in the catchment. The higher relative importance of the 10-day rainfall compared to the 1-day rainfall in determining the severity of flood peak is evident. The highest 1 and 2 day rainfalls are for a summer event with low rainfall over longer preceding time periods. Hence dry antecedent conditions mitigated the flood potential but if this rainfall had occurred as part of a wetter longer time period then an extreme

flood event would have been generated. Longer time periods than 10-days are required to fully illustrate the effect of antecedent conditions on flood severity.

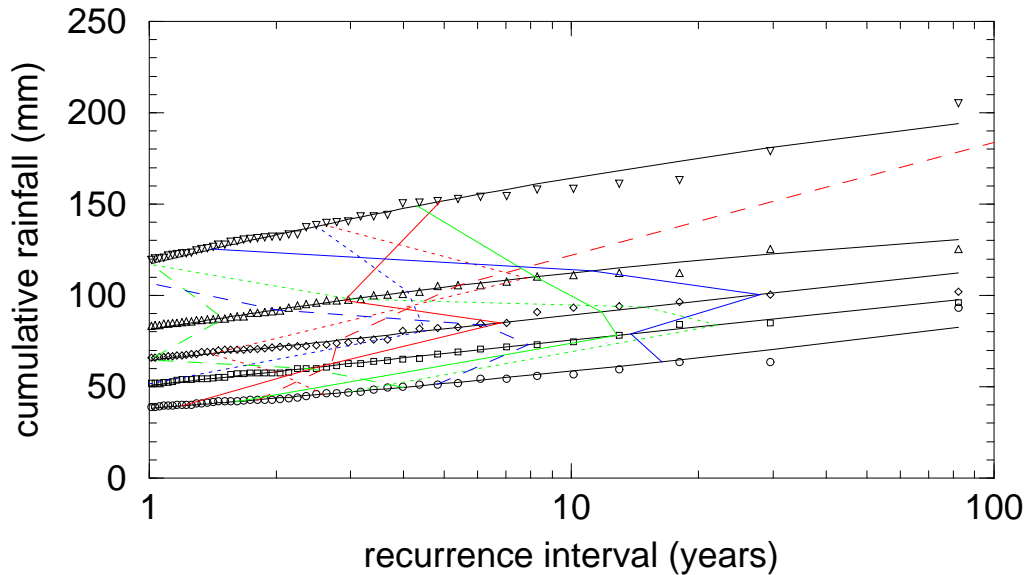


Figure 4. Catchment rainfall frequency (black lines) for 1-day (circles), 2-day (squares), 3-day (diamonds), 5-day (triangles) and 10-day (upside-down triangles) cumulative periods. Rainfall over the same time periods preceding the highest nine flood peaks in red (peaks 1 – 3), green (4 – 6), blue (7 – 9). Peaks 1, 4, 7 solid lines; 2, 5, 8 dashed lines; 3, 6, 9 dotted lines.

### 4.3 Event rating

Floods can be assessed according to the ranking of the preceding catchment rainfall over different time periods and the importance of the combined impact of rainfall over the different temporal scales. Results can be compared from a variety of catchments in terms of factors such as area, type (permeability, topography etc) and spatial location to determine underlying dominant patterns of flood generation. High ranking rainfall events which did not cause floods are also of interest and for linking with weather types.

## 5 Extreme floods and preceding circulation types

Circulation type classifications (CTCs, also sometimes referred to as weather type classification) have been developed to summarise and characterise the daily variability of the climate in a number of atmospheric circulation patterns which occur most frequently. These patterns, also called circulation types (CTs) aim to discriminate typical atmospheric phenomenon observed within a region, and have become useful tools for describing and analysing climate conditions and corresponding weather. Subjective classifications have developed through recognition of the recurrence of the atmospheric circulation in certain modes (El-Kadi and Smithson, 1992). The Lamb catalogue (the manual original catalogue extends from 1861 to 1997) (Lamb, 1972) is a classification scheme designed for the British Isles which has been used to study hydroclimatology relationships (see review by El-Kadi and Smithson, 1992). The *Grosswetterlagen* classification, that characterises European weather types, is another well known subjective classification with a manual catalogue dating back to 1881 (Hess and Brezowsky, 1977).

