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Urbanisation impacts on storm runoff along a rural-urban gradient

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1 Introduction

Urban development brings an increase in impervious surfaces that reduces rainfall infiltration to underlying soils and surface storage capacity (Booth, 1991) with a concomitant rise in the degree of artificial drainage that acts to convey runoff through more efficient pathways (Boyd et al., 1994). The combined effects include an increase in storm runoff (Burn and Boorman, 1993) and volume (Kjeldsen et al., 2013), reduction in baseflows (Simmons and Reynolds, 2013) and shortening of catchment response times (Smith et al., 2005; Anderson, 1970) resulting in a more flashy response (Baker et al., 2004). Urbanisation thus presents a particular challenge to planners as the development of previously rural or low urban density catchments will potentially alter the rainfall-runoff response and require careful planning to manage the changes in the timing and quantity of water moving through the catchment. Coupled with projected increased frequency of extreme rainfall events as a result of climate change, this poses a significant environmental risk in the form of pluvial and fluvial flooding (Bell et al., 2012; Eigenbrod et al., 2011; Poelmans et al., 2011).

Many studies on the hydrological impacts of urbanisation have been based on field observations (e.g. Hood et al., 2007; Kauffman et al., 2009; Sheeder et al., 2003) and increasingly utilise models calibrated to observations (Bach et al., 2014). In both cases, suitable hydrological metrics are required to quantify hydrological response and subsequently attribute response to differences in land use. Arbitrary flow statistics are not always suitable for quantifying the hydrological impacts of land-use change (LUC) (Mcintyre et al., 2013) and for urban storm events, Braud et al. (2013) show the storm hydrograph provides the most suitable means for comparing hydrological response. In addition, relevant information describing how the catchment differs from a control or baseline condition is required. LUC in urban areas is highly complex and as such the diversity of the urban fabric is generally represented by either: urban land-use type (e.g. urban/suburban: Morton et al., 2011), density of urban development (e.g. dwelling units per acre: Jacob and Lopez, 2009), and most generally imperviousness (Arnold and Gibbons, 1996; Dams et al., 2013).

While impervious surfaces are important for driving urban runoff, permeable surfaces still have an important role in urban catchments (Berthier et al., 2004) and can make up a considerable portion of the catchment area. In UK cities, gardens alone account for between 22% and 27% of city area (Loram et al., 2007). The partitioning of precipitation between runoff and infiltration on pervious soils is affected by soil type (Boorman et al., 1995) and the soil-moisture state of the soil (Brady, 1984), but in urban areas factors such as compaction have also been shown to significantly alter the hydrological response (Yang and Zhang, 2011). Antecedent soil moisture has been shown to have variable impacts upon runoff across different urban surfaces and in different soil-moisture states (Hollis and Ovenden, 1988; Hood et al., 2007; Smith et al., 2013; Ragab et al., 2003) leading to considerable uncertainty when modelling the hydrological response of mixed urban-rural catchments (Kjeldsen et al., 2013). Given the current interest in the role of soils in urban catchments as part of green infrastructure to control storm runoff and reduce flooding (Kelly, 2016; POST, 2016) this uncertainty highlights a pressing need to better understand the role of soil moisture in urban soils in altering the impacts of urbanisation on runoff from storm events.

The relationship between urbanisation and storm runoff on the basis of change in impervious area has become generalized in lumped hydrological model structures (e.g. ReFH: Kjeldsen, 2007) to characterise the urban environment (Salvadore et al. 2015). However, despite early indications that impervious area alone is insufficient to explain catchment response (Hall, 1977), there has been limited empirical research (e.g. Braud et al. 2013; Sillanpää and Koivusalo, 2015) on the link between urbanisation and storm runoff across a suitable range of hydrological metrics. While there have been a number of studies investigating ecological diversity along an rural-urban gradient (e.g. McDonnell et al., 1997; Clergeau et al., 1998; Kroll et al., 2012) few have investigated hydrological response along an rural-urban gradient (e.g. Schoonover and Lockaby, 2006). The objectives of this study, therefore, are to assess: (i) whether a lumped-catchment spatial measure of urbanisation can explain the observed variability in catchment response to storm events along a rural-urban gradient; and (ii) the extent to which antecedent soil moisture conditions modify that relationship. These objectives provide the structural sub-headings used the following Methods, Results and Discussions sections.

2 Study Sites

The Thames basin in southern England (Fig. 1) is the largest drainage basin in the UK (Crooks and Kay, 2015) and has a temperate mid-latitude climate. The basin contains the rapidly urbanising towns of Swindon (Population 210,000) and Bracknell (Population 77,000). Both are located in low-lying river catchments gauged by the Environment Agency (EA) at Water Eaton (station number 39087) and Binfield (station number 39052) respectively. High spatial and temporal resolution monitoring of flow and precipitation was undertaken over a four year period from May 2011 to October 2015 across eight independent sub-catchments within these two river catchments (Fig. 1; Table 1).

FIGURE 1: EA catchments at Swindon and Bracknell, showing study catchments, monitoring locations and land cover. Inset shows EA catchment locations within Thames basin and the United Kingdom.

3 Methods

3.1 Hydro-meteorological urban monitoring networks

Precipitation was monitored at 8 locations (shown as Raingauge in Fig. 1) at a 15 min resolution with tipping bucket raingauges (Casella TBRG), with network design following BSI (2012a). Data were quality controlled for errors relating to low/high intensity, missing data, and synchronization between sensors, following national (BSI, 2012b) and international guidelines (WMO, 1994; WMO, 2008). Additional 15 min rainfall data from tipping bucket raingauges located within the catchment at Swindon (R249744) and close to the catchment boundary at Bracknell (R274918), were provided by the EA (shown as EA raingauge in Fig. 1). These are quality controlled and in-filled using observations from a national network, and provided a continuous and robust source of data for in-filling and calibration of monitoring raingauge observations when data were missing or erroneous. Estimates of areal rainfall for both catchments were obtained using arithmetic and Thiessen polygon weighting methods (BSI, 2012b). The Thiessen polygon approach, widely used in urban hydrological studies (e.g. Blume et al., 2007; Yue and Hashino, 2000), was found suitable for Swindon due to the distribution of monitoring raingauges and central location of the EA gauge relative to the study-sub-catchments. For Bracknell the arithmetic mean was judged to be more appropriate due a number of factors including: i) the relative size of the study area and overall distribution of observation gauges across the catchment (BSI, 2012b), ii) recurring issues of under-catch or tampering for observation gauges; and iii) the overall effect of a low weight applied to the EA gauge if the Thiessen polygon approach was used (being located outside of the study sub-catchments – see Fig. 1) which significantly reduced observation accuracy relative to this gauge.

Discharge was monitored at 5 min resolution using ultrasonic Doppler shift instruments (Unidata Starflow 6526H), with a velocity and depth accuracy of ±2% and ±0.25% respectively, mounted to the bed of suitable hydraulic structures according to ISO (2010). Depth and velocity data were quality controlled, and processed using measured cross sections to derive flow using the methods outlined by Blake and Packman (2008). Ratings developed from spot-gaugings of depth and flow (SonTek FlowTracker) were used to calibrate observations of depth and velocity across the channel cross section, and increase accuracy. Additional concurrent flow data at a 15 minute resolution for each catchment outlet EA gauging station (39087, 39052: Fig. 1) were provided by the EA.

3.2 Objective 1: Hydrological response along a rural-urban gradient

3.2.1 Catchment characterization

Catchment descriptors (Table 2) for the EA catchments and the selected study catchments were obtained from the UK Flood Estimation Handbook (FEH) web service (https://fehweb.ceh.ac.uk/). These indicate that the catchments are sufficiently similar in altitude (ALTBAR), climate (SAAR; RMED-1H), soil (SPRHOST, PROPWET), and baseflow indices (BFIHOST) to allow comparison among the study sub-catchments. Catchment area was determined using a combination of a 10 m resolution digital terrain model (DTM) and storm drainage mapping to accurately identify catchment boundaries as these can be altered by urban development and artificial drainage (Braud et al., 2013). The study catchments differ geomorphically in area (AREA), slope (DPSBAR) and mean drainage path length (DPLBAR), while the predominant difference in land use was in terms of urban extent (URBEXT). Although the Bracknell study catchments have slightly higher levels of pond/reservoir attenuation (FARL), they are all >0.9 which is not considered to have a significant effect on high flows (Bayliss, 1999).

