Contrasting seasonality of storm rainfall and flood runoff in the UK and some implications for rainfall-runoff methods of flood estimation

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ABSTRACT

Using data from 520 gauging stations in Britain and gridded rainfall datasets, the seasonality of storm rainfall and flood runoff is compared and mapped. Annual maximum (AMAX) daily rainfall occurs predominantly in summer, but AMAX floods occur most frequently in winter. Seasonal occurrences of annual daily rainfall and flood maxima differ by more than 50% in dry lowland catchments. The differences diminish with increasing catchment wetness, increase with rainfalls shorter than daily duration and are shown to depend primarily on catchment wetness, as illustrated by variations in mean annual rainfall. Over the whole dataset, only 34% of AMAX daily flood events are matched to daily rainfall annual maxima (and only 20% for 6-hour rainfall maxima). The discontinuity between rainfall maxima and flooding is explained by the consideration of coincident soil moisture storage. The results have serious implications for rainfall-runoff methods of flood risk estimation in the UK where estimation is based on a depth–duration–frequency model of rainfall highly biased to summer. It is concluded that inadequate treatment of the seasonality of rainfall and soil moisture seriously reduces the reliability of event-based flood estimation in Britain.

Key words | flood, matching, rainfall, rainfall-runoff, seasonality, soil moisture

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INTRODUCTION

Seasonality is an obvious feature of most global climates and is demonstrated in seasonal variations in extreme rainfall and flood occurrence. In Britain, long-duration frontal rainfall and occasional snow dominate in winter, while convective storms in summer increase the frequency and intensity of short-period rainfall. This seasonality is intensified by higher temperatures and evaporation in summer compared with winter, with resulting seasonal variation in soil moisture status at the onset of storm rainfall.

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An early illustration of the contrast in the seasonality of storm rainfall is provided by the Flood Studies Report (FSR) (NERC 1975) which showed how monthly and seasonal maximum rainfall compare as a percentage of annual maxima in Britain. Seasons were defined as 'summer' (six months: May–October) and 'winter' (six months: November–April) (Volume II, Meteorological Studies Table 3.9). The contrast between summer and winter rainfall was shown to be greatest in areas of low average annual rainfall (standard average annual rainfall (SAAR) 500–600 mm) compared with wetter areas (SAAR >2,000 mm) and was much stronger at short durations (1 hour) compared with durations of 1 day or more. Dales & Reed (1989) found that the mean date of occurrence of annual maxima daily rainfall ranged from mid-August in eastern and central England to late October in SW England. Jakob (1995) studied the average occurrence date of 1-day POT (peaks-over-threshold) rainfall extremes and showed that in Scotland and Wales, most events occur during late autumn and winter, whereas in most of England the average date is in summer and early autumn.

Flood occurrences show a very different seasonal pattern. Bayliss & Jones (1993) examined the seasonality of flooding using four 3-month seasons, showing that winter (December/January/February) is the dominant season for flooding in all areas of the country but with a tendency for an earlier autumn (September/October/November) peak in wetter areas to the north and west. They noted a strong connection with soil moisture deficit because these areas return to near field capacity earlier in the year than those in the south and east. Few stations (mostly urban and small catchments) have summer as peak flood season.

Black & Werritty (1997) identified patterns of seasonal flooding in Scotland using a common 10-year period for a database of 156 gauging stations in Scotland and northern England. They found that most rivers have at least 78% of events in the October–March half-year – later in the year in the east. Although November mean day values are common for both peak rainfall and floods in the west, peak rainfall seasonality becomes generally earlier with distance east while mean day of flood becomes later. Their analysis of controlling factors includes the effect of the catchment area, lake extent and soil moisture status. Macdonald *et al.* (2010) carried out a similar analysis for Wales using 30 years of gauged river-flow records (1973–2002). Flooding occurred earlier in small catchments draining higher elevations in north and mid-west Wales. Low altitude regions in West Wales experienced flooding during October–January, while large eastern-draining catchments experienced later flooding (January–February).

The mismatch between the seasonal timing of extreme rainfall and extreme flood runoff in Britain has been known and investigated for several decades. Archer (1981), using gauged flow data from 46 catchments in northeast England, showed that monthly maximum daily rainfall peaked in summer but never coincided with the seasonality of monthly flood runoff which peaked in autumn in upland catchments and in January in dry lowland catchments. The seasonality of flood runoff was observed to be more closely associated with the seasonality of soil moisture deficit than with that of rainfall maxima. In an example lowland catchment (Skerne at Bradbury), the month of maximum daily rainfall (July) had not a single flood >0.25 year return period in a 21-year record. Cunderlik & Burn (2002) noted that catchments that exhibit a weak relationship between extreme rainfall and flood timing are mainly due to more frequent periods of soil moisture deficit and higher catchment permeability. Webster (1999) also examined the relationship between rainfall frequency and flood frequency and also noted the effects of catchment wetness and soil characteristics and particular problems in permeable catchments.

Seasonality is an important property with respect to flood risk estimation but its effects are usually considered with respect to statistical methods which have two key components – estimation of an index flood, QMED (the median annual flood discharge) and the derivation of growth factors to higher return periods based on a pooling group of hydrologically similar catchments. Pooling schemes are typically based on grouping catchments according to their similarity of catchment topography and local climate. For example, the updated Flood Estimation Handbook (FEH) methodology (Kjeldsen *et al.* 2008), adopted as standard practice in the UK, uses catchment area (AREA), average annual rainfall (SAAR), floodplain extent (FPEXT) and reservoir and lake fraction (FARL). Similarity in flood seasonality is recommended only as a means of reviewing and possibly adapting an initial pooling group. However, other pooling approaches have been developed which are based directly on flood seasonality (Ouarda *et al.* 1993; Burn 1997; Merz *et al.* 1999; Cunderlik & Burn 2001). Burn (1997) used flood seasonal regime descriptors to pool catchments in the Canadian Prairies and demonstrated that this resulted in the effective estimation of extreme flood quantiles. Cunderlik & Burn (2001) described a method of assessing catchment similarity for pooling using seasonality indicators for UK catchments including a flood regime pattern descriptor which describes the similarity of two catchments in terms of the monthly relative frequencies of flood occurrence.