The study of the relationships between the atmospheric circulation and the surface environment shows great potential for basic and applied research (Yarnal, 1993). An example is the analogue weather forecasting, where past synoptic patterns and accompanying weather are matched to current synoptic patterns and forecasts are made according to this past weather information (O'Hare et al., 2005) and such techniques are used routinely operationally (Obled et al., 2002). A more recent application of CTCs is the verification of the performance of General Circulation Models (also called Global Climate Models GCMs; e.g. (Anagnostopoulou et al., 2009; Goodess and Palutikof, 1998), the analysis of possible changes in atmospheric circulation, and the downscaling of GCM outputs (Wilby, 1997), using automatic circulation classification procedures. Comparisons of historical CTCs (obtained from observed pressure fields) and GCM-derived CTCs representation of current and future climates help in identifying systematic biases in GCM climatology trends and possible future changes.

Links between CTCs and some specific weather-related events have been investigated for many years, for example – cyclone tracks (e.g. Bartholy et al., 2006), flood events (Duckstein et al., 1993) or drought states (Fowler and Kilsby, 2002). In Europe, specific CTs have been shown to be linked to wet/dry periods. For example, the Cyclonic Lamb weather types are described by '*rainy, unsettled conditions, often accompanied by gales and thunderstorms. May represent rapid passage of depressions across the country [UK], or to the persistence of a single deep depression*' (O'Hare et al., 2005). When extended to the full catalogue, such empirical relationships can be used to build weather generators conditioned according to CTs (e.g. Fowler et al., 2005; Schubert, 1994; Wilby, 1995).

Direct links between weather type and extreme floods are, however, rarely investigated at a large spatial scale. Understanding the atmospheric conditions which trigger such large-scale events would help to improve preparedness, and have potential to limit damages and to mitigate impacts in enabling better flood-risk assessment and anticipation. A methodology to undertake such analysis is described in this section.

### 5.1 Selection of flood-generating circulation types

Once the flood POT series have been established, date and magnitude of the highest flood are the two pieces of information available. In traditional flood analysis, the magnitude of a selected flood event is associated with its probability of non-exceedence, or the average number of years between this flood event and a flood of equal or higher magnitude. Here, the focus is on the date of occurrence of POT

floods, aiming to identify if the days leading to a POT event are characterised by specific atmospheric conditions.

For each day when POT event occurred, the circulation type of that day, and of several preceding days, are also selected, to form a parallel time series (Table 1).

| Date       | Flow   |             | Classification A (OGWL) |           | Classification B (PECZELY) |           |
|------------|--|-------------|-------------------------|-----------|----------------------------|-----------|
|            | Discharge<br>(m <sup>3</sup> s <sup>-1</sup> ) | Flood event | CTA                     | CTA Freq. | CTB                        | CTB Freq. |
| 08/05/1999 | 554  |             | 6                       | 0.18      | 5                          | 0.06      |
| 09/05/1999 | 558  |             | 6                       | 0.18      | 8                          | 0.06      |
| 10/05/1999 | 608  |             | 6                       | 0.18      | 9                          | 0.12      |
| 11/05/1999 | 643  |             | 3                       | 0.12      | 9                          | 0.12      |
| 12/05/1999 | 976  |             | 3                       | 0.12      | 1                          | 0.29      |
| 13/05/1999 | 1099   | 1           | 2                       | 0.12      | 1                          | 0.29      |
| 14/05/1999 | 954  |             | 13                      | 0.12      | 4                          | 0.06      |
| 15/05/1999 | 826  |             | 13                      | 0.12      | 13                         | 0.12      |
| 16/05/1999 | 633  |             | 13                      | 0.06      | 1                          | 0.29      |
| 17/05/1999 | 608  |             | 12                      | 0.06      | 2                          | 0.06      |
| 18/05/1999 | 626  |             | 16                      | 0.06      | 10                         | 0.12      |