URBEXT provides a readily available index of UK catchment urban land cover for use in hydrological applications and is a key catchment descriptor used in flood estimation procedures in the UK (IH, 1999). URBEXT is a weighted fraction of Urban and Suburban land cover (Bayliss, 1999: Eq.1) and is derived here for 2015 from contemporary mapping of land cover mapping products (Morton et al., 2011). “Suburban” is defined as mixed development and green space, while “Urban” areas contain near continuous development with few green spaces (Fuller et al., 2002). URBEXT is used here to identify the relative extent of urban development and impervious surfaces within catchments and has been shown by Miller & Grebby (2013) to provide a robust measure of imperviousness for catchment scales. For the study catchments the URBEXT ranges from 0.06 for a predominantly rural study catchment to 0.60 for a well-developed town centre study catchment containing mixed urban land cover (Table 2).

$$URBEXT = Urban + 0.5\ Suburban \qquad 1)$$

3.2.2 Event identification

A wide range of methods exist to select storm events based on either identifying a rainfall event (Hollis & Ovenden, 1988), isolating peak runoff values in a series (Smith et al. 2013), or a combination of the two (Burns et al. 2005). Events were selected across the eight catchments (Table 2) using a set of pre-defined criteria applied in sequence (Table 3). Hydrograph separation, event window definitions and time-based metric definitions are shown in Figure 2. The first stage involved identifying isolated rainfall events based upon exceedance of a pre-defined value. The second stage utilised an automated baseflow separation technique that drew upon a combination of methods reviewed in study of published event-based hydrograph separation methods by Blume et al. (2007). This identified the starting point in the hydrograph rising limb and applied a linear interpolation to the point at which the hydrograph recession meets baseflow – defined as the minimum value within a baseflow-end 'window'. Finally visual analysis of rainfall-runoff plots was used to filter out erroneous or multiple events.

FIG 2: Hydrograph separation with event instants used to select independent events and time instants used to derive time-based metrics of storm events

3.2.3 Metrics of hydrological response

A number of hydrological response metrics were identified to be important in quantifying storm runoff in urban catchments. Following correlation analysis seven, independent, volume- and time-based hydrograph metrics were selected (Table 4: Fig. 2). Volume-based metrics facilitate comparison in the quantity of storm runoff between the study catchments. Time-based metrics aid comparison of shape and duration based elements of hydrological response to rainfall events.

Peak flow (QMAX) and direct runoff (DR) provide a measure of runoff response during an event, while the percentage runoff (PR) expresses the conversion of rainfall to runoff. Time-to-peak (T_P), also known as time-of-rise, indicates catchment responsiveness on the rising limb of the hydrograph (Mcdonnell et al., 1990). Flood duration (ϴ) provides an indication of overall hydrograph shape relative to direct runoff duration and indicates the 'flashiness' or kurtosis of catchment response to runoff (Braud et al., 2013). Lag-time provides a measure of the duration between rainfall and runoff and was calculated using two methods reported by Dingman (1994) (Fig. 2). As study catchments varied by both area and to a lesser degree slope (Table 1), hydrograph metrics must therefore be scaled to account for geomorphic differences. While volume-based metrics can be converted to specific discharge using study catchment area (runoff per unit area), it can be more difficult to compare time-based metrics. Lag-time, for example, has been shown to be a function of both area and slope (Watt and Chow, 1985).

Flood duration has been shown by Robson & Reed (1999) to be a function of T_P:

$$\Theta = 2.99\, {T_P}^{0.77} \qquad 2)$$

while T_P itself has been shown by Kjeldsen (2007) to be a function of a number of FEH catchment descriptors ($r^2 = 0.74$):

$$T_P = PROPWET^{-1.09} DPLBAR^{0.6} (1 + URBEXT)^{-3.34} DPSBAR^{-0.28} \qquad 3)$$

The descriptor PROPWET does not differ significantly between catchments and URBEXT is used to define the urban gradient, leaving the remaining parameters DPLBAR and DPLBAR to scale T_P and Θ for each catchment so that standardised values (T_{PS} and Θ_s) are available for direct comparison:

$$T_{PS} = \frac{T_P}{DPLBAR^{0.60}\, DPSBAR^{-0.28}} \tag*{4)}$$

$$\Theta_S = \frac{\Theta}{DPLBAR^{0.60}\, DPSBAR^{-0.28}} \tag*{5)}$$

Catchment lag-time is related to the ratio $L/\sqrt{S}$, where L is basin length and S is slope, and that the ratio provides a means of comparing lag-times between catchments of different area and slope (Anderson, 1970; Laenen, 1983). Slope is taken from the FEH catchment descriptor DPSBAR (Bayliss, 1999) while length is estimated from mapping (Table 1). Scaled T_{LC} and T_{LPP} are thus standardised to T_{LCS} and T_{LPPS}:

$$T_{LCS} = \frac{T_{LC}}{L/\sqrt{S}} \tag*{6)}$$

$$T_{LPPS} = \frac{T_{LPP}}{L/\sqrt{S}} \tag*{7)}$$

Data normality was tested using the Shapiro-Wilk statistic and subsequently transformed if found to be non-normal ($p<0.05$) using the Box-Cox transformation (Box and Cox, 1964). Thyer et al. (2002) indicate that the Box-Cox transformation is widely used for transforming hydrological data to a normal, or Gaussian, distribution, as required for parametric tests such as ANOVA. Where metric values could take a zero, a minor positive offset was applied prior to transformation, with any constant subtracted from later analyses. All response metrics required transformation as data was highly non-normal. Log transformation of each metric provided some improvement but subsequent step-wise Box-Cox transformation (2 decimal places) with power parameter values (λ) to reduce the Shapiro-Wilk p statistic was undertaken using an optimization routine for each metric and proved more effective. Independent testing of the transformation on each sites data distribution was undertaken to ascertain that the result was a normal distribution for each study catchment, and not simply the dataset as a whole. Shapiro-Wilk p statistics values for independent sites were found to be significantly higher than the un-transformed site values and dataset as a whole, and histograms became more normal in appearance. This validated the use of the applied Box-Cox transformation λ values. It was not possible to transform URBEXT as it's bounded, while the distribution of SMD is heavily skewed towards zero for long periods limiting any transformation to a normal distribution. Statistical analysis for difference in geometric means between study catchments and along the urban gradient utilised analysis of variance (ANOVA). Tukey's 'Honest Significance Difference' (HSD) function was utilised to confidence intervals on the means of each site and was found suitable as it incorporates an adjustment for sample size to counter the potential bias towards sites with more data. The resulting values were recorded for each site to identify significant differences between study catchments and between soil moisture conditions.

3.3 Objective 2: Role of antecedent soil moisture

Antecedent soil moisture conditions have been shown to affect the responsiveness of a catchment to rainfall (Penna et al., 2011) and are considered important initial conditions in a range of hydrological models that seek to model storm runoff generation (e.g. TOPMODEL: Quinn and Beven, 1993; ReFH: Kjeldsen, 2007). Soil moisture deficit (SMD) defines the amount of amount of water required for a soil to reach field capacity and provides an indication of antecedent soil moisture, shown to affect high flow generation (Michele and Salvadori, 2002). SMD was obtained for the EA catchments from the relevant 40 km x 40 km grid squares of the UK Meteorological Office rainfall and evaporation system (MORECS) (Hough and Jones, 1997).

To classify the antecedent condition Meyles et al. (2003) have shown that a classification of preferred states in soil moisture applied in Australia by Grayson et al. (1997) holds true for the UK, whereby ‘wet’ soils with a value at or around field capacity (SMD = 0) will generate more runoff while ‘dry’ soils with higher SMD generate less runoff. We defined a wet catchment as one near to field capacity and used observed data to identify the value at which conditions could be classed as wet and more conducive to runoff generation. To determine a suitable break in SMD with which to classify soils as either wet or dry we used MORECS SMD data and peak flow data to identify a value indicative of a seasonal change that has observable impacts on runoff generation from the two least urban catchments (S2, B1: Table 2). The variable response of catchments under wet and dry conditions was tested statistically to ascertain if the antecedent soil moisture of catchments play a contributory role in determining the response of catchments along the urban gradient.