Seasonality, and the mismatch between the seasonal occurrence of storm rainfall and flood flows, also has serious practical consequences for those methods of flood risk estimation that rely on annual statistics of storm rainfall amount, duration and time distribution. The rainfall-runoff (RR) method of flood estimation is one of two recommended for general use in the UK (Institute of Hydrology 1999). Some effects of the seasonality of storm rainfall and runoff are identified explicitly in recent versions of the method, but we contend that the full implications of seasonality have not yet been appreciated. The role of seasonality in successive versions of the RR method is reviewed below.

Seasonality and flood risk estimation using UK RR models

The RR method of flood estimation was developed as part of the FSR (NERC 1975). It has gone through several revisions in the FEH (Institute of Hydrology 1999), 'Revitalisation' (Kjeldsen *et al.* 2005) and in Stewart *et al.* (2010). Although details have changed, the basic philosophy of the method remains the same. While a specific peak discharge may be produced from an infinite number of combinations of rainfall properties and antecedent catchment wetness, the object of the RR method is to reduce this variety to manageable proportions. The FSR RR method was based on the results of a simulation study to provide criteria for the selection of combinations of antecedent moisture condition and the return period of design rainfall to produce flood hydrographs with a specified return period. Although more complex in design and implementation than the alternative statistical method, it has the advantage of providing a full design hydrograph along with a peak discharge of given annual probability. The effects of the seasonality of storm rainfall and runoff are identified explicitly not only in recent versions of the method (i.e. the ReFH method) but also implicitly in these and earlier versions.

At the core of the FSR and subsequent RR methods is the provision of a depth–duration–frequency (DDF) model of *all year* rainfall mapped over the country. The FSR version used an interpolation between 2-day and 60-minute rainfall to provide estimates of rainfall of the given return period and duration for locations throughout the country. No explicit allowance was made for differences in seasonal rainfall magnitude but, given the dominance of intense short-period rainfall in summer, the annual series is strongly biased towards summer rainfall, especially at durations of less than 1 day. In addition, for individual catchments there was no explicit allowance for differences between summer and winter in initial catchment wetness as expressed through a Catchment Wetness Index (CWI); the design percentage runoff between events of different return periods only varied with the design storm precipitation. The CWI does vary between catchments with SAAR but even here it varies minimally for catchments with an annual rainfall >850 mm and is biased towards winter conditions. The FSR RR method provided alternative seasonal design storm profiles for summer and winter but for the majority of catchments with urban and suburban land cover with urban extent (URBEXT) <0.125, the winter profile was recommended as 'on predominantly rural catchments floods normally occur in winter'. Hence, flood estimation was based on a rainfall magnitude biased towards summer, winter antecedent conditions and a winter storm profile.

As shown below summer-based annual maximum (AMAX) rainfall only rarely leads to an AMAX flood. The FSR implicit means of accounting for the mismatch of rainfall and flood occurrence was through inequality of the rainfall return period and the peak flow return period. Thus, an 81-year return period storm rainfall was specified to result in a flood peak return period of 50 years. This may have been a logical way of dealing with the mismatch of rainfall biased towards summer and flow biased towards winter. However, there was no corresponding means of providing an upward bias in the return period between lower rainfall in winter and the higher flow return period, such as was noted by Webster (1999).

The FEH adopted the general principles of the FSR model but developed a new rainfall DDF model based on a much larger dataset than had been available for FSR (Institute of Hydrology 1999). It adopted a 2-year rainfall depth (RMED) rather than the 5-year rainfall of FSR as the index variable but again with respect to annual maxima rather than subdivided by season. That summer rainfall events dominate in determining the all-year growth curve was acknowledged. The procedure continued to apply a scaling factor to allow unequal rainfall and flow return periods as the FSR and to use the same basis for the application of winter or summer rainfall profiles. The longer datasets permitted more flexible regionalisation.

However, Babtie (2000) found that estimates for 150 years 1-hour rainfall were substantially higher in the FEH than in the FSR, except for parts of eastern Scotland; estimates were more than 50% greater in many upland areas in the west and in much of eastern England. Estimates of *T*-year flood magnitudes were generally found to be higher than FSR estimates (Spencer & Walsh 1999; Ashfaq & Webster 2002). Ashfaq & Webster (2002) did not discuss seasonality but identified serious problems with the estimation of percentage runoff in catchments with rainfall <800 mm – potentially related to the mismatch of rainfall and flood seasonality. In addition, the combination of the FSR design model with the FEH DDF was generally believed to result in design floods of excessive magnitude and exceeded estimates using the FEH statistical method (Kjeldsen *et al.* 2005).

As a result, a revitalisation of the FSR/FEH model was initiated, referred to as ReFH. It specifically recognised problems arising from the combination of design storm rainfall mainly in summer and typical winter soil wetness. However, the design rainfall continued to use the DDF model developed for FEH using *annual* (rather than seasonal) maximum rainfall (Faulkner 1999). ReFH then used a 'seasonal correction factor' as a multiplier of annual rainfall to determine a seasonal design rainfall depth. This factor was derived by fitting a ratio between annual and seasonal maxima for daily and sub-daily rain gauges (mainly in central England) against annual rainfall (SAAR) for a range of durations and for each season. For the winter season, it was modelled using an exponential distribution (ReFH Appendix G), but it is noted that the graphical relationship shows a very wide spread of points, with progressively increasing spread for durations of less than one day and for catchments with SAAR less than 1,000 mm. For a given catchment, separate seasonal estimates are not recommended but, as in previous versions, catchments were allocated to winter or summer seasons on the basis of the predominant season of flooding, winter for rural catchments and summer for urban catchments.