**Table 1. Example of flood and circulation type inventory for two classifications for May 1999 flood on the Rhine @ Diepoldsau. Flood event equals to 1 when a POT flood was sampled that day; CTA (resp. CTB) refers to the Index of the Circulation Type of Classification A (resp. Classification B) for the corresponding date; CTA (resp. CTB) Freq. refers to the overall frequency of occurrence of CTA (resp. CTB). The CT numbering is for illustration only. Classifications used are from the COST733 cat1.2. For review on circulation types in Europe, see [www.COST733.org](http://www.COST733.org).**

## 5.2 Statistical analysis: frequency and persistence of circulation types

Two statistical analyses are performed on the circulation type information, following a methodology developed by (Duckstein et al., 1993), evaluating the links between a circulation type and the occurrence of a flood event. The POT3 series are recommended (i.e. selection of the largest 3N peaks, where N is the number of years of record).

The indicators can be derived for the whole year, or for specific seasons. This allows to explore if different mechanisms generate flood at different time of the year.

### 5.2.1 Indicator of frequency anomaly

The indicator PI1 (in %) calculates the ratio between the frequency of occurrence of a circulation type CT<sub>i</sub> during a flood event to that for any day, in percent:

$$PI1(i) = \frac{n_1(i)}{n_2(i)} \quad i=1, \dots, C$$

with  $n_1(i)$  being the relative number of days with pattern CT<sub>i</sub> in N\* days up to the flood, and  $n_2(i)$  – the relative number of days with pattern CT<sub>i</sub>, and C – the number of classes of CTC. Note that the indicator cannot be estimated when no flood event has been recorded during the season. The indicator also includes the day of the flood.

Estimation can be made on the entire series (PI1<sub>year</sub>) or on specific seasons (PI1<sub>season</sub>). It has been suggested by Duckstein et al. (1993) and is a modified version of the effectiveness correlation of Cony et al. (2008): if PI1(i) is greater (lower) than 1, the pattern occurs more (less) frequently before/during a

flood than it does normally (i.e. CT<sub>i</sub> does (does not) contribute much to the flood). For example, PI<sub>1</sub> = 0 when CT<sub>i</sub> has never occurred during/before an observed flood, while PI<sub>1</sub>=1.8 indicates that the CT<sub>i</sub> occurred 8 times more often during/before the flood than any other period. The statistical significance of the frequency anomaly for the entire classification (all classes considered together) is evaluated through the  $\chi^2$  statistics with the following null hypothesis: 'the frequency of a weather type during floods is the same as for any day'.

There is a delay between the time when rain falls on the catchment and the moment when streamflow reaches a gauging station, generally linked to the size of the catchment (i.e. the streamflow takes longer to reach the gauging station because it has a long distance to follow), the soil type and vegetation of the catchment, the presence of storage (such as lakes, man-made water storage reservoirs etc). It is sometimes called the concentration time. Hence, it is worthwhile to analyse not only the atmospheric conditions of the day of the flood, but also of those preceding the flood. In that case, PI<sub>1</sub> is derived for N\* number of days before the day of the flood (including the day of the flood). N\* represents the number of days preceding a flood when the weather could significantly influence flood production processes, and could be interpreted as an upper limit of the concentration time of the basin.

### 5.2.2 Indicator of persistence prior a flood event

The indicator PI<sub>2</sub> measures the conditional probability of finding at last k days out of N\* with CT<sub>i</sub>, given that a flood occurred on day zero:

$$PI_2(i) = \text{pr}(CT_i \text{ for } \geq k \text{ days, } 0 \leq k \leq N^*) \quad i=1, \dots, C$$

This indicator measures the 'persistence' (not in the strict sense of number of consecutive days, but number of days within a period) of CT<sub>i</sub> associated with a flood event, important factor in the river basins antecedent conditions: a high PI<sub>2</sub> indicates that CT<sub>i</sub> has generally been observed for several days before flood events. This conditional probability is compared with the binomial probability of at least k days out of N\* of CT<sub>i</sub> using historical frequencies of occurrence. This indicator has first been suggested by Duckstein et al. (1993).

### 5.2.3 Regional indicator

Local evaluations of PIs for a CTC can be discussed at the European level by mapping PI(i) at the river basins outlets. While useful to evaluate single CTC, this soon becomes fastidious for a large number of CTCs. Moreover, spatial evaluation is necessary to assess how well CTCs can describe large-scale flooding.