4 Results

4.1 Objective 1: Hydrological response along a rural-urban gradient

4.1.1 Hydrological summary

Rainfall data over this period highlight two important periods (Fig. 3). First the relatively low rainfalls experienced during the winter of 2011/12 in contrast to the following wet spring and winter of 2012/13, (Parry et al., 2013). Second, the winter storms of 2013/14 during which the UK endured its wettest winter on record and suffered considerable widespread flooding (Muchan et al., 2015). Event rarity was assessed using the updated FEH 2013 DDF model (Stewart et al. 2015) available from the FEH Web Service (fehweb.ceh.ac.uk). Storms were generally found to not be extreme, with a summer storm on 29/07/2015 (29 mm in 6 hours: return period, T = 4.5 years) being the only event exceeding a return period of 2 years, and the largest storm occurring on 23/12/2013 (32 mm in 23 hours: T = 1.6 years). Flows show a similar monthly pattern but were higher at all times in Swindon than at Bracknell, primarily a result of the large baseflow contribution from the sewage treatment works within the catchment. In the Swindon catchment there were some gaps in the flow data (Fig. 3) during summer 2014 due to a recording malfunction.

FIGURE 3: Monthly rainfall and flow for Environment Agency rainfall and gauging stations at Swindon (39087) and Bracknell (39052). The blue upper envelope marks the long-term maximum monthly rainfall for Swindon.

4.1.2 Selected events

Figure 4 shows a breakdown of the selected 336 useable events by catchment and season – with summer defined as April to September. The mean number of useable events per season at all sites was 21, and variability in the number of events at each sites primarily reflects the length of monitoring data available but also the quality of data at sites and periods of equipment malfunction. The data indicates that study catchments with lower levels of urbanisation URBEXT ≤ 0.26) exhibit more winter than summer events compared to the study catchments with higher urbanisation levels where summer events are dominant.

FIGURE 4: Histogram of storm events by site and season (summer defined as April to September) for each sub-catchment with mean frequency of all study catchments indicated by dashed red line.

4.1.3 Standardizing time-based metrics

Across the eight sub-catchments, Pearson's product moment of coefficient of correlation (ρ) revealed AREA to be highly correlated with mean and maximum drainage path length (DPLBAR: ρ =0.99; LDP: ρ = 0.96) but not with slope (DPSBAR: ρ = -0.11). URBEXT was not correlated with other catchment descriptors (ρ < 0.3). To assess the effectiveness of the scaling on removing the effects of area (AREA) and slope (DPSBAR) the relationships between both descriptors and time-based metrics - before and with the resulting scaling applied - are assessed and illustrated in in Figure 5.

FIGURE 5: Time-based hydrograph metrics against AREA and DPSBAR before (a, b) and after (a_S, b_S) scaling (eqs. 4 – 7). Data are fitted with a linear model fitted with significance (p) of fitted model slope (* denotes $p < 0.05$) and model equation reported. Grey shading shows the 95% confidence interval.

Prior to scaling, the clear relationship between AREA and time–based metrics is evident (Fig. 5a), with the relationship being both positive and significant ($p < 0.05$). Following scaling (Fig 5a_S) the effect of AREA has been removed, with a near zero and non-significant slope ($p > 0.05$). Scaling has the effect of increasing metric values in the smaller study catchments (below 5km^2), and having little impact on the larger study catchments – with some minor variability due to slope. DPSBAR is also shown to have a significant effect upon all four metrics ($p < 0.05$) (Fig. 5b) however the relationship is negative. Scaling (Fig 5b_S) results in a near zero regression slope for all time–based metrics, primarily through increases to values in the steeper catchments, and significantly reduces the relationship except $T_{LCS.}$ In summary, the scaling methods have proved effective at removing the effects of catchment size and slope.

4.1.4 Analysis of storm hydrographs along rural-urban gradient

The variability in response among study catchments along the rural-urban gradient is illustrated in Figure 6, showing the area weighted event hydrographs for each study catchment. Some general patterns can be observed as URBEXT increases tenfold from S2 (0.06) to S3 (0.60).

- Baseflow is clearly a higher proportion of flow in the less urban study catchments, and while it generally drops with increasing urbanisation, there is clear inter-catchment variability.
- Variability in hydrograph shape across the selected events (grey) compared to the mean (red) generally decreases with urbanisation.
- The mean hydrograph peak is significantly lower than the largest event, particularly in the more rural catchments (URBEXT ≤ 0.14).
- For study catchments with URBEXT ≥ 0.26 the hydrograph becomes flashier but there is clear inter-catchment variability that does not follow the urban gradient.

FIGURE 6: Comparison of area weighted event hydrographs (grey) and mean hydrograph (red) among study catchments (Table 1, Fig. 1) with catchment UREBEXT in brackets (ordered top left to bottom right by URBEXT)

The hydrographs in Figure 6 demonstrate some of the generalised observations that are applied to urban catchments reported in the literature, but also indicate that there are inter-catchment differences that do not fit such generalizations. Table 5 and Figures 7 and 8 outline statistical analyses of how the metrics vary along the urban gradient of catchments studied.

FIGURE 7: Boxplots of normalised peak flow (Q_{max}), storm runoff (DR), and percentage runoff (PR) across the study catchments – URBEXT in brackets. Box-plots sharing the same letter have means that are not significantly different.

An analysis of the volume-based metrics (Fig. 7) reveals significant increases in peak flows (Q_{max}) between the less urban (URBEXT ≤ 0.14) and more urban (URBEXT ≥ 0.26) catchments. The pattern is less clear for PR, and DR does not become significantly higher until URBEXT reaches 0.42 (S4). There is an apparent increase in the means along the urban gradient (Table 5), however there is no consistent trend and few significant differences between the more urban study catchments despite very different levels of urbanisation (0.26 – 0.6). The only signficant difference observed is a higher Q_{max} at S5.

FIGURE 8: Box-plots of scaled and normalised time-to-peak (T_{PS}), flood duration (Θ_S), time lag-to-peak (T_{LPPS}), and time lag-to-centroid (T_{LCS}) across study catchments – URBEXT in brackets. Box-plots sharing the same letter have means that are not significantly different.

The time-based metrics (Fig. 8) show an overall reduction in all metrics along the urban gradient but with significant inter-catchment variability. There are differences between the less urban study catchments (URBEXT ≤ 0.14) and most metrics suggest longer response times for these compared to shorter times in more urban study catchments (URBEXT ≥ 0.26). The pattern in the more urban study catchments varies between metrics, with Θ_S showing the greatest variability between study catchments and highlighting a significantly shorter flood duration (1.6 h) at S5 (Table 5) than all other study catchments. The differences between B2 and S1, both of similar URBEXT, and the lack of difference between S1 and S4, despite a large difference in URBEXT, both suggest controls being in place that alter the response time. Taken together the time-based metrics demonstrate that while there is a drop in response times between the less urban and more urban study catchments, there is no clear urban gradient among the more heavily urbanised study catchments and that URBEXT is a poor indicator of catchment response time in such heavily modified catchments.

4.2 Objective 2: Role of antecedent soil moisture

A value of 7.6 mm was identified as being the value separating a seasonal change from typically wet soils during winter (October – March) to dry soils during summer (April – September). To validate this we also assessed flow data and observed that the value was also indicative of a change in runoff response as evinced in peak flows from the two least urban catchments (S2, B1: Fig. 9). The value is close to the 6 mm value used in the UK flood estimation methods to distinguish between a wet and dry catchment (Bayliss, 1999).

Plots of antecedent soil moisture deficit versus each of the metrics (Fig. 9) provide an indication of the relationship between antecedent soil moisture and runoff response. For all volume-based metrics, broadly similar relationships between SMD and storm response are observed within catchments of similar URBEXT. The least urban study catchments (S2 and B1) show similarly rapid decrease in PR, DR and Q_{MAX} with increasing SMD. For the study catchments with an URBEXT of 0.26 only S1 shows a consistently negative relationship with SMD. For the more heavily urban study catchments (URBEXT≥0.42) little or no change in metric values with increasing SMD is demonstrated, except a positive relationship with Q_{max} at site S5.

