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TRENDS IN ANNUAL AND SEASONAL MAXIMA OF DAILY RAINFALL AND PEAK RIVER FLOW

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ABSTRACT

With the public perception that climate has been changing in the last decades, more and more doubts are raised regarding the validity of the assumption of stationarity for hydrological processes. In this work we explore, in a descriptive and preliminary way, trends for annual and seasonal maxima in daily rainfall and peak river flow, applying a linear regression model allowing the mean of the distribution to vary with time. Over a longer period (50 years), trends do not seem to be significant, while there is indication of some slight, although not spatially coherent, trends in shorter series (20 years). Particularly in summer, there seem to be little concordance in the direction of trends for rainfall and flow, suggesting that other factors, such as evaporation, land use change, water management practices, etc, affect the river flows. Another concern is whether or not the standard linear regression can cope with extreme records. We discuss these issues and look into possible alternative approaches.

1 INTRODUCTION

In the United Kingdom (UK), estimates of design rainfall and floods are obtained primarily through application of tools and techniques presented in the Flood Estimation Handbook (FEH, Faulkner (1999) and Robson and Reed (1999)) and its subsequent updates. Use of these techniques rely on the fitting of statistical extreme value models to observed annual maxima series (AMS) of both rainfall and peak river flow acquired from a large number of rain and flow gauges located throughout the country. The current generation of statistical models is formulated based on the assumption of stationarity, assuming that the underlying statistical properties (e.g. mean and standard deviation) of the AMS do not change over time. While the assumption of stationarity provides a convenient analytical framework, it is clear that it is, at best, an approximation when considering data from real catchments impacted by a multitude of anthropogenic activities such as construction of reservoirs, urbanisation and channel alignment. An additional complication is added when considering the impacts of climate change and variability on the occurrence of hydro-meteorological extremes, both in the past and the future. In recognition of the potential impacts of environmental change on extremes, a suite of methods has been developed to post-adjust design flood estimates obtained from the stationary framework for possible effects of urbanisation and climate change. *Kjeldsen* (2010) presented a procedure for adjusting L-moment ratios for effects of urbanisation using the spatial extent of urban land-cover within a catchment, and it is generally considered sound practise to increase design flood estimates by 20% to take into account potential effects of climate change in year 2085 (*Wilby et al.*, 2008).

Several studies have investigated the existence, or not, of trends in hydro-meteorological records from the UK. Based on analysis of AMS and peaks-over-threshold (POT) series of peak flow recorded at more than 1000 gauging stations, *Robson* (2002) concluded that there was no consistent evidence of trend in UK flood series. A subsequent study by *Hannaford and Marsh* (2008) of hydrological flow records from 87 undisturbed 'benchmark catchment' concluded that there was evidence of upward trend in high flow data (but not annual maximum) from maritime-influenced upland catchments in the north and west of the UK, but no compelling evidence for trend in lowland areas and in the south and east of the country. Trend in UK extreme rainfall data have been studied by *Jones et al.* (2012) who reported an increase of intensity in long duration events, but a decline in intensity for short-duration summer rainfall.

The objective of this study is to undertake a preliminary investigation of trends in contemporary UK datasets of annual and seasonal maxima series (AMS and SMS) of both rainfall and river flow. An estimate for trends in time is obtained via ordinary least square regression, assuming a log-normal distribution for annual and seasonal maxima: the estimated trends can then be translated into a magnification factor which describes how the maximum rainfall and river flow have been changing on a given time scale. We then plot the magnification factor for each rain and river gauge in order to identify possible clusters of upward or downward trends and similarities between changes in rainfall and river flow.

2 METHODOLOGY

The non-stationary frequency model adopted in this study for exploring trends in both annual and seasonal maxima series of rainfall and river flow is based on a two-parameter log-normal distribution (LN2) as suggested by *Vogel et al.* (2011). Assuming a stationary series of extremes, the quantile function x_T derived from a LN2 distribution for a given return period T is defined as

$$x_T = \exp\left(\mu_y + z_T \sigma_y\right) \quad (1)$$

where μ_y and σ_y are the mean and standard deviation of the log transformed maxima series $y_t = ln(x_t)$ and z_T is the standard normal variate with an exceedance probability defined as $p = 1/T$. For the case on non-stationary data, *Vogel et al.* (2011) presented a simple extension to the stationary model in Eq. (1) by allowing the mean of the LN2 distribution to change over time while maintaining a constant standard deviation. The equivalent non-stationary version of the LN2 quantile function is