The ReFH design method was calibrated to ensure that flood frequency curves derived from the method correspond with those derived from the FEH statistical method. The inequality between rainfall growth curves and flow growth curves derived from a pooled analysis of AMAX series was perceived as a problem; the rainfall growth curves were steeper. This implied that rainfall inputs must be reduced by a greater amount at high return periods than at low return periods. The FSR/FEH solution of using a scaling factor between rainfall and a flow return period was thus abandoned in favour of an equal relationship, 'in order to increase transparency'. Instead, an adjustment (α parameter) was introduced as a multiplier for the initial soil moisture condition (C_{ini}) to ensure that the design rainfall of a given return period translates to the same return period flow by reducing runoff production as return period increases. Although Kjeldsen *et al.* (2005) state that the parameter α 'does not have a direct physical interpretation,' it seems clearly related to seasonality and the design values were specified separately for winter (rural) catchments and summer (predominantly urban) catchments. In both cases, the effect of α is to reduce runoff production as the rainfall return period increases but by a larger amount on summer catchments. Subsequent versions of RefH (ReFH2 onwards) developed an approach for estimating C_{ini} that did not require the alpha factor through the use of an alternative C_{ini} model.

As the estimates by the ReFH method were designed to correspond with FEH statistical estimates rather than observed flood frequencies, it lost some of its value as an independent flood peak estimation method and possibly incorporated some of the bias and uncertainty associated with the statistical method. Its main advantage then was in providing a flood hydrograph of the specified return period.

In response to concerns, expressed by reservoir engineers, about the apparently high flood estimates when applied to very high return periods, a revision of the FEH DDF model was commissioned by Defra (Stewart *et al.* 2010). The main focus of the report was to develop a new statistical model of point rainfall DDF for the UK, especially relevant to longer return periods for reservoir safety evaluation. In addition, further analysis was carried out on ratios of winter/annual and summer/AMAX rainfall for each duration and return period, and concluded that simple predictive models for the ratios could be obtained using SAAR as a single explanatory variable. A new set of seasonal correction factors was derived to use alongside the all-year model. An alternative approach for setting initial conditions was developed based on revised models for setting C_{ini} using the 1:2 year QMED and by reference to QMED estimates for observed data. For Scottish catchments, datasets suggested that there was no significant relationship between C_{ini} and the magnitude of the event and no strong seasonal dependency (Wallingford Hydrosolutions 2016). However, this conclusion may be questioned on the basis of the events used for simulation, as addressed in the discussion.

The intention of this paper is not to provide a new revision of the RR method but rather to draw attention to fundamental problems associated with the representation of seasonality which have persisted through each of the revisions. From the starting point of identifying and mapping the disparity between the seasonality of storm rainfall and flood runoff, the focus is on the influence of the seasonality of initial wetness conditions as exemplified by soil moisture content and mean annual rainfall (SAAR).

Data

AMAX peak flow datasets were obtained from the UK Hiflows database (version 3.1.2, now superseded by the National River Flow Archive holdings). Annual maxima rather than POT have been used because analysis by Archer (1981) indicated that seasonality changes with the annual number of POT peaks that are included; as the number increases (and flood magnitude decreases), there is a tendency for a greater frequency of winter floods. Stations were selected based upon quality criteria defined by HiFlows as well as the available record length. HiFlows uses a quality categorisation based upon whether a station is 'suitable for QMED (median annual flood discharge) estimation', and whether it is 'suitable for pooling'. For this analysis, only those stations that are 'suitable for pooling' have been selected, giving a catchment set of 520. This station subset has then been further refined by removing stations with short record lengths. This was to ensure that for each station, there was a minimum of 20 years of overlapping rainfall and flow record. The resulting station subset of 480 stations contains stations whose flow records cover the period 1960–2002 (for consistency with the gridded rainfall data). The use of the HiFlows quality categorisation provides a basic check on station suitability, principally through the assessment of the rating curve. The second filtering process then ensures that the records used for analysis have a similar length and cover approximately the same time period. HiFlows AMAX is extracted on a water-year basis. Figure 1 shows the geographic spread of stations.

Catchment averaged daily rainfall for each gauged location has been calculated from a gridded 5 km dataset, produced by the UK Met Office (Met Office et al. 2017). Catchment averaged rainfall has been calculated as a simple arithmetic average of the 5 km grid cells contained within, and intersected by, the catchment in question, and AMAX daily rainfall data have been extracted on a water-year basis. Rainfall time series covers the period 1958–2002. Six-hourly AMAX rainfall data are based on a 1 km gridded hourly rainfall dataset for Great Britain using data from over 1,900 quality controlled gauges for the period 1990–2014 (CEH-GEAR1 hr) (Lewis et al. 2018b).

Estimates of monthly soil moisture storage are provided by the CEH Grid-to-Grid hydrological model (Bell et al. 2018). The model is driven by observed climate data (CEH-GEAR rainfall and MORECS potential evaporation) and provides outputs of monthly soil moisture content (mm water/m soil) on a 1-km grid for 1960–2015.

METHOD

The analysis comprises the following:

1. The percentages of annual maxima of daily rainfall and flood peak flow, which occur in summer and winter, are mapped to demonstrate regional variations.
2. The concurrence of dates of AMAX daily and 6-hour rainfall and flood peaks is mapped and analysed.
3. The concurrence of dates of seasonal AMAX floods and AMAX rainfall is mapped.
4. The role of soil moisture is investigated by determining seasonal variations for catchments with a range of mean annual rainfall.
5. On the basis of the above analysis, the implications of seasonality for the various versions of the RR method of flood estimation are discussed.

Figure 1 | The percentage of AMAX daily rainfall (a and c) and peak flow (b and d) occurring in summer (a and b) and in winter (c and d).