FIGURE 9: Change in metrics (Table 4) with SMD by catchment with linear fit and 95% confidence intervals shown in grey. (Y axis is log scale)

The time-based metrics reveal less significant and less consistent changes along the urban gradient, compared to the volume-based metrics (Fig. 9) reflecting the increased variability observed in Figure 8. The relationship between SMD and response time for the less urban study catchments is not significant, while for those at URBEXT 0.26 the relationship is consistently negative, in particular showing that at S1, increasingly dry conditions result in a rapid drop in T_{PS} and Θ_s. The heavily urban study catchments (URBEXT≥0.44) are not significantly affected by SMD, although there is a weak positive relationship between T_{LPPS} and SMD in S5.

The interaction between site and soil moisture has been shown to be significant ($p < 0.05$) across all selected metrics and Table 6 reports the differences between study catchments under dry and wet antecedent conditions. Antecedent soil moisture was found to significantly reduce all volume-based metrics in dry conditions for study catchments with an URBEXT of 0.06 and 0.14, but not the majority of more urban study catchments (URBEXT≥0.26). This was particularly evident at S2 where Q_{MAX} (74.3 $ls^{-1}km^{-2}$), DR (2.4 mm) and PR (17.2%) under wet conditions were between 750% and 1200% higher than in a dry state (9.8 $ls^{-1}km^{-2}$, 0.2 mm, and 2% respectively), reflecting the large range of values recorded as shown in Figure 8. The exception was found comparing DR and PR at S1 where values in dry (0.9 mm and 7.2%) were significantly less than wet conditions (8.6 mm and 53.9%), explaining the large ranges shown in Figure 8. Except S1 the results suggest antecedent soil moisture does not significantly affect the volume of runoff generated during storm events or the variability along the urban gradient between the more urban study catchments.

Despite a large range of T_{PS} and Θ_S values (Fig. 8) and clear effects upon volume-based metrics (Table 5) no significant difference has been shown in the response time of the least urban S2 and B1 under drier conditions for any metric (Table 6). While response time values decrease under drier conditions the lack of a significant reduction in response times is reflected in all study catchments except S1 (URBEXT=0.26) and to a lesser degree catchment B3 where only T_{PS} is reduced when dry. No substantial change is observed in the pattern of T_{LPPS} along the urban gradient. In summary, there is no consistent pattern of antecedent soil moisture affecting the timing of runoff along the urban gradient, with only site S1 exhibiting consistent impacts across the applied metrics.

5 Discussion

5.1 Objective 1: Hydrological response along a rural-urban gradient

This study builds upon early and contemporary empirical studies into the impacts of urbanisation on runoff (e.g. Hall, 1977; Boyd, 1995; Roy and Shuster, 2009; Zhang and Shuster, 2014) to determine if a lumped-catchment spatial measure of urbanisation explains variability in catchment response to observed storm events along a rural-urban gradient.

The volume-based metrics (Fig. 7) show an increase in urbanisation between an URBEXT of 0.14 and 0.26 acts to increase peak flow generation, while the increase in storm runoff and percentage runoff is more gradual. While no specific threshold value is provided with which to identify at what level the effects of urbanisation on storm runoff become apparent, the ranges identified adds to the evidence of there being a gradual change in behaviour along an urban gradient between more rural and more urban catchments (Shuster et al., 2005; USGS, 2003; Sillanpää and Koivusalo, 2015; Mejía et al., 2015) and fit within the range of reported threshold values of between 5% (Kjeldsen, 2010), to around 20-25% (Brun and Band, 2000). An increase in the volume of runoff with increasing urbanisation is a common finding from urban hydrological studies (Leopold, 1968; Jacobson, 2011; McGrane, 2015), particularly for less extreme storms (Hollis, 1975). Our observation of no systematic increases in runoff volume metrics across the more urban catchments (URBEXT ≥ 0.26) is however, not well reflected in the wider literature. The results could indicate that either: i) the volume of runoff is not affected by changes in urban extent within this range, or ii) there exist differences between the catchments that act to render them similar in volume of response. The former theory is substantiated by observations from Hammer (1972) and Miller et al. (2014) who found the impacts of progressive urban expansion would be more extreme at lower levels of development in smaller catchments, but there is little similar evidence to support the lack of variability in more heavily modified catchments. The data is perhaps also suggestive of a threshold being crossed and the catchments passing into such an altered state in which pervious areas are so fragmented and altered as to effect no significant change in the volume of runoff with increasing urbanisation, agreeing with the 'stressed' ecosystem classification proposed by Schueler (2000) for catchments with 26-100% impervious cover. Explanations for the latter could include variability in the actual imperviousness of urban surfaces, as no surface is truly 100% impervious (Hollis, 1988) and imperviousness varies over time, with season, and by surface type (Redfern et al., 2016). There is also the role that distribution and connectivity of pervious and impervious surfaces relative to a catchment outlet and storm drainage will play in making such truly effective impervious area (Shuster et al., 2005; Graf, 1977). Other contributory factors include observations that impacts of urban land cover vary with rainfall magnitude (Gallo et al., 2013b) and that rural contributions become increasingly important with greater storm magnitude (Sheeder et al., 2003).

Reduction in catchment response time with urbanisation is another common finding from urban studies (Fletcher et al., 2013; McGrane, 2015) and while there were more significant reductions in time-based metrics along the rural-urban gradient compared to volume metrics, the pattern between the more urban catchments (URBEXT≥0.26) was highly variable and requires consideration of drivers other than urban extent. That significant differences were observed between the less urban study catchments (URBEXT≤0.14) compared to more urban study catchments fits well with observations from reported literature that urbanisation generally will reduce time-to-peak (Williams, 1976; Sillanpää and Koivusalo, 2014), flood duration (Braud et al., 2013) and lag-time (Anderson, 1970). What is clear however from the more urban study catchments (URBEXT≥0.26) is that once catchments become more heavily modified other processes not represented by URBEXT start to significantly affect the conveyance time of runoff.

The observations reported here are of international interest as empirical observations in small urban catchments are limited and imperviousness is widely used in catchment scale studies. The limitations of spatial measures of urbanisation such as imperviousness for attribution and modelling are increasingly being identified in international studies, particularly where stormwater infrastructure is present (Meierdiercks et al. 2010) and when considering high flows (Ogden et al. 2011; Braud et al. 2013). Runoff timing in particular has been shown to be more a function of stormwater infrastructure than land use (Smith et al. 2013). Accordingly there is growing interest in the application of alternative measures of urbanisation such as methods to characterize urban form using landscape metrics (Jiao, 2015).

5.2 Objective 2: Role of antecedent soil moisture

We found antecedent soil moisture to affect the quantity of runoff generated in storm events for some of the study catchments but to have little effect on the more urbanised study catchments (URBEXT≥0.42). The clear relationship between soil moisture and runoff volume in catchments with large rural areas is demonstrative of significant correlations between runoff and antecedent soil moisture reported in the literature (Meyles et al., 2003; Penna et al., 2011; Zhang et al., 2011). The diminished role of soil moisture in more urban catchments is less clear, some evidence suggesting wetter soils cause higher runoff (Ragab et al., 2003) and other studies finding antecedent soil moisture does not significantly impact storm hydrological response (Smith et al., 2013). The latter view, as found here, supports the view of Shuster et al. (2005) who surmised a reduction in soil water storage potential with increased impervious area, as shown by Booth et al. (2002), correspondingly decreases the importance of antecedent soil moisture in runoff.

The lack of an observed relationship between SMD and time-based metrics suggests that soil moisture does not generally control how quickly catchments respond to storm events, the flashiness of the response, or the lag-time between the rainfall and runoff. That no differences were observed in the least urban catchments was surprising as studies under more natural catchments show that antecedent conditions can affect catchment response times (Penna et al., 2011; Haga et al., 2005). Similarly there is evidence from more urban studies that under drier conditions lag-times are increased in locations with more green space (Hood et al., 2007), but again this was not replicated in this study.