$$x_T(t) = \exp\left(\mu_y(t) + z_T \sigma_y\right) \quad (2)$$

where $\mu_y(t)$ indicate that the mean value is now considered a time dependent parameter. The observations in the non-stationary extreme series are assumed to be described by a log-linear model as

$$y_t = \ln(x_t) = \alpha_0 + \alpha_1 t + \varepsilon_t \quad (3)$$

where α_0 and α_1 are regression model parameters and ε_t is the regression model error. As the predictions made using the regression model in Eq. (3) can be considered the mean as a function of time, these estimates can be substituted into Eq. (2) as $\mu_y(t)$. Using the model specified above, *Vogel et al.* (2011) devised a simple index of trend in the quantile function by considering the ratio (or magnification factor, M) between the T year event derived at two times separated by Δt years apart, i.e.

$$M = \frac{x_t(t + \Delta t)}{x_t(t)} = \exp(\alpha_1 \Delta t) \quad (4)$$

where α_1 is the slope of the regression model in Eq. (3). In this study the time period Δt is set to 10 years so that M can be interpreted as a decadal magnification factor (*Vogel et al.* 2011). The magnification factor can be derived for any distribution, but the LN2 distribution provides a convenient and transparent analytical solution. Moreover, only for the LN2 distribution does the return period under consideration T not enter into the analytical expression of the magnification factor calculation: this allows for a more objective comparison across possible return periods.

The analysis in this work investigates the changes of the mean value of maximum floods and rainfalls, and assumes that variability is constant throughout the period of record. It would be interesting, although out of the scope of this work, to investigate whether the variability, or higher order moments of the data, are changing with time.

3 NATIONAL DATASET OF EXTREME RAINFALL AND FLOW

The rainfall and flow extremes data used in this study have been extracted from existing databases extensively covering the whole of the UK. Further details are provided below.

3.1 River flow data

The flood data used in this study come from the monthly maxima peak flow data from the UK National River Flow Archive (NRFA), from which annual maximum series (AMS) and seasonal maximum series (SMS) of peak flow were extracted. Only catchments which are classified as being both 'suitable for QMED' and 'suitable for Pooling' in the Environment Agency's HiFlows-UK database dataset v.3.1.1 (*Environment Agency*, 2010) have been included in the study to promote good data quality for the particular purpose of a trend study. A minimum record length of 20 years was imposed when computing the magnification factor and the trend analysis was finally performed on data from a total of 524 catchments. The average record length was 40.36 and the median 40. The longest record is the Dee at Manley Hall (gauging station 67015) for which data is available between 1936 and 2012.

3.2 Rainfall data

Annual and seasonal maximum one-day rainfall totals have been extracted from a national database of rainfalls observed at gauges located throughout the UK. These data derive from the Met Office rain gauge network. Similarly to river flow, a minimum record length of 20 years was imposed when selecting rainfall series used for computing the magnification factor. The trend analysis was performed on data series from a total of 3793 rain gauges. The average record length was 35.46 and the median 31. The longest records are at Oxford and Armagh (stations 256225 and 947811, respectively) for which data are available between 1853 and 2004.

In order to allow a comparison between the results for the flow and rainfall data, the same annual and seasonal time windows were applied when extracting the maxima. Thus, annual maxima series were extracted based on the calendar year maxima, and the summer and winter seasons were defined as May to October, and November to the successive April, respectively. It should be noted that the rain gauge network is much denser than the river flow network, and both network are not homogenously scattered across the country; some areas inevitably have a better coverage than others. Also, the record length for rain and flow gauges in the same region can be quite different, making difficult any direct comparison between regional clusters of upward or downward trends in rainfall and flow. A possible solution for this issue would be to only analyse stations for which data cover a given period, but this has not been pursed in this work,

4 RESULTS

The magnification factor, M, in equation (4) was computed for the annual and seasonal maxima series (AMS and SMS), for both flow and rainfall data, using all the available data for each station where the record length exceeded 20 years. Since the method presented in Section 2 assumes that the data come from a LN2 distribution, a Shapiro-Wilk test at a significant level $\alpha_{SW} = 0.025$ was performed on the residuals of the model fitted in equation (3). If the test gave indication of normal residuals, and therefore an indication of an appropriate model, a further test on the significance of the regression coefficient $\alpha_1$was performed at a significance level $\alpha_{RC} = 0.1$.