RESULTS

Comparing seasonal maximum rainfall and flow

As a first step in assessing the variability of the seasonality of rainfall and flow, the percentage of AMAX daily rainfall and peak flow occurring in summer is illustrated in Figures 1(a) and 1(b). The seasons are defined as used in the FEH RR method, i.e. summer is May–October and winter is November–April. The contrast between the timing of rainfall and flow AMAX is striking. Over the greater part of eastern England and Scotland more than 60% of AMAX daily rainfall occurs in summer, whereas in the same areas, fewer than 20% of AMAX peak flows occur in summer. Summer peak flow occurrences are exceptionally higher in urban catchments, mainly around London. The summer percentage of AMAX daily rainfall progressively diminishes westward to wetter upland catchments: a few catchments in the Lake District and northern Scotland have <20% of AMAX daily rainfall in summer, but the majority of catchments in Wales and Scotland fall in the range of 20%–40%. However, in these areas, even fewer AMAX flow events occur in summer, with the majority of catchments having <20%.

Winter patterns of percentage rainfall and flow (Figures 1(c) and 1(d)) are the inverse of the summer patterns, with the west and north generally showing AMAX rainfall percentages >60% but commonly <20% in the southeast. In winter, AMAX flow events are often >80% of the annual total.

The contrast between AMAX rainfall and flow frequency in summer for given ranges of SAAR is highlighted in Figure 2. At SAAR <700 mm, AMAX rainfall is above 70% and summer AMAX flows around 20%; the difference in frequency is more than 50%. Summer AMAX rainfall frequency falls steadily with increasing SAAR; falling below 50% at 1,000 mm SAAR, whereas summer flood frequency increases slightly at SAAR >1,000 mm, then remains steady for catchments with the highest SAAR levels. At SAAR >900 mm, there is a rapid fall in the difference so that at SAAR >1,000 mm, the difference is generally <20%, with a slow decrease at the highest SAAR. This analysis is based on daily rainfall AMAX but, as shown later, the discrepancy becomes even greater for

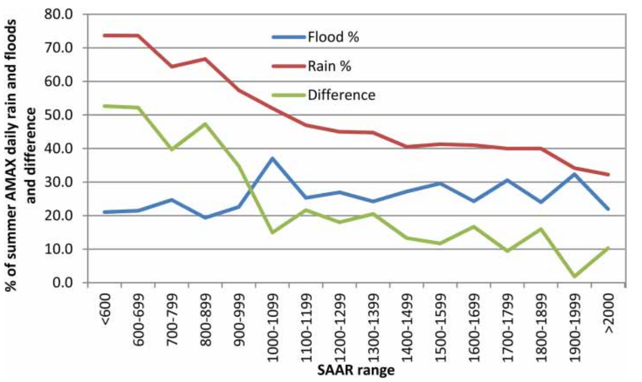

Figure 2 | The percentage of AMAX daily summer rainfall and summer flood occurrence and the difference for given ranges of SAAR.

AMAX rainfall of <1-day duration, typical of the design duration for catchments using RR methods.

Matching of daily AMAX rainfall and flow

The seasonal incidence of AMAX floods and rainfall is described above, but the following section looks in more detail at the concurrence of individual AMAX rainfall and AMAX flow events. Given the use of AMAX rainfall in the RR method of flood estimation, consideration is given to the frequency with which peak flow events are matched to annual rainfall maxima. In the first instance, matching is with respect to readily available daily rainfall AMAX (Figure 3(a)). Matching assesses whether or not a rainfall event could reasonably be considered to have generated a flood flow peak and the percentage of events matched for each catchment is mapped. The analysis does not consider the magnitude of the events in either record. Allowance is made for a lag between rainfall and runoff by assuming correspondence from rainfall on the day of the flood and the previous day, but seven large catchments with longer lag, such as Trent and Severn, are omitted from the analysis.

The median number of matched events for the whole of Britain is 34%. Regionally many catchments in southeast England have fewer than 15% matched dates and, with few exceptions, matched occurrences are <30%. Matched dates increase in numbers westward to wetter upland catchments in Wales, the Lake District and Pennines and in Scotland but even here very few catchments have >50% matched events (7% of catchments). With respect to

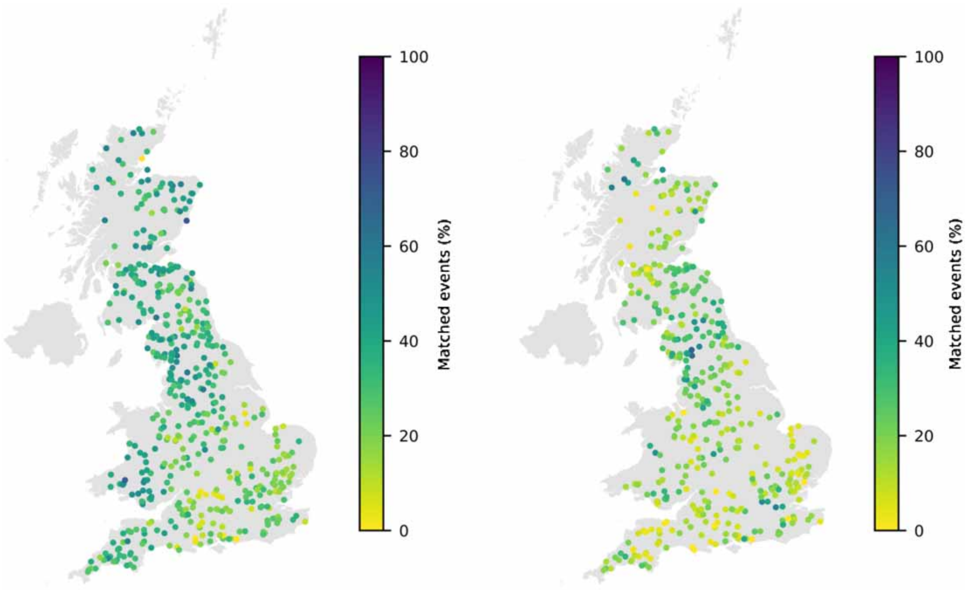

Figure 3 | (a) The percentage number of flood peaks at each gauging station that are matched to daily rainfall maxima. (b) The percentage number of AMAX flood peaks that are matched to AMAX 6-hour rainfall.

annual rainfall, the average number of matched events for SAAR <600 mm is 18%, increasing steadily to 42% for catchments with SAAR >1,800 mm. There is little difference in the percentage matched between small and large catchments. Likewise, there are similar percentages for rural catchments (URBEXT <0.01) (36%) and those with URBEXT >0.1 (32%). However, the percentage matched appears to dip for intermediate URBEXT from 0.04 to 0.10 to an average of 25.5%.