The combined results from both volume- and time-based metrics suggest some evidence for SMD affecting runoff volume in less urban catchments but not the timing of storm runoff. This suggests that in rural catchments a reduced runoff volume in drier conditions is not accompanied by a significant decrease in catchment response time. The lack of any consistent impact of SMD on either volume of timing of runoff in the more urban catchments (URBEXT ≥ 0.26), except S1, suggests it does not play a role in runoff generation when developed areas begin to dominate the catchment land cover. The significant reductions in both volume- and time-based metrics at S1 under drier conditions is further evidence of this, whereby despite a high URBEXT the dominant land cover is Rural (64.5%: Table 1). Under such conditions it is likely to be effectively reducing the contributing area of storm runoff as the majority of rainfall infiltrates into the previous soil storage space.

The role of soil moisture in runoff generating processes remains uncertain in urban environments with mixed pervious and impervious surfaces (McGrane, 2015) and requires further study considering the current international research interest into the role that urban green spaces and SuDS are in controlling flooding (Palla and Gnecco, 2015) and their value in terms of ecosystem services (Duku et al. 2015).

5.3 Contributing urban factors not covered by URBEXT or imperviousness

The limitations of using a lumped spatial measure of urbanisation such as URBEXT or imperviousness are particularly evident in observations from: i) catchments with similar levels of URBEXT but accompanied by highly divergent responses to storm events; and ii) catchments with similar responses but different levels of URBEXT. The response of the study catchments could be explained by a number of potential factors explored within the wider international literature,

Urban drainage - Evidence from other studies suggests a combination of increased peak flows and reduced response times may be a result of storm drainage systems that act to speed up the conveyance of runoff and increase peak flow (Roy and Shuster, 2009) especially when the connectivity of these systems is high (Shuster et al., 2005). Events from S5 (0.46) would seem to be indicative of such a catchment, and the catchment drainage is dominated by artificial drainage. It has been shown that for larger catchments impervious area and road density are good explanatory variables for lag-times (McEnroe and Zhao, 2001) but at smaller scales it becomes necessary to consider the effective impervious area (EIA) (Booth and Jackson, 1997). This is the hydraulically connected impervious area where runoff travels over impervious surfaces directly to storm drainage (Han and Burian, 2009). This has been shown to vary considerably between development types (Roy and Shuster, 2009) and be potentially much less than total impervious area (TIA) (Ebrahimian et al., 2016). A number of studies have sought to relate TIA to EIA, however low fits of linear relationships between the two measures are reported, with variations according to age of developments, local topography, ownership, and regulations. (Alley and Veenhuis, 1983; Wenger et al., 2008; Roy and Shuster, 2009). A paired catchment study by Hood et al. (2007) provides a particularly relevant example of how variable the response of a similarly urban catchment can be due to the drainage layout and connectivity. Clearly URBEXT or imperviousness alone cannot provide this level of information, highlighting the need for ancillary information on urban drainage and its connectivity, particularly in smaller urban catchments.

Soils - S1 (0.26) had reductions in both volume- and time-based metrics with drier conditions, while other study catchments with large rural fractions (S2, B1) only had decreases in runoff volume, and the similarly urban B2 (0.26) was unaffected by SMD. This is indicative of a seasonal or soil-moisture related control mechanism independent of URBEXT that is controlled by the high relative non-urban fraction, as previously discussed. It suggests that while catchments S1 and B2 have a similar URBEXT and level of pervious surfaces, the fragmented pervious 'urban' soils in the mainly Suburban B2 do not respond in the same way as the continuous 'rural' soils. This highlights the need to consider the relative extent of undeveloped areas surfaces, not just pervious and impervious surfaces, as urban soils may not behave like more natural rural soils.

Urban distribution - Distribution of urban area towards the outlet can lead to a flashier response (Zhang and Shuster, 2014) possibly explaining the particularly fast response at B2 whereby urbanisation appears concentrated towards the monitoring point. A measure of location of impervious surfaces relative to the catchment outlet would provide some clear measure of such a factor. Such a measure is already available as a catchment descriptor in the UK (URBLOC: Bayliss, 2000) but has not to date been used in flood estimation, primarily as the focus has been upon larger less urban catchments.

Artificial attenuation – Despite being significantly more urban, the adjacent B3 (URBEXT = 0.44; Urban = 16%: Table 1) and B2 (URBEXT = 0.26; Urban = 3.5%) have surprisingly similar responses as measured by both volume and time-based metrics. Both are highly modified with large scale drainage systems, but the wider literature suggests that in B3 the presence of retention ponds have which have been noted are likely to have some form of artificial control that act to slow down the movement of water and reduce flood peaks, and (Table 1). Such impacts are supported from wide variety of observations comparing catchments with and without stormwater controls (Hood et al., 2007) or the impacts of implementing SuDS (Palla and Gnecco, 2015) and form a key element of sustainable flood management in urban areas (Defra, 2014). A catchment measure of artificial attenuation from SuDS features would complement catchment descriptors for urban drainage in cases where the former is designed to cancel out the latter, and be additional to natural attenuation.

Natural attenuation – S4 (0.42) has response times similar to a catchment that is less urbanised (S1: 0.26) but no indication of seasonal SMD control, and longer times than catchments of similar URBEXT (B3: 0.44, S5:0.46). This is perhaps indicative of features that act to attenuate the runoff response such as sustainable urban drainage systems (SuDS) (Jarden et al., 2015) which have been noted as only isolated instances within the catchment (Table 1). More likely, given its size and location, is that flows are attenuated by a large area of natural green space (Fig. 1) that has been observed to frequently flood, a solution often outlined in literature on urban flood management to attenuate peak flows (Wilby, 2007, Hamel et al., 2013; CIWEM, 2010). These surfaces are not currently included in the natural attenuation index used here (FARL) that covers only rivers and lakes but are considered in a more recent descriptor for flood plan extent (FPEXT) (Kjeldsen et al., 2008). The FEH FPEXT values for S4 are however low (0.077) but another FEH index of location (FPLOC) (0.74) indicates this area is located such that is has a large contributing area and could play a greater role in attenuating upstream flows. Such indexes when combined with more information on the spatial distribution of impervious surfaces and storm drainage could be of particular use in attributing the for the reduced response times of urban catchments with such large continuous features of green space downstream of urban areas.

Urban soils and soil moisture - While the observations of the role of SMD in urban storm runoff are valuable given the paucity of studies on urban soil hydrology (Ossola et al., 2015) a degree of caution must be attached in that SMD here is derived from MORECS and is not from measured data within the urban catchments. Given urban soils can be highly modified and compacted, with resulting reduced water holding capacity (Chen et al., 2014) in-situ SMD could be highly divergent from MORECS values and infiltration potential reduced, resulting in runoff more typical of impervious surfaces (Redfern et al., 2016). Shuster et al. (2005) note that the hysteric behaviour of soils could also be changed and alter the lag-times of runoff. More detailed information on local soils, their state, and local soil moisture could provide a better picture on the overall level of perviousness and the role of soils in small urban catchments. This could involve some resampling of local soils and tests to ascertain compaction, with results used to alter catchment soil indexes such as HOST used here.

Further investigation would be required to define more hydrologically relevant measures of land use and antecedent conditions and to determine whether they improve attribution of storm runoff in small urban catchments. Additionally, the practical implications for implementation in methods such as the FEH require additional assessment, as there are limited gauged sites in small urban catchments (Faulkner et al. 2012) and benefits might only occur at certain scales.

5.4 Study limitations

This study has been based upon using high-resolution monitoring equipment to study detailed rainfall-runoff processes at the resolutions and locations necessary to better understand the impacts of urbanisation on both the volume and timing of runoff, but has a number of limitations that could be improved in further research:

- While data availability over the monitoring period is variable between study catchments this reflects the real-world constraints of urban hydrological monitoring and difficulties of working with high-resolution data (Hutchins et al., 2016).
- Errors and uncertainty occur in data, but by following standard guidance on data collection and quality control, and using modern monitoring technology, these have been minimised.
- Event lag-times of were calculated from areal rainfall, and this could affect the reported lag-times accuracy, particularly in small catchments. This was minimised by having a good coverage of observation gauges (Fig. 1). Further research could focus on spatial variability of rainfall and storm type relationships with observed response.
- For the more urban study catchments (URBEXT≥ 0.42) there was a bias towards more summer events (Fig. 2), however this could simply reflect the lack of significant runoff being generated during summer in more rural catchments.
- SMD was derived for a large area which, given the scale and variability of land use within the catchments studied may be unrepresentative. In addition, Hess et al. (2016) have shown that the spatial variability of evapotranspiration is low in this region.
- Study locations are in a temperate climate and results may not be transferrable to semi-arid (Hawley and Bledsoe, 2011) or cold climates (Sillanpää and Koivusalo, 2015).