A spatial indicator, RPI (for Regional PI) is defined which evaluates the spatial coherence of the local relationships:

$$RPI(i) = \frac{\sum_{r=1}^B \text{Score}_{PI}(i,r)}{B} \quad i=1, \dots, C$$

with Score<sub>PI</sub>(i,r) being the score obtained by CT<sub>i</sub> for river basin r, B – the total number of river basins, and C – the number of classes of CTC.

The scores are given according to the ranked PI(i,r) standardised by the number of classes to allow comparison of relative performances of CTCs of different number of classes: Score<sub>PI</sub>(i,r)= 1/C for the lowest PI(i) of r, and Score<sub>PI</sub>(i,r)= C/C = 1 for the highest PI(i) of r. For each CT<sub>i</sub>, there is one RPI per PI, i.e. for each N\* and k combination for both PI<sub>1</sub> and PI<sub>2</sub>.

Two RPIs are of particular interest. The maximum RPI measures the spatial coherence of the CT<sub>i</sub> with the strongest relationship with flood events:  $RPI(i) = 1$  indicates that CT<sub>i</sub> has systematically the strongest relationship with floods for all considered river basins, and hence, there is a strong spatial coherence in the flood-generating mechanism described by CT<sub>i</sub>. Lower RPIs reflect lower spatial coherence for the flood-generating CT<sub>i</sub>.

The minimum RPI informs on the spatial coherence of the 'flood-poor' CTs: a value of  $1/C$  indicates that the same CT<sub>i</sub> has systematically the weakest relationship with floods in all considered river basins, and could be an indicator of potential absence of flood across Europe. Higher values show a weaker spatial coherence in the flood-poor CT<sub>i</sub>.

### 5.3 Example: flood events and linked Objective Hess-Brezowski circulation types

The methodology was tested on nearly 500 catchments of Europe (Figure 5), using flow data from the Global Runoff Data Center (<http://grdc.bafg.de/servlet/is/Entry.987.Display/>), the European Water Archive (<http://ewa.bafg.de/>), the UK National River Flow Archive (<http://www.ceh.ac.uk/data/nrfa/index.html>) and the French Banque Hydro (<http://www.hydro.eaufrance.fr/>).

The circulation-type classification tested is the objective *Großwetterlagen* classification (OGWL) derived using the ERA-40 re-analysed mean sea level pressure (Uppala et al., 2005) using an automatised version of the Hess-Brezowski classification (James, 2007) developed within the EU COST733 ([www.cost733.org](http://www.cost733.org)). The classification comprises 29 types and covers the area 30N - 76N and 37W - 56E.