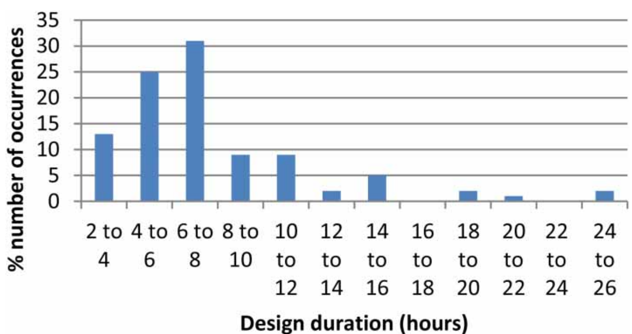

Figure 4 | The percentage number of catchments in each range of design duration catchments selected for analysis in the UK RR method (Kjeldsen *et al.* 2005).

Matching of 6-hour AMAX rainfall and peak flow

Rainfall statistics for most seasonality studies in the UK are based on daily rainfall (Black & Werritty 1997; Macdonald *et al.* 2010). As shown by the FSR (Vol. II) analysis, the seasonality of sub-daily rainfall becomes progressively focused on the summer season with decreasing duration, given the intensity of short-period convective storms. The effect of duration is particularly important for the application of the UK RR method where the design storm duration is based on the time to peak (T_p) of the unit hydrograph modified by annual rainfall. Since the RR method is recommended for use only on catchments <500 km^2, design durations are generally much less than a day. Figure 4 shows the time distribution of design durations for catchments analysed in Kjeldsen *et al.* (2005). Only 2% of catchments have design durations >24 hours and 70% are <8 hours. The median design duration is 6.6 hours. The frequency of matching of 6-hour maximum annual rainfall with peak flow events was selected and is shown in Figure 3(b) and contrasted with that of AMAX daily rainfall.

Although the 6-hour dataset covers a shorter period than for daily rainfall, a regional comparison of daily and 6-hourly rainfall matching with flood runoff in Figure 3 shows clearly the reduction in matching for the shorter rainfall duration. Catchments with <10% matching dates are spread widely over southern and eastern England but even appear in some wetter areas of Scotland. The average over all catchments is 20% matched, reduced from 34% for daily rainfall. Catchments with SAAR <600 mm have an average matching of 10%, increasing steadily to 25% for catchments with SAAR >1,500 mm. Sorted by AREA, the smallest catchments (<20 km^2) have the largest matched percentage (23%), but there is no obvious relationship between the area and matched percentage for the full range of catchments (>20 km^2). With respect to URBEXT, the pattern of 6-hourly matching is similar to that for daily rainfall maxima with similar matched percentages for rural catchments (URBEXT <0.01) (24%) and urbanised catchments (URBEXT 0.10–0.40) (23%) but a reduction for intermediate catchments (0.04–0.10), which generally ranges from 12% to 18%. The average matching of the nine most heavily urbanised catchments (URBEXT >0.40) is strikingly different from other catchments at 39%, higher than that for daily rainfall AMAX. This possibly reflects the rapid response to intense summer rainfall.

Matching of AMAX daily rainfall and AMAX flow in the given season

We now consider the percentage of summer and winter AMAX floods that are caused by AMAX daily rainfall in Figures 5(a) and 5(b).

Although the percentage of AMAX flows that occur in summer is low (Figure 1(b)), the percentage of these events that are generated by an AMAX rainfall (biased towards summer) is high (Figure 5(a)). This is the case irrespective of location or catchment wetness; catchments with over 80% matching AMAX rainfall and summer flow occur from northwest Scotland to southeast England. This pattern results from either exceptional intensity or amount of summer rainfall or from an unusual coincidence (in dry catchments) between exceptionally high summer initial wetness and storm rainfall. In contrast, very few AMAX winter flows are generated from an AMAX rainfall event (Figure 5(b)). This is especially the case in lowland