6 Conclusion

This study used high-resolution rainfall-runoff data from 8 small catchments at varying levels of urbanisation, in order to determine if a spatial measure of urbanisation can explain variability in catchment response to storm events along a rural-urban gradient and whether antecedent soil moisture modifies the relationship between urbanisation and storm runoff. The results suggest that generalised relationships between urbanisation and storm runoff, whereby increased urbanisation leads to higher peak flows and increased runoff, along with reduced catchment response times, are not well represented in real-world data. The observations showed that runoff volume per unit area has little variation once catchments become significantly urbanised (URBEXT ≥ 0.42), and that the both volume and timing of runoff in particular are likely to be affected by other factors in addition to urban extent or impervious cover. Analysis of antecedent soil moisture and hydrological metrics suggest that SMD only affects runoff volume in catchments dominated by "Rural" (non-urban) land cover, and runoff timing does not follow any clear rural-urban gradient. Taken together the results suggest only minor improvements could be gained in attribution of storm runoff through refined estimates of impervious surfaces at such scales, and that further work is required to determine what contributing factors are causing the observed variability in timing of runoff along the rural-urban gradient.

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TABLE 1: Land cover and hydrologically relevant features of the Study catchments (B1 – B3 Bracknell, S1 – S5 Swindon)

Study catchment	Land cover (%)			Catchment land cover and hydrological description
	Urban	**Suburban**	**Rural**	
B1	0.7	27.1	72.2	Mixed farmland with low density housing development in upper reaches. Natural drainage channel with large inline water body in upper reach.
B2	3.5	44.4	52.1	Suburban high-density housing with woodland. Natural drainage channel with inline retention features and STW outfall in upper reaches that imports waste-water from outside of catchments.
B3	16	55.5	28.4	Town centre with mixed housing, industry and commercial with forested areas and green spaces. Highly modified drainage channel passing mostly underground and through storm retention ponds.
S1	19	16.5	64.5	Town centre commercial, housing and industry with grazing farmland in upper reaches. Natural drainage channel with large number of storm drainage inflows.
S2	0	12.1	87.9	Predominantly rural grazing farmland with pockets of housing. Natural drainage channel with floodplain and small ponds.
S3	31.4	57.1	11.5	Town centre with mixed housing, industry and commercial with green spaces along stream corridor. Predominantly natural drainage channel with significant storm drainage inflows and some channelisation in upper reaches.
S4	1.3	80.7	18	High-density peri-urban housing and commerce with large central green space. Natural drainage channel with storm drainage inflows, isolated SuDS, and natural catchment area reduced due to storm-drainage in S5.
S5	16.3	59.7	24.1	High-density peri-urban housing and commercial development with isolated green spaces. Fully artificial storm drainage with isolated SuDS.

Table 2: Catchment flow data records and FEH catchment descriptors (* HOST refers to the Hydrology Of Soil Type classification used in the UK (Boorman et al., 1995), ** indicates derived values)

	EA_39052	**B1**	**B2**	**B3**	**EA_39087**	**S1**	**S2**	**S4**	**S4**	**S5**
AREA (km^2)**	51.96	18.37	12.49	12.55	82.5	28.97	3.24	5.98	3.09	2.18
Data start	10/1987	10/2013	10/2013	11/2014	10/1987	11/2013	11/2013	05/2011	04/2011	04/2011
ALTBAR - Mean catchment altitude (mASL)	75	72	84	80	109	121	122	102	110	110
BFIHOST - Base flow index derived from HOST*	0.36	0.29	0.51	0.43	0.39	0.38	0.67	0.32	0.43	0.43
SPRHOST - Standard HOST* percentage runoff	41.5	44.7	34.6	38.2	42.6	42.5	25.5	46.6	40.2	40.2
DPLBAR - Mean drainage path length (km)**	7.46	4.77	3.9	3.75	9.31	5.82	2.12	2.84	2.11	1.79
Length - Maximum catchment length from outlet (km)	8.56	5.31	6.08	6.26	15.03	6.69	3.07	4.08	3.14	2.44
DPSBAR - Catchment steepness (m/km)	24.7	17.9	25.8	30.2	27.4	35.8	33.8	14	33.7	40.61
FARL - Index of flood attenuation from reservoirs and lakes	0.94	0.93	0.98	0.96	0.99	1	0.94	1	1	1
PROPWET - Index of proportion of time soils are wet	0.29	0.29	0.29	0.29	0.34	0.34	0.34	0.34	0.34	0.34
RMED-1H - Median annual max 1	12.6	12.6	12.7	12.6	9.6	9.6	9.7	9.4	9.6	9.6

hour rainfall (mm)										
SAAR - 1961-90 standard-period average annual rainfall (mm)	676	679	686	672	698	707	712	683	688	688
URBEXT$_{2015}$ - Fractional urban extent in 2015**	0.24	0.14	0.26	0.44	0.26	0.26	0.06	0.6	0.42	0.46

TABLE 3: Event selection criteria (illustrated in Figure 2).

Stage 1 - Rainfall	- Minimum 2mm rainfall in 4 hours to define rainfall event (0.5mm/hr) - Events separated by period defined by baseflow window (Bf.window) - No rain exceeding 0.5 mm occurs during pre-event period (Ev.pre - Ev.start) and zero rainfall 2 hours prior to event start - No rain exceeding 0.2 mm following event end (Ev.end) - No gaps between rainfall 'spikes' during event window (Ev.start – Ev.end) exceeding 3 hours
Stage 2 – Storm runoff and baseflow	- Only single event hydrographs - Baseflow calculated for event runoff
Stage 3 - Rainfall-runoff	- User selection of timing for periods defining post event window (Ev.post) and baseflow window (Bf.window) based on catchment size and hydrograph - No significant increase in flow before rainfall event start (Ev.start) - No rainfall driving runoff post event recession (Ev.post) - No mistiming in response – e.g. significant delay between rainfall and runoff

TABLE 4: Selected volume- and time-based hydrograph metrics used to quantifying storm runoff

Hydrograph metric	**Description**	**Reference application**
Volume-based		
Qmax (l/s/km^2)	Peak flow during a storm event - expressed over a unit of catchment area	Hollis & Ovenden (1998)
PR (%)	Measure of the percentage of rainfall generating direct runoff	Burn & Boorman (1993)
DR (mm)	Stormflow over and above baseflow occurring if storm did not occur	Shaw et al. (2011)
Time-based		
T_P (h)	Time to peak flow from start of storm runoff	Galllo et al. (2013); IH (1999)
ϴ (h)	Flood duration of event hydrograph corresponding to Q/Qmax = 0.5 in median hydrograph	Braud et al. (2013)
T_{LPP} (h)	Lag time between peak rainfall intensity and peak hydrograph flow	Scheeder et al. (2003)
T_{LC} (h)	Lag time between event centroid of rainfall and centroid of hydrograph	Hall (1984)

Table 5: Mean values for each selected metric across the study catchments, in order of URBEXT. Means with the same letter across study catchments are not significantly different to each other.