First, the results are presented for the AMS of peak flow (Figure 1(a)) and daily rainfall (Figure 1(b)). In both plots, most of the regression models turned out to be not significant at the given significance level. In addition, except for a few river flow records, significant magnification factors are fairly close to 1, indicating a relatively small upward or downward trend. No obvious clustering of positive or negative trends can be identified. What does appear as a local pattern is the cluster of non-normality of the residuals in the southeast of the country: it would seem the log-normal distribution is not appropriate to model the maximum values of the peak flow in parts of the southeast. This largely coincides with outcrops of permeable aquifers in this particular area, which exerts a strong influence on the local hydrology, with the considerable underground storage leading to slowly responding catchments. The strongest negative trend in AMS peak flow data (Figure 1(a)) occurs at the gauging station on the North Tyne at Tarset (station 23005). A closer inspection of the meta-data for this catchment shows that the observed trend does not represent a natural decrease in the flow, but rather reflect the large influence of the Kielder reservoir constructed in 1980. For the second smallest value of M, recorded for the Yeo at Veraby (station 50012) in south west England, a more careful inspection of the data shows an abrupt change in the data. It is uncertain what, exactly, caused this, but it explains the strong negative trend. Similarly, the data from the gauging station on the Usway Burn at Shillmoor (station 22003), located in northeast England, show an abnormal change which is likely to be the cause for the high value of the M value found here.

Next, the results for the summer maxima series of both peak flow (Figure 2(a)) and daily rainfall (Figure 2(b)) are displayed. In Figure 2(a), beside the strong negative trend shown again for station 23005, there is a cluster of catchments with a downward trend in summer maxima peak flow in the south-eastern part of England. In contrast, localized clusters of increased summer maxima peak

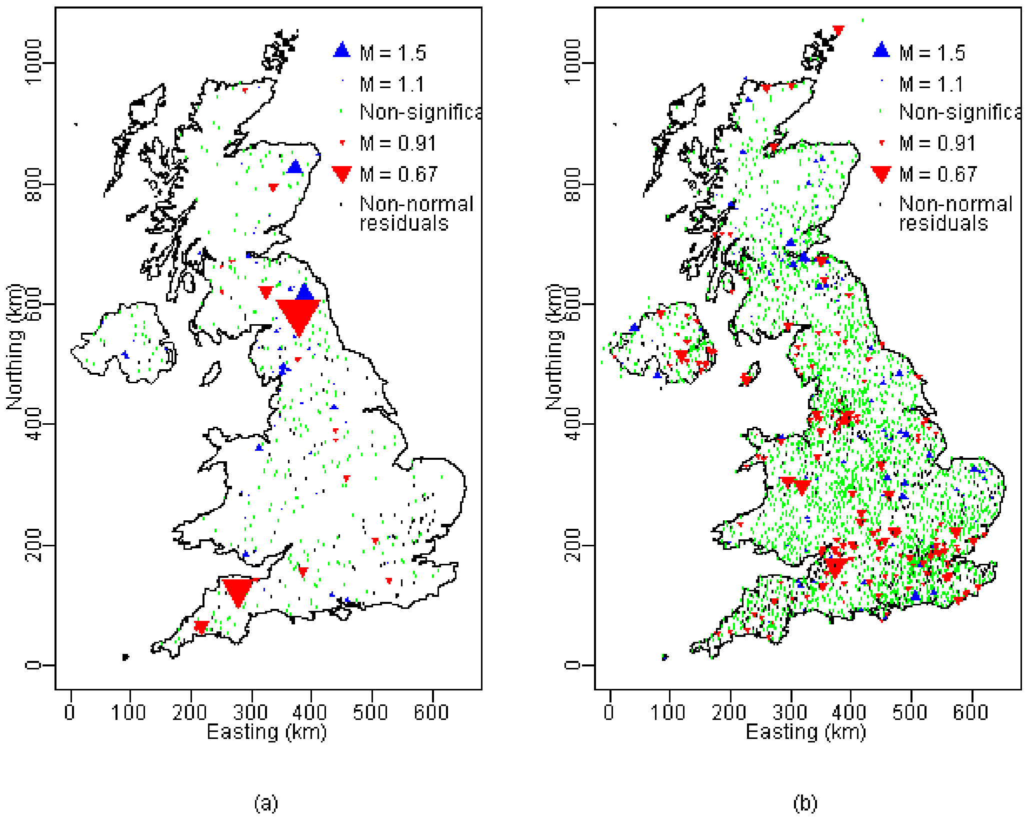

Figure 1. Magnification factor *M* for annual maxima of river flows (a) and daily rainfall (b - © British Crown copyright 2013, the Met Office) with a record length of at least 20 years.

flow are evident in Northern Ireland, south Wales and Cornwall. Intriguingly, there is no evidence of a corresponding upward trend in the daily rainfall series in these locations. In contrast, when a relevant change can be observed in these locations it would be in most cases a decrease in the daily rainfall maxima.