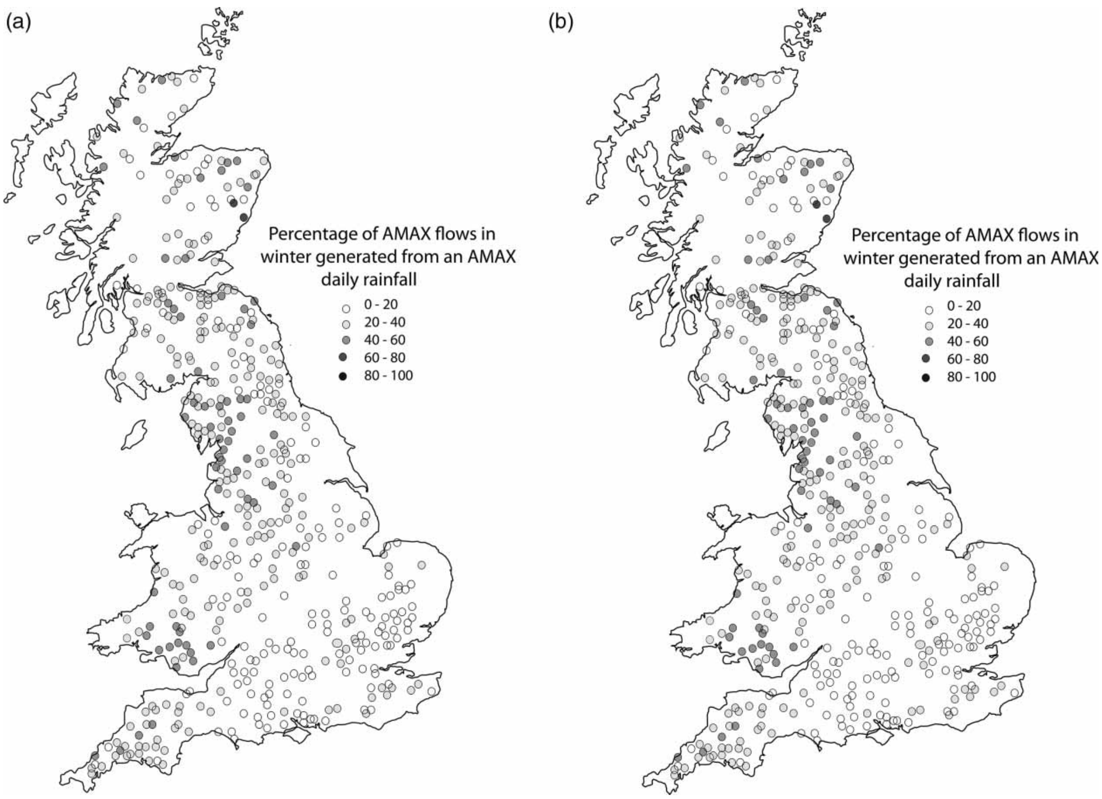

Figure 5 | The percentage of (a) summer and (b) winter AMAX flood maxima generated by an AMAX daily rainfall.

catchments in southeast England where most catchments have fewer than 20% of events matched.

Seasonality of soil moisture content

River flooding depends not only on incident rainfall on a catchment but also by 'losses' mainly caused by storage and delay in soil and substrate. Losses vary not only by catchment depending on soil permeability but also by current soil moisture storage which depends heavily on rainfall seasonality and specifically on antecedent rainfall in the current season which determines soil moisture storage at the onset of a storm. The seasonality of soil moisture storage is investigated using soil moisture outputs from the Centre for Ecology and Hydrology Grid-to-grid hydrological model (Bell *et al.* 2018) with the 1-km grid aggregated to catchment averages. Four catchments with a range of wetness (Figure 6) are used to compare between catchments and between months and seasons. For each catchment, the variability of monthly moisture storage is shown for 10%, 25%, 50%, 75% and 90% probability of occurrence in relation to the mean annual maximum soil moisture storage for the given catchment. We have focused on three catchments in the SAAR range where the contrast between seasonal rainfall and flow frequency AMAX is greatest and most rapidly changing with SAAR (Figure 2). These also represent lowland catchments where economic activity and potential economic loss from flooding is greatest. Clog y Fan is used