Catchment	S2	B1	B2	S1	S4	B3	S5	S3
URBEXT	0.06	0.14	0.26	0.26	0.42	0.44	0.46	0.6
n	36	38	26	26	85	11	50	64
Qmax (l s^{-1} km^{-2})	47.5 ^{c}	33.7 ^{c}	105.2 ^{ab}	95.4 ^{b}	141.6 ^{a}	192.4 ^{a}	719.4 ^{d}	116.9 ^{ab}
DR (mm)	1.5 ^{c}	1.7 ^{bc}	1.9 ^{ab}	4.5 ^{ab}	2.8 ^{a}	3.3 ^{a}	3.2 ^{a}	2.6 a
PR (%)	10.9 ^{d}	12.5 ^{bd}	16.6 ^{ab}	28.8 ^{ac}	23.6 ^{ac}	26.6 ^{ac}	28.2 ^{c}	24.8 ^{ac}
T_{PS} (h)	13.3 ^{d}	8.7 ^{cd}	4.1 ^{ab}	7.1 ^{ac}	8.2 ^{c}	4.9 ^{ac}	2.7 ^{b}	4.6 ^{a}
Θ_{S} (h)	39.0 ^{e}	15.2 ^{f}	4.8 ^{a}	11.2 ^{cd}	9.6 ^{d}	4.4 ^{ab}	1.6 ^{f}	6.8 ^{bc}
T_{LPPS} (h)	21.0 ^{e}	10.9 ^{f}	4.8 ^{a}	7.5 ^{bd}	9.0 ^{d}	3.6 ^{abc}	3.4 ^{ac}	4.8 ^{bc}
T_{LCS} (h)	15.1 ^{d}	8.2 ^{e}	1.2 ^{a}	4.7 ^{c}	5.8 ^{c}	1.5 ^{ab}	2.0 ^{b}	2.3 ^{a}

Table 6: Mean metric values for each study site under wet and dry conditions. Values sharing the same superscript letter are not significantly different, while highlighted values indicates catchment means that are significantly different between wet and dry conditions as defined using soil moisture deficit (SMD).

	Wet (SMD ≤ 7.6mm)								**Dry (SMD > 7.6mm)**							
Catchment	S2	B1	B2	S1	S4	B3	S5	S3	S2	B1	B2	S1	S4	B3	S5	S3
URBEXT	0.06	0.14	0.26	0.26	0.42	0.44	0.46	0.6	0.06	0.14	0.26	0.26	0.42	0.44	0.46	0.6
n	21	17	10	12	35	5	23	24	15	21	16	14	50	6	27	40
SMD	1.7	0.6	0.3	0.8	1.3	0.0	1.1	0.9	64.6	61.6	59.2	64.7	59.3	83.9	57.0	63.6
Qmax (l s^{-1} km^{-2})	74.3 ^{bc}	57.8 ^{c}	102.8 ^{abc}	152.4 ^{ab}	149.1 ^{a}	154.5 ^{ab}	667.1 ^{d}	118.6 ^{ab}	**9.8** ^{c}	**14.1** ^{c}	106.7 ^{ab}	46.4 ^{b}	136.4 ^{a}	224.1 ^{a}	763.9 ^{d}	115.8 ^{a}
DR (mm)	2.4 ^{a}	3.1 ^{a}	2.5 ^{a}	8.6 ^{b}	3.2 ^{a}	3.0 ^{ab}	3.8 ^{ab}	2.7 ^{a}	**0.2** ^{d}	**0.6** ^{cd}	1.5 ^{ab}	**0.9** ^{bc}	2.6 ^{a}	3.6 ^{a}	2.6 ^{a}	2.5 ^{a}
PR (%)	17.2 ^{a}	21.9 ^{a}	19.8 ^{ab}	53.9 ^{c}	26.4 ^{ab}	27.5 ^{ab}	34.0 ^{b}	29.4 ^{ab}	**2.0** ^{e}	**4.9** ^{de}	14.7 ^{ab}	**7.2** ^{bd}	21.5 ^{c}	25.9 ^{ac}	23.1 ^{ac}	22.1 ^{c}
T_{PS} (h)	15.1 ^{d}	9.8 ^{cd}	5.0 ^{ab}	11.4 ^{ab}	8.5 ^{cd}	5.9 ^{abc}	3.0 ^{b}	4.7 ^{a}	10.7 ^{e}	7.8 ^{de}	3.2 ^{abc}	**3.3** ^{de}	8.0 ^{bd}	**4.0** ^{abcd}	2.4 ^{c}	4.5 ^{a}
Θ_S (h)	43.7 ^{c}	16.1 ^{b}	6.1 ^{a}	18.3 ^{b}	10.0 ^{a}	4.8 ^{a}	2.1 ^{d}	7.5 ^{a}	32.4 ^{c}	14.5 ^{f}	3.9 ^{a}	**5.1** ^{ab}	9.2 ^{d}	4.0 ^{ab}	1.2 ^{e}	6.4 ^{b}
T_{LPPS} (h)	21.1 ^{c}	10.7 ^{bc}	5.6 ^{a}	10.1 ^{b}	9.3 ^{b}	4.1 ^{a}	3.8 ^{a}	4.9 ^{a}	20.7 ^{c}	11.0 ^{d}	4.2 ^{a}	5.2 ^{a}	8.8 ^{d}	3.2 ^{ab}	3.1 ^{ab}	4.7 ^{b}
T_{LCS} (h)	15.9 ^{d}	8.4 ^{c}	1.5 ^{a}	8.1 ^{c}	5.7 ^{c}	1.4 ^{ab}	1.7 ^{b}	2.2 ^{a}	14.0 ^{c}	8.0 ^{e}	1.0 ^{a}	**1.7** ^{a}	5.7 ^{d}	1.6 ^{ab}	2.1 ^{b}	2.4 ^{a}