In Figure 3 the corresponding results are shown for the winter maxima series of peak flow (a) and daily rainfall (b). No obvious spatial clusters can be found in the derived magnification factors for the winter peak flows, while it would seem that the winter maximum daily rainfall in southern Scotland is showing an increase over time. Both the winter and annual maxima peak flow series reveal clusters of catchments with non-normal residuals in the aquifer outcrop areas of the southeast of the UK, whereas this pattern is less clear for the summer analysis.

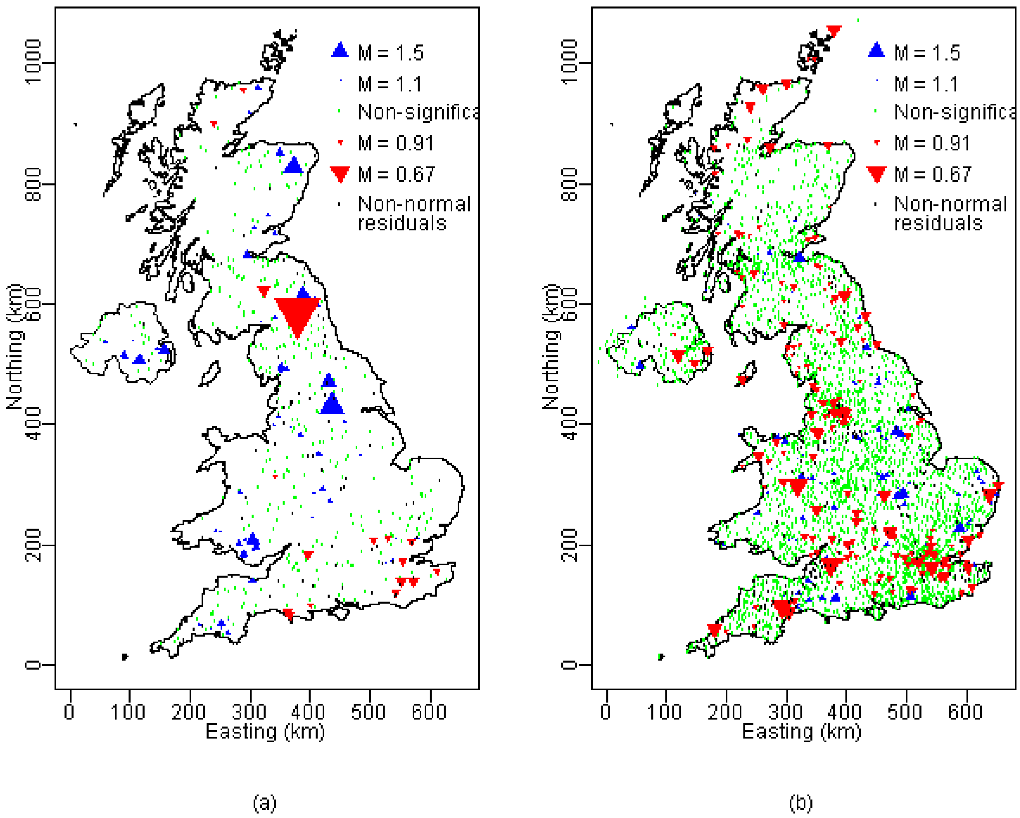

Figure 2. Magnification factor *M* for summer maxima of river flows (a) and daily rainfall (b - © British Crown copyright 2013, the Met Office) with a record length of at least 20 years.