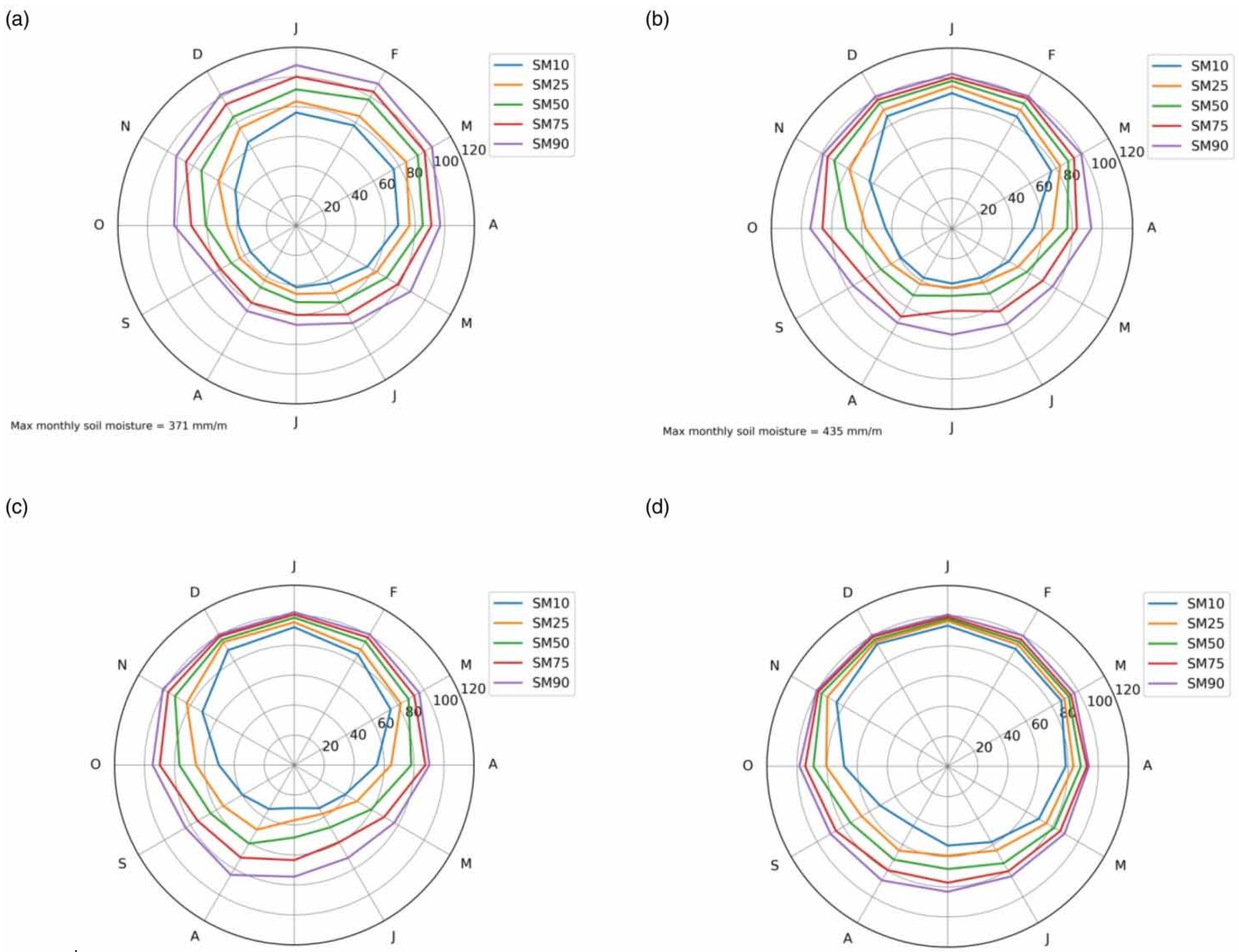

Figure 6 | Variations in monthly soil moisture storage as the percentage of mean annual maximum showing median, 10%, 25%, 75% and 90% occurrence for the period 1960–2015 for (a) Blackwater at Appleford bridge, (b) Cherwell at Banbury, (c) Wansbeck at Mitford and (d) Taf at Clog y Fran.

as a contrast. The analysis does not define field capacity – soil may be saturated and exceed field capacity. The catchments are as follows:

The Blackwater at Appleford Bridge is a dry lowland catchment in East Anglia with SAAR of 572 mm and an area of 247 km^2 with the bedrock of London clay and chalk overlain by boulder clay. Seasonally, 80% of AMAX flows occur in winter but only 26% of daily AMAX rainfall. Just 20% of AMAX flows and daily rainfall AMAX are matched (and 7% of 6-hour AMAX rainfall).

The Cherwell at Banbury is a headwater tributary of the River Thames with SAAR of 664 mm and an area of 199 km^2 and mainly impermeable geology. Seasonally, 84% of AMAX flows occur in winter.

The Wansbeck at Mitford is a mainly lowland catchment in northeast England with SAAR of 794 mm and an area of 287 km^2 with an extensive boulder clay cover to rocks of variable permeability. Seasonally, 79% of AMAX floods occur in winter compared with 50% of daily AMAX rainfall. 31% of AMAX flows and daily rainfall events are matched.

The Taf at Clog y Fran is a steep catchment in south Wales with an annual rainfall of 1,420 mm and an area of 217 km^2 with a mainly impermeable geology. Seasonally, 71% of AMAX flows occur in winter and 53% of daily AMAX rainfall. 36% of AMAX flows and rainfall are matched.

The obvious common feature of these catchments is that soil moisture content (SM) is at a maximum in winter coinciding with the seasonality of flood peaks. SM is at progressively longer duration near the maximum from drier (Figure 6(a)) to wetter (Figure 6(d)) catchments. For the Blackwater, the driest catchment (Figure 6(a)), SM does not peak until February and March and is low during the summer even in the wettest years. The transitional months of April and October are particularly revealing with respect to the influence of SM on flood occurrence. Through the autumn SM increases slowly at Blackwater and Cherwell and October SM is lower than in April. At these dry catchments and at 59% of catchments with SAAR <700 mm, a larger percentage of peak flows occurs in April than in October, in spite of the fact that April is a month of infrequent storm rainfall and low average monthly totals. October floods are with few exceptions more common than April floods on wetter catchments. This observation supports the conclusion that soil moisture is a strong determining factor in the seasonal occurrence of AMAX floods. With increasing wetness, SM in the River Wansbeck (Figure 6(c)) reaches an earlier maximum in December. The Taf (Figure 6(d)) shows a little change in median SM from November to April and continuing high levels for the remainder of the year providing the potential for greater correspondence of rainfall and flood seasonality.

DISCUSSION

FSR (1975) put forward an ambitious generalised plan to assess flood frequency both in terms of peak discharge and hydrograph profile for catchments in the British Isles in the form of a RR model. Reservations about reliability have led to repeated revisions of the procedure (as described above) with some account given to seasonality. However, the focus of each stage of revisions from the original FSR has been with respect to the DDF model based on *annual* rainfall maxima at different durations. As can be seen from the analysis, the rainfall annual maxima occur predominantly in summer, whereas AMAX peak flows occur predominantly in winter. Hence, there is a serious mismatch between the input and the output to achieve the flood estimates. The mismatch becomes more serious at shorter durations. With each version, the possibility of creating separate DDFs for summer and winter has been mooted but considered too demanding of time and resources to prepare. Instead, winter and summer rainfall statistics have been achieved by the manipulation of the annual data.

In our analysis, we have accepted the convention of considering seasonality in terms of two seasons: summer, where soil moisture deficits are usually high, and winter, where soils are expected to be close to field capacity. However, the potential flood risk varies continuously throughout the year. If a RR method is to continue in use, perhaps it is time to reconsider the need for separate seasonal DDFs and the best subdivision of the year between winter and summer.

The perceived advantage of the RR method over the statistical method is in the provision of a design flood hydrograph, although the statistical method is widely recognised to give more reliable estimates of the probability of peak discharge estimates. An alternative method of synthesising a design hydrograph based on the generalisation of the shape of observed flood hydrographs was described by Archer *et al.* (2000) and can be used in conjunction with estimates from the statistical method. This method has now been generalised for use in ungauged as well as gauged catchments and is widely used in Ireland (O'Connor *et al.* 2014).