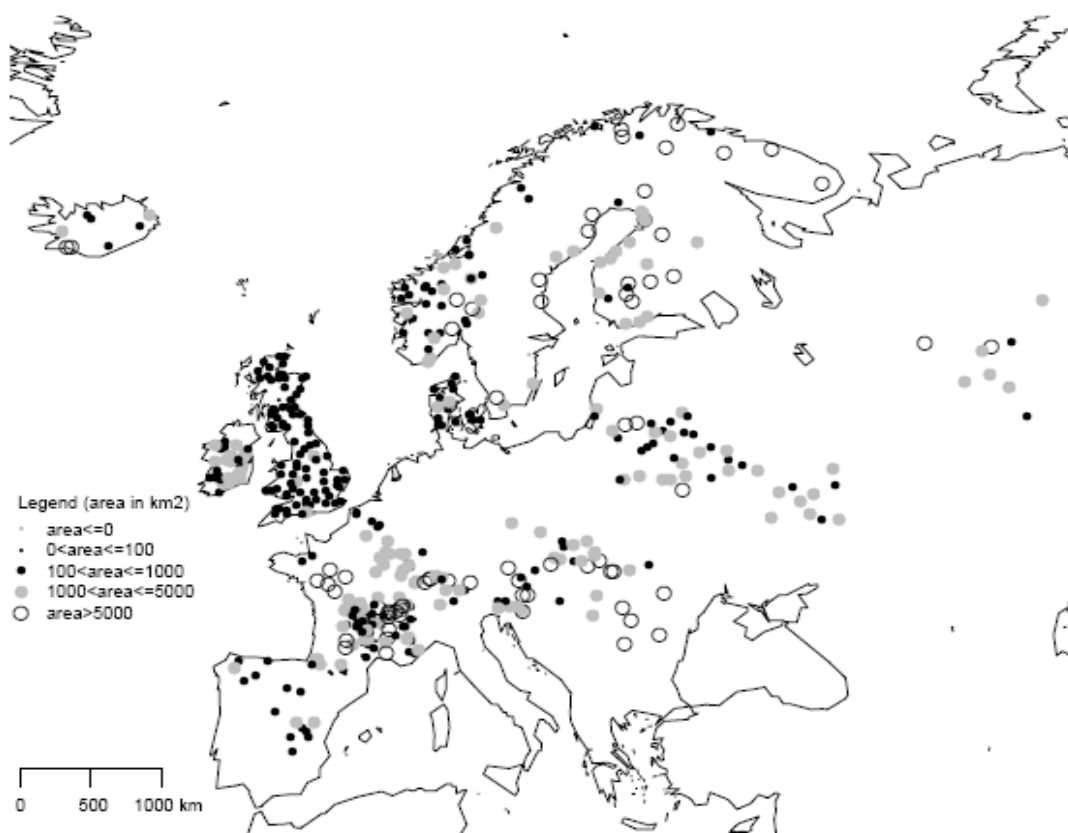
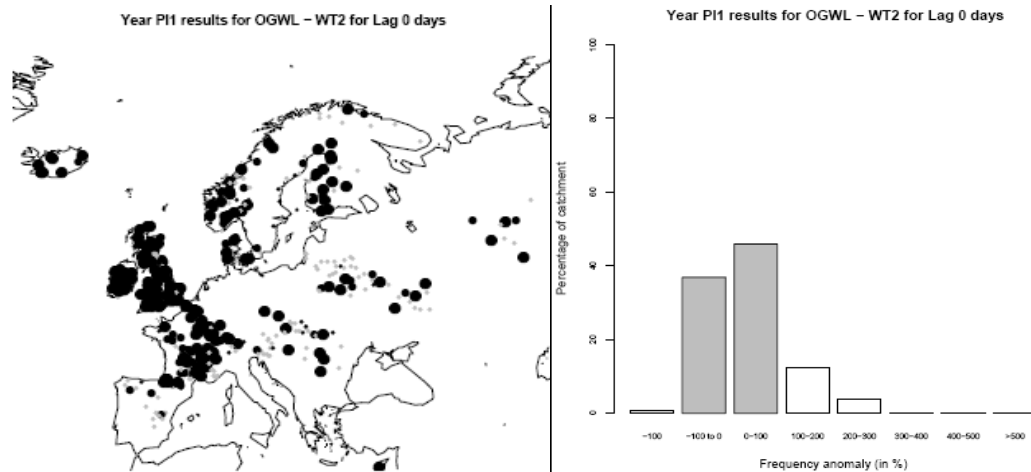


Figure 5. Outlets of the river considered basins.

For each river basin, frequency anomaly  $PI1$  is calculated. Figure 6 shows results obtained for the frequency anomaly indicator  $PI1$  calculated for the days of the flood event considering the circulation type  $WT2$  of OGWL. The size of the dots is proportional to the value of  $PI1$  (the larger the dot, the larger the frequency anomaly). The colour of the dot describes the significance: black dots show significant results, while grey dots signify a non significant relationship, the significance of the frequency anomaly being assessed using the  $\chi^2$  test. With automatic calculation of  $PI1$  for catchments over Europe, it is possible to investigate if the same atmospheric conditions, as described by circulation and weather types, are more often associated to flood events than others.