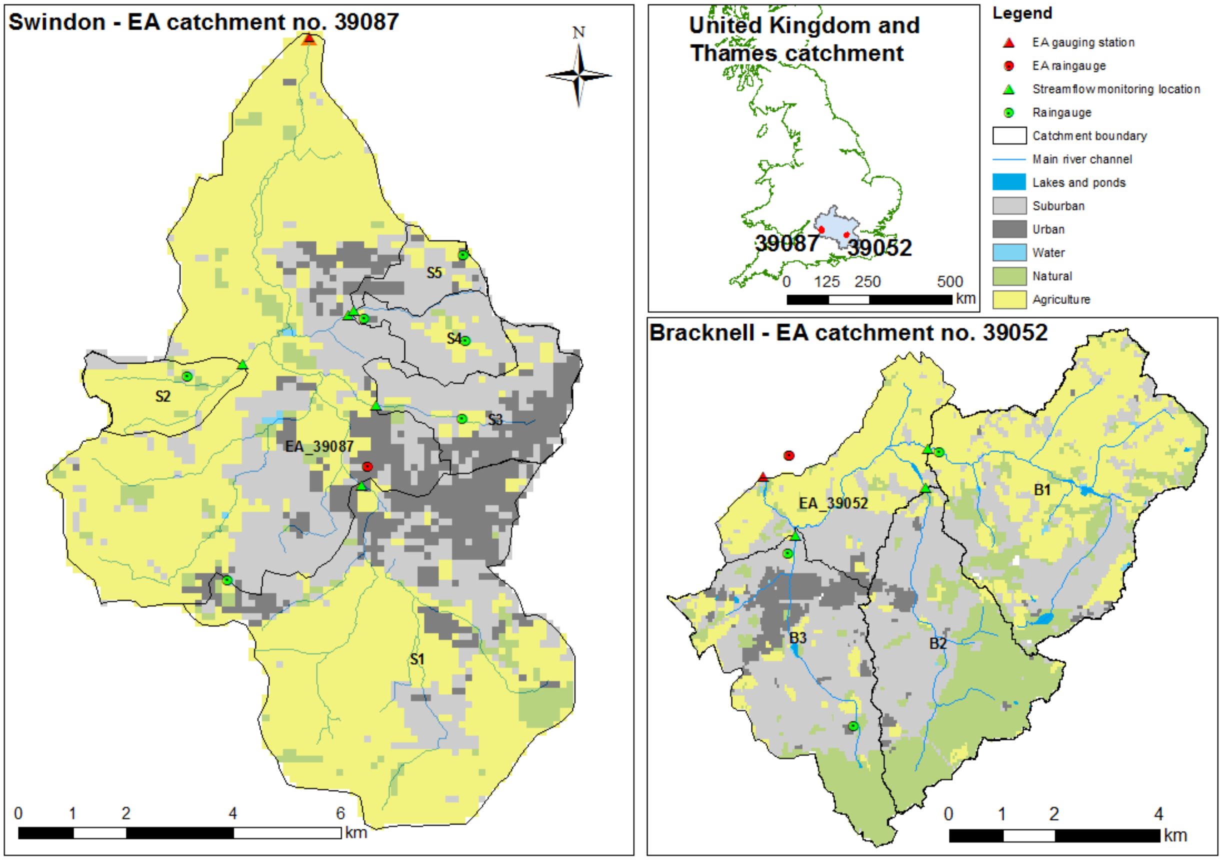
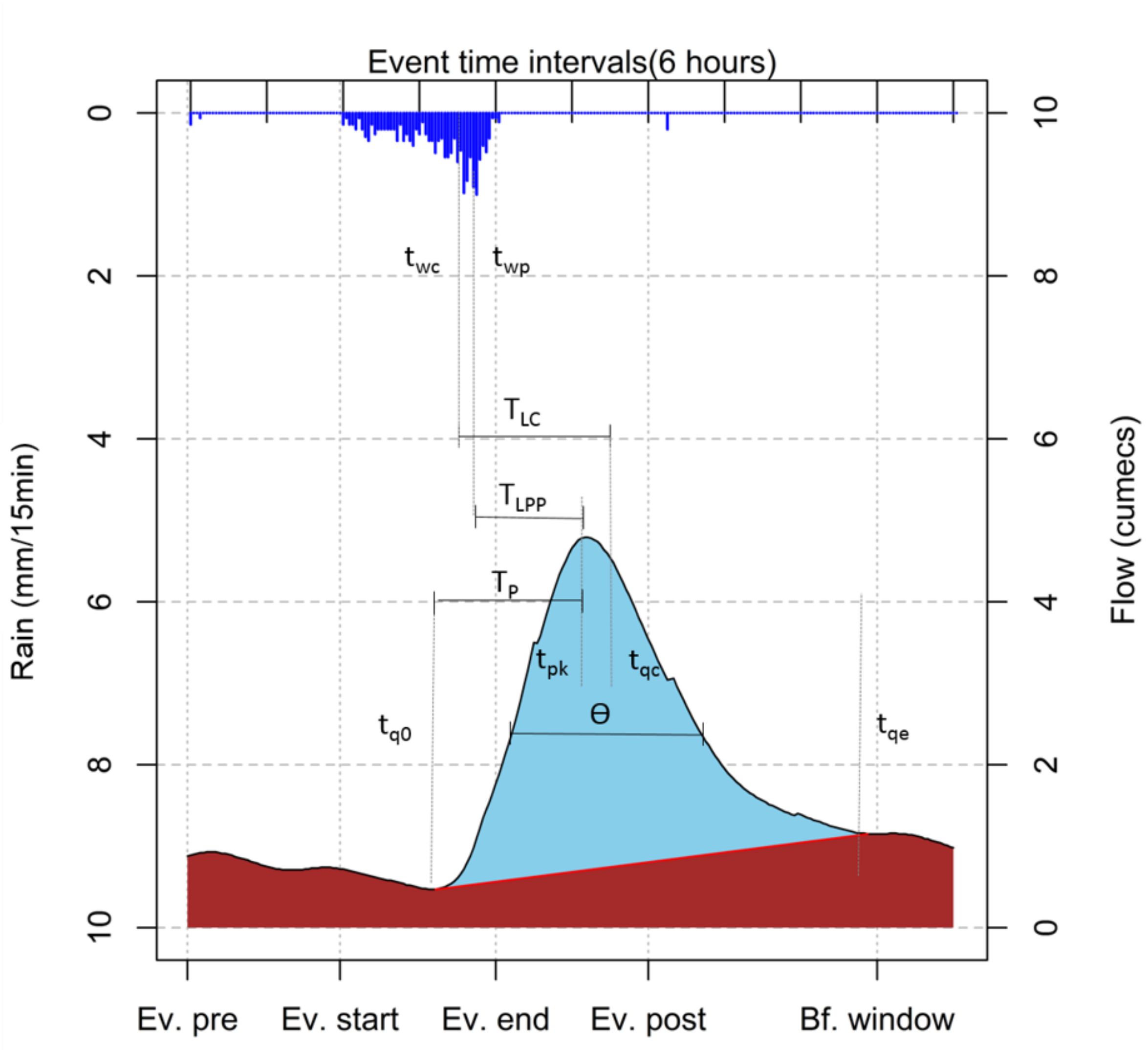


FIGURE 1: EA catchments at Swindon and Bracknell, showing study catchments, monitoring locations and land cover. Inset shows EA catchment locations within Thames basin and the United Kingdom.



Time instants

t_{wc} = centroid of precipitation

t_{wp} = peak of precipitation

t_{q0}= start of stormflow

t_{pk}= peak stormflow

t_{qc}= centroid of stormflow

t_{qe} = end of stormflow

Time metrics

T_P= time-to-peak

T_{LC}= centroid lag time

T_{LPP}= peak lag time

Θ= flood duration

Event instants

Ev.pre = pre-event window

Ev.start = event rainfall start

Ev.end = event rainfall end

Ev.post = post event window

Bf.window = baseflow window

FIG 2: Hydrograph separation with event instants used to select independent events and time instants used to derive time-based metrics of storm events

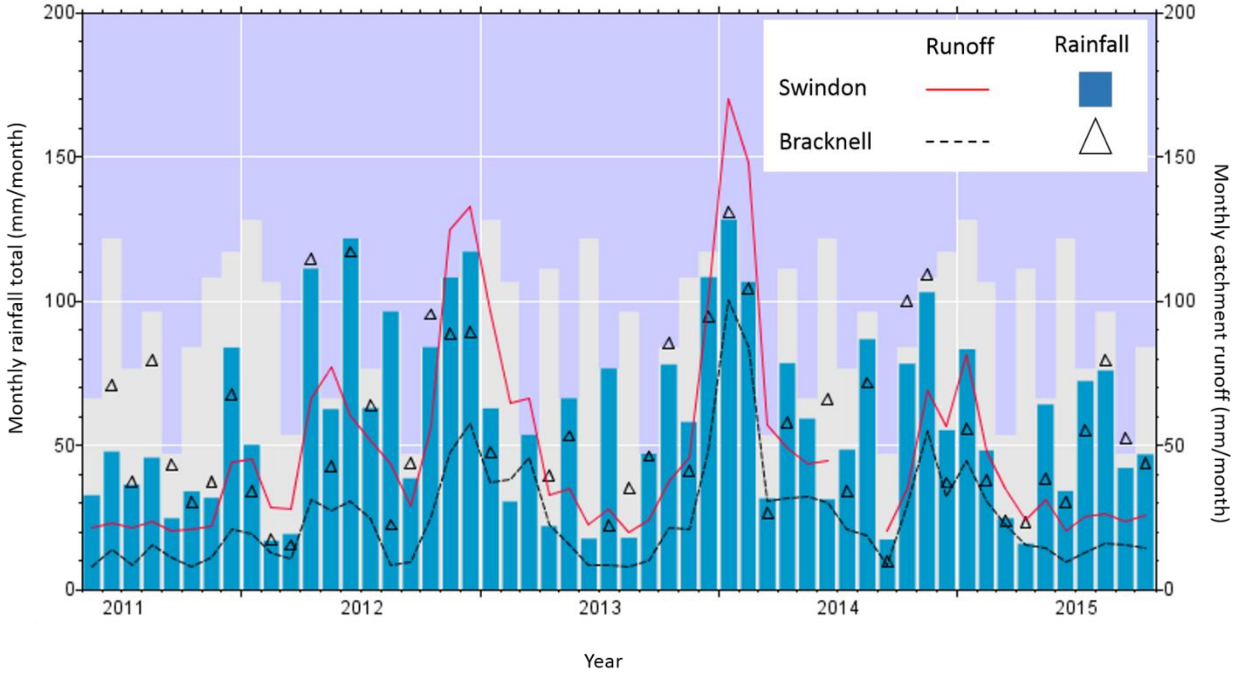


FIGURE 3: Monthly rainfall and flow for Environment Agency rainfall and gauging stations at Swindon (39087) and Bracknell (39052). The blue upper envelope marks the long-term maximum monthly rainfall for Swindon.