However, given the limitations in addressing seasonality as well as the use of a single idealised unit hydrograph, consideration must be given to abandoning the RR approach altogether in favour of continuous simulation (Boughton & Droop 2003; Lamb *et al.* 2016). This methodology employs a long rainfall series (either observed or more powerfully, synthetic) to drive a continuous RR model simulation. The model then automatically accounts for antecedent soil moisture and seasonality, and generates an ensemble of flood peaks which can be analysed as required to estimate flood frequency. In addition, continuous simulation delivers 'hydrographs' and volumes, over multiple time scales which are more realistic (and crucially for robust design, diverse) than the Unit Hydrograph single idealised event shapes. Modern computational platforms and databases now allow the systematic and national application of these methods. (Lewis *et al.* 2018a). While the input rainfall series (either observed or synthetic) can straightforwardly represent seasonality, a key limitation of this approach is how well the extremes are represented, especially in terms of clustering in time, which is crucial to the antecedent conditions. Observed series by definition are not long enough to adequately represent the variability of the most extreme floods (i.e. of 100-year return period and higher). Recourse to synthetic rainfall series allows much longer return periods to be addressed, and recent developments (e.g. Serinaldi & Kilsby 2014) can successfully reproduce observed variability of extremes. Nonetheless, fundamental challenges remain in validating such approaches due to short observed records, which also prevent the clear identification of trends in extremes in the face of considerable natural variability (Serinaldi & Kilsby 2015).

A hidden problem of seasonality may arise from the data with which C_{ini}, the initial catchment wetness, has been determined. The set of events used to create the FSR RR method used only those events where flooding occurred (and not the full set of rainfall events, including those which did not cause flooding), whereas in estimation mode the full rainfall AMAX set is applied. Thus, since only those rainfall events were used which caused flooding, these were inevitably biased towards winter events and those in which soil moisture deficits were sufficiently high (or rainfall exceptional). The derived C_{ini} values are likely to be high and less variable in comparison to the values applied to the full rainfall set. This issue was first raised by Archer & Kelway (1987) with respect to the FSR RR method pointing out that the number of excluded events was greater in drier than in wetter catchments. The result of recombining a truncated percentage runoff set with a complete rainfall set may be to overestimate the discharge for frequent events, especially on dry catchments. There has been no subsequent change in the procedure for the updated versions.

The comparison of seasonal AMAX rainfall and flood peaks shows that dates of occurrence are infrequently matched, especially on dry catchments, whereas there is much greater correspondence in flood and soil moisture seasonality. The analysis confirms earlier conclusions by Archer (1981) and Bayliss & Jones (1993) that occurrence and variability of soil moisture deficit are strongly connected with the seasonality of flood occurrence.

The results of this analysis also have a bearing on projections of changes to the future river flooding based on climate change projections. Lowe *et al.* (2018), in UKCP18, note that overall projections of summer rainfall to 2100 indicate a decline over most of the country with the greatest reduction in the south of England of −40% relative to the baseline of 1981–2000. However, Kendon *et al.* (2014) note that, despite this overall reduction, intense summer rainfall events may become more common in future, suggestive of increased flood risk. The latest high-resolution 'convection-permitting' climate model projections suggest that alongside this droughts are likely to be more intense with more prolonged periods of high soil moisture deficits (e.g. Chan *et al.* 2018). Given the current role of soil moisture in limiting river flooding from intense rainfall, the intensification of storm rainfall may not lead to greater river flooding in summer unless there is a concurrent increase in the risk of wetter initial conditions. The reverse is more likely to be the case. In contrast, winter rainfall is projected to increase by >20% by 2080–2099 for much of the UK under most emission scenarios (Lowe *et al.* 2018). The combined effects of increased rainfall and soil moisture storage are likely to lead to more extreme winter flooding and enhance the contrast between winter and summer flood seasonality.

The analysis as described has certain limitations; it refers to flood risk from rivers but not from surface water where the seasonality of pluvial flooding is predominantly in summer and linked more directly to the seasonality of intense rainfall (Archer & Fowler 2015). In addition, it considers the seasonality of all AMAX river floods but does not distinguish the seasonality of the most extreme floods which may differ from the full AMAX dataset. Risks from extreme summer floods such as occurred in 2007 and 2012 are particularly noted when there was a concurrence of intense rainfall with unusually wet catchments (Marsh & Hannaford 2007; Parry *et al.* 2013). Further research should be conducted, based on a selected number of top-ranked floods for each gauged record. In response to previous criticisms of the RR method (Archer & Kelway 1987; Archer 1997), it has been argued that it is not appropriate to highlight weaknesses in individual elements of the package since the calibration to match observed flood frequency curves was achieved through the combination of elements (the UK, percentage runoff, DDF and baseflow) (Lowing 1998). However, it does seem appropriate to ensure that a combination of elements is realistic in relation to observed behaviour on catchments as a whole and particularly whether this continues to be relevant to climate change. The methods to the most recent version show a general lack of realism with respect to seasonality.

CONCLUSIONS

1. With respect to flood risk assessment, AMAX peak river discharge is always caused by heavy or intense rainfall (or snowmelt).
2. AMAX rainfall at 6 hours and daily only rarely causes AMAX flood (especially in dry catchments).
3. Thus, heavy rainfall is a necessary but not sufficient condition for flooding to occur.
4. AMAX daily and sub-daily rainfall occurs predominantly in summer; AMAX flooding occurs predominantly in winter.
5. The discontinuity between rainfall and flooding is explained by the consideration of coincident soil moisture storage.
6. On dry catchments, the seasonality of flooding coincides with the seasonality of soil moisture storage more than with intense rainfall.
7. The discordance between seasonal rainfall maxima and seasonal flooding is of theoretical relevance and practical importance for flood risk estimation using the FSR/FEH RR methods as the methods are based on AMAX rainfall statistics heavily biased towards summer, particularly in the south and east of the UK.
8. With respect to climate change, an increase in the intensity of rainfall in summer may not lead to an increase in flooding unless there is an increase in the probability of concurrent catchment wetness.
9. For the better simulation of the effects of antecedent soil moisture on flood generation, continuous simulation offers an effective way forward, potentially handling automatically not only the observed variability but any changes in seasonality projected by the new generation of climate models.

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