**Figure 6. Frequency anomaly  $PI1$  derived for the whole year for circulation type  $WT2$  of the OGWL (a) map (b) histogram of results. Size of dots proportional to  $PI1$ , and colour shows significance of results (black: significant; grey: non-significant).**

## 6 Flood extremes at regional and continental scales

### 6.1 Example of large-scale floods and associated damage in Europe during 1985-2009

River flooding is a complex phenomenon that can be caused by a number of mechanisms. Floods differ by spatial and temporal scales. There have been many local, potentially very dramatic, flood events (e.g. flash floods). However, spatial coverage of some disastrous floods in Europe is regional and even continental. Table 2 illustrates a sample of large-scale floods extending beyond national borders of a single country from the time period of last 25 years (1985-2009), with information on flood period and affected countries stemming mostly from Dartmouth Floods Observatory.

Since 1950, there have been 12 flood events in Europe (flash floods and river floods) with number of fatalities exceeding 100 in each (Barredo, 2007), therein five events in Italy (1951, 1954, 1966, 1968, 1998) and two each in Romania (1970, 1991) and Spain (1962, 1973). The killer-flood in Spain in 1962 was the only event in the last 50 years in Europe leading to more than 1000 fatalities.

The severe floods in Europe in the 2000s were mostly caused by heavy rain. The most destructive deluge occurred in August 2002, when in five countries (Czech Republic, Germany, Austria, Hungary, and Romania) the number of flood fatalities reached 55 and the material damage soared to 20 billion US\$. Since in September 2002 another major flood (with 23 fatalities and 1.2 billion US\$ in material damage) occurred in France, the year 2002 is recognized as the record-holding year in Europe in the category of highest material damage caused by floods. Serious floods in the UK in October-November 2000 caused 13 fatalities and over 8.9 billion US\$ in damage. Multiple waves of heavy rains, leading to destructive floods with dozens of fatalities and billion-high damage occurred in Romania in 2005, while in August 2005, several European countries experienced another major flooding, again with billion-high material damage. In June and July 2007, in result of several waves of intense precipitation, total material flood damage of 8 billion US\$ and insured damage of 6 billion US\$ were registered in multiple shires (counties) of the UK.

| Year | Month | Countries  |
|------|-------|--|
| 1991 | Aug.  | Austria, Germany, Poland, Hungary                            |
| 1993 | Dec.  | France, Germany, Netherlands, Belgium, Luxembourg            |
| 1995 | Jan.  | France, Germany, Netherlands, Belgium, Luxembourg            |
| 1997 | Jul.  | Czech Republic, Poland, Germany, Slovakia, Ukraine, Hungary  |
| 1998 | Nov.  | Ukraine, Slovakia, Romania, Hungary                          |
| 1999 | Feb.  | Romania, Hungary, Ukraine                                    |
|      | May   | Germany, Austria, Switzerland                                |
|      | Jun.  | Slovakia, Romania, Czech Republic                            |
| 2000 | Apr.  | Serbia, Romania, Hungary, Ukraine                            |
| 2001 | Mar.  | Ukraine, Hungary, Romania                                    |
| 2002 | Aug.  | Czech Republic, Germany, Austria, Slovakia, Hungary          |
| 2004 | Jul.  | Slovakia, Poland, Hungary, Romania                           |
| 2005 | Aug.  | Switzerland, Austria, Germany                                |
| 2006 | Mar.  | Romania, Czech Republic, Germany, Austria, Slovakia, Hungary |
| 2007 | Sep.  | Czech Republic, Austria, Hungary                             |
| 2008 | Aug.  | Czech Republic, Germany, Austria                             |
| 2009 | Jun.  | Poland, Czech Republic                                       |

**Table 2. A sample of large-scale floods in Europe, extending beyond national borders of a single country from the time period of last 25 years (1985-2009), Principal source of information: Dartmouth Floods Observatory, plus other sources listed in the WATCH Flood Catalogue (Kundzewicz & Choryński, 2010).**

Even if most dramatic floods in Europe in the last decades have been rain-caused, rapid snowmelt has also led to flood disasters, even if snow cover has been, on average, decreasing in the warming climate. The winter of 2005/2006 was cold and snowy over much of European continent, so that a thick snow cover built up and its rapid melt (in some areas, superimposed on heavy rain) resulted in major flooding in such countries as Romania, Hungary, Greece, Turkey, Bulgaria, Serbia-Montenegro, Czech Republic, Slovakia, Germany, Austria, with fatalities and high material damage.