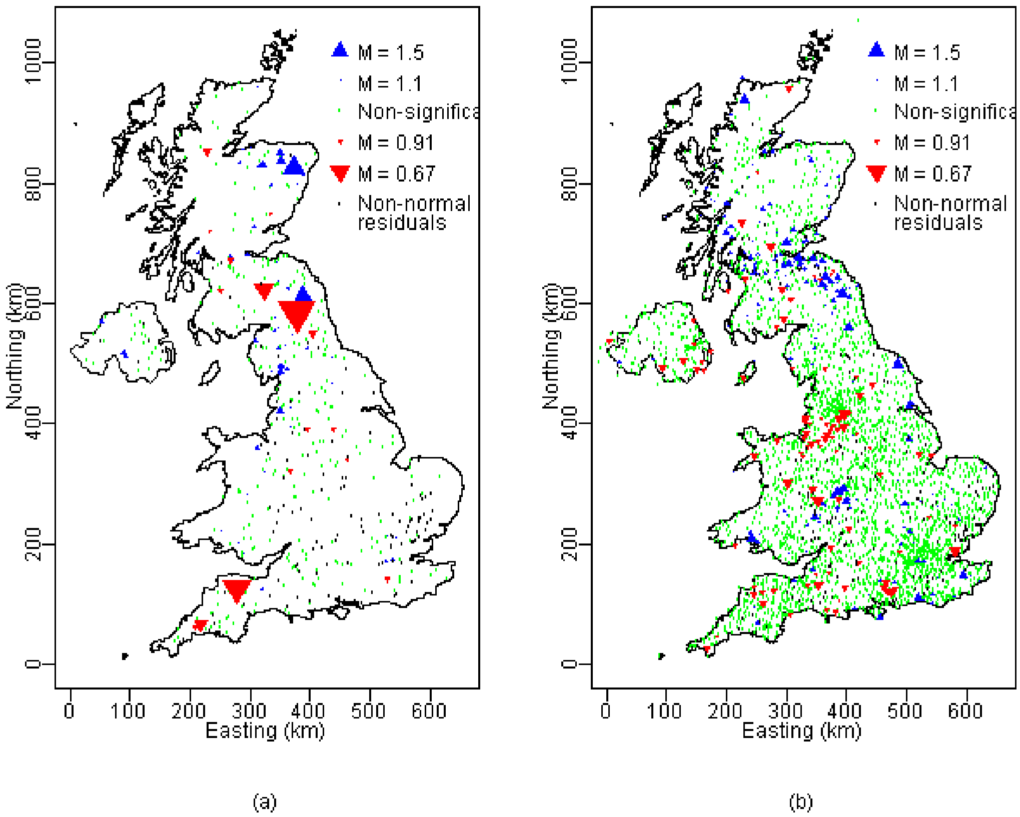

Figure 3. Magnification factor *M* for winter maxima of river flows (a) and daily rainfall (b - © British Crown copyright 2013, the Met Office) with a record length of at least 20 years.

5 SUMMARY AND CONCLUSION

The results presented in this paper explored if relevant trends in long-term series of peak flow and daily rainfall could be identified in the UK. Trend estimation relied on ordinary least square regression on log-transformed annual and season maxima. The analysis was based on the most comprehensive databases of hydro-metrological extremes covering the entire UK. The study did find some localised evidence of both upward and downward trend in the extremes series. However, the fact that the strongest magnification factors in peak flows have been found in catchments for which the presence of strong human influence or data issues were evident, underlines that it is important to consider such anthropogenic effects as changes in land-use and reservoir construction in further studies. This will provide a more valid assessment of the degree of non-stationarity evident from the data due to other factors, such as climate change. Importantly, the changes identified in annual and seasonal maxima series of peak flow do not seem to be replicated in the maxima series from nearby rain gauges, suggesting that more research is required to understand the drivers of non-stationarity.

This study is the starting point for a more in-depth investigation into the nature of non-stationarity of hydrological phenomena in the UK. The use of the LN2 distribution simplifies the approach and reduces the problem of calculating the magnification factor to a standard least square problem. However, least square regression estimates are known to be sensitive to outliers, especially in relatively short records, but corresponding results obtained using robust regression (not presented here) do not differ much from the results obtained by using ordinary least squares.

Further, the assumption of log-normality might be inappropriate for the flow data in some catchments (for example the permeable catchments in the southeast) and for some rainfall data (possibly because of high skewness in more convective areas).

Finally, the spatial structure of the data has not been taken into account in this work. It is well-known that maximum series of both flow and rainfall extremes recorded at neighbouring gauges will be strongly correlated (e.g. *Keef et al*., 2009). This inter-site dependence needs to be accounted for in the significance tests in order to provide a more correct assessment of the significance level of the observed trend estimates.

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