## 6.2 Simple large-scale flood indicator for regional and continental scales

Compared to droughts, floods are events generally relatively localised (on a particular stretch of a river) and short (few hours to few weeks). Indices for large-scale characterisation of floods are thus seldom developed. In this report, we have adapted a methodology originally developed to characterise river flow droughts to high flows, and tested the results on two regions of Great Britain.

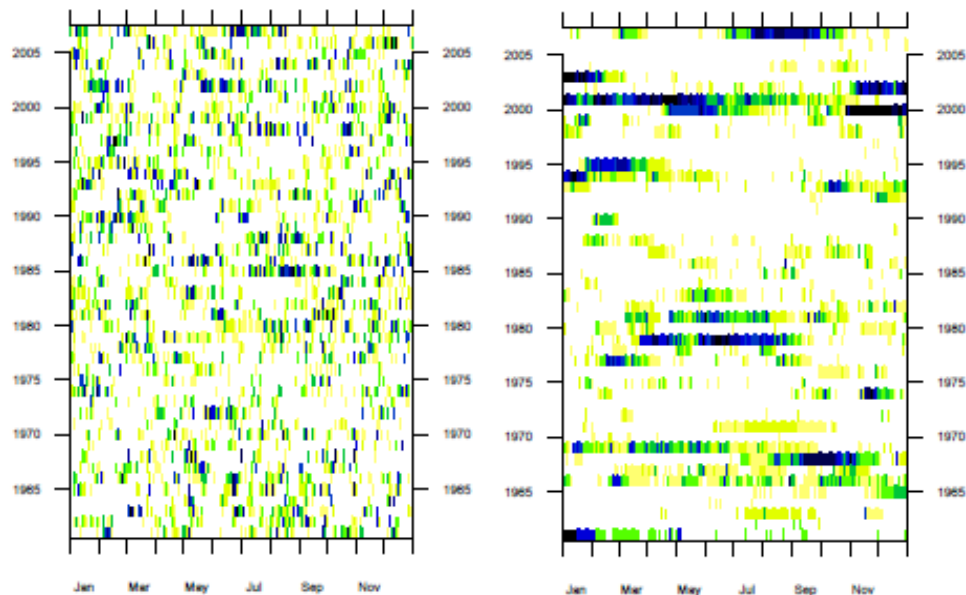
The methodology follows the concept of the Regional Deficit Index developed by (Demuth and Stahl, 2001) in the EU-funded project ARIDE (ENV4-CT97-0553). For high flows, the concept is summarised briefly here:

1. Evaluate when the daily river flow of a given river basin is above a given threshold, representative of high flows for a typical day for the period of the year, for example the 10<sup>th</sup> percentile of mean daily flow for that river basin and this period of the year. A window of +/- 15 days around the target day has been tested here.
2. Create a surplus series for that river basin, where days are associated with 1 if the river flow is greater than the threshold, and 0 otherwise.
3. Analyse all surplus series for all river basins with available data of a region, and group them according to when they experience a surplus or not (i.e. group together all sites with 1/0 occurring the same days): this will create surplus-homogeneous regions (in terms of flood

occurrence). The regions might not necessarily be geographic entities, but for droughts, this is often the case. The advantage of geographically confined regions is an easier interpretation of the results.

4. For each region, calculate, for any day, the proportion of river basins under surplus: this is simply the arithmetic average of the surplus series of each river basin of the region for each day. This represents the spatial coherence of the flood. A high value (1 is the maximum) indicates that the entire region experiences a high flow that day, thus describing a severe flood event; a low value indicates that no part or only a small part of the region experience a high flow that day, thus showing localised events that cannot be described as severe large-scale floods. This generates the Regional Flood Index series for each region.

The methodology was implemented for the period 1961-2007 using observed daily river flow series from the UK National River Flow Archive. As a first test, no cluster analysis was undertaken, but results were derived for two British regions: the north-west Scotland, and the most permeable catchments of south-east England. The resulting Regional Flood Index series are illustrated in Figure 7, where the RFI for each year is represented horizontally (from January in the left to December in the right), and the years arranged vertically (1961 bottom to 2007 top). Blue and black indicate a high spatial coherence, while white and yellow show a low spatial coherence.



**Figure 7. Regional Flood Index series for two regions of the UK, north-west Scotland (left) and the most permeable catchments of south-east England (right). White and yellow indicate low spatial coherence, while blues and black show a high spatial coherence.**

Figure 7 shows two very different regions: in Scotland (left), large-scale flood events are short-lived but can be spatially consistent (dark shades) which might be due to the responsive river flow regime of the region, mainly on impermeable rocks. By contrast, prolonged large-scale floods are identified in the permeable catchments of south-east England (right), such as the 2000-2001 and the summer 2007 floods, known to be significant events in this region, interspersed by multi-year of flood-poor periods, such as the early 1970s and the last 1980.

The methodology was tested on already existing regions regrouping the most permeable catchments of South East England within a benchmark of British catchments of the National River Flow Archive,

considered homogeneous. Improved results could be obtained when undertaking a specific clustering analysis, but this preliminary analysis shows very promising results, proving the concept of RFI.

## 7 Methodology to derive a flood catalogue

Two flood catalogues will be derived, one purely automatic (objective catalogue) based on river discharge and/or rainfall only, and one resulting from varied information including economic and social damages (subjective catalogue). The methodology for both is presented in the next sections.

### 7.1 Subjective flood catalogue

The idea behind the subjective flood catalogue (Kundzewicz and Choryński, 2010) is backed by the following observations:

- Information on past floods is scattered, and fragmentary;
- Floods are spectacular and raise general interest;
- Flood-related damages have grown by the factor of 10 in the last 50 years.
- Comprehensive catalogue of floods does not exist and is much needed.

The subjective flood catalogue aims to cover the pan-European scale, with particular reference to Member States of the European Union. The temporal is restricted to post-1900 events, but some information on earlier flood events is also included. The catalogue refers to river floods only. The output consists of an electronic data base and, later, a book-form catalogue.

There are multiple criteria for inclusion of entries in the catalogue. The principal criterion relates to the impact of river floods (measured by the material damage, number of fatalities, flood magnitude, and severity, as defined by Dartmouth Flood Observatory); further - maximum discharge, and then – opportunity.

Indeed, it was attempted to use the existing opportunities to compile a useful listing of flood-related information. Among the principal sources of information were: Dartmouth Flood Observatory (global coverage, based on satellite imagery; including discharge, flood generating mechanisms, information on damages, and being up-dated on a regular, daily, basis, but not extending long into the past, some entries need closer look) and Catalogue of Large Floods (2nd edition of 2004, edited by Reg Herschy and published by IAHS Press) containing information on the largest flood discharges, catchment areas, flood generating mechanism. In the latter reference, a great many entries were not updated since the first edition due to the difficulty in gathering newer, post-1984 data. Also information residing in national meteorological and hydrological services; and many national sources (publications, reports) collected by Kundzewicz were used.

### 7.2 Objective flood catalogue

The RFI series and illustrations such as Figure 7 can be used to identify periods where different regions experience large-scale floods, as defined by spatially coherent high flow periods. Such catalogues can be consolidated with anecdotal evidence and regional knowledge of historical hydrological events, as well as catalogues obtained from subjective analysis.

Using such information, statistics such as season, length, strength and frequency of large-scale floods can be easily assessed, and temporal evolution between different regions can be investigated.

The advantage of the RFI methodology is that it could be used to derive 'future' catalogues from river flow projections, for example output from Regional or Global Hydrological Models. First, the methodology must be evaluated using gridded (modelled) runoff and discharge data instead of

observed river flow time series. Second, tests will be made to evaluate using rainfall information, similarly to the methodology developed by (Lloyd-Hughes et al., 2009) for droughts using the Standardized Precipitation Index.

## 8 Concluding remarks

This report has presented a range of methodologies to analyse large-scale floods at local, regional and continental scales and to understand the antecedent conditions (in particular in terms of rainfall and atmospheric circulation) preceding large-scale floods. The report has also presented new methodology to incorporate non-stationarity in flood frequency analysis, important in a context of climate change. Finally, two techniques to derive catalogues of historical floods for Europe were presented.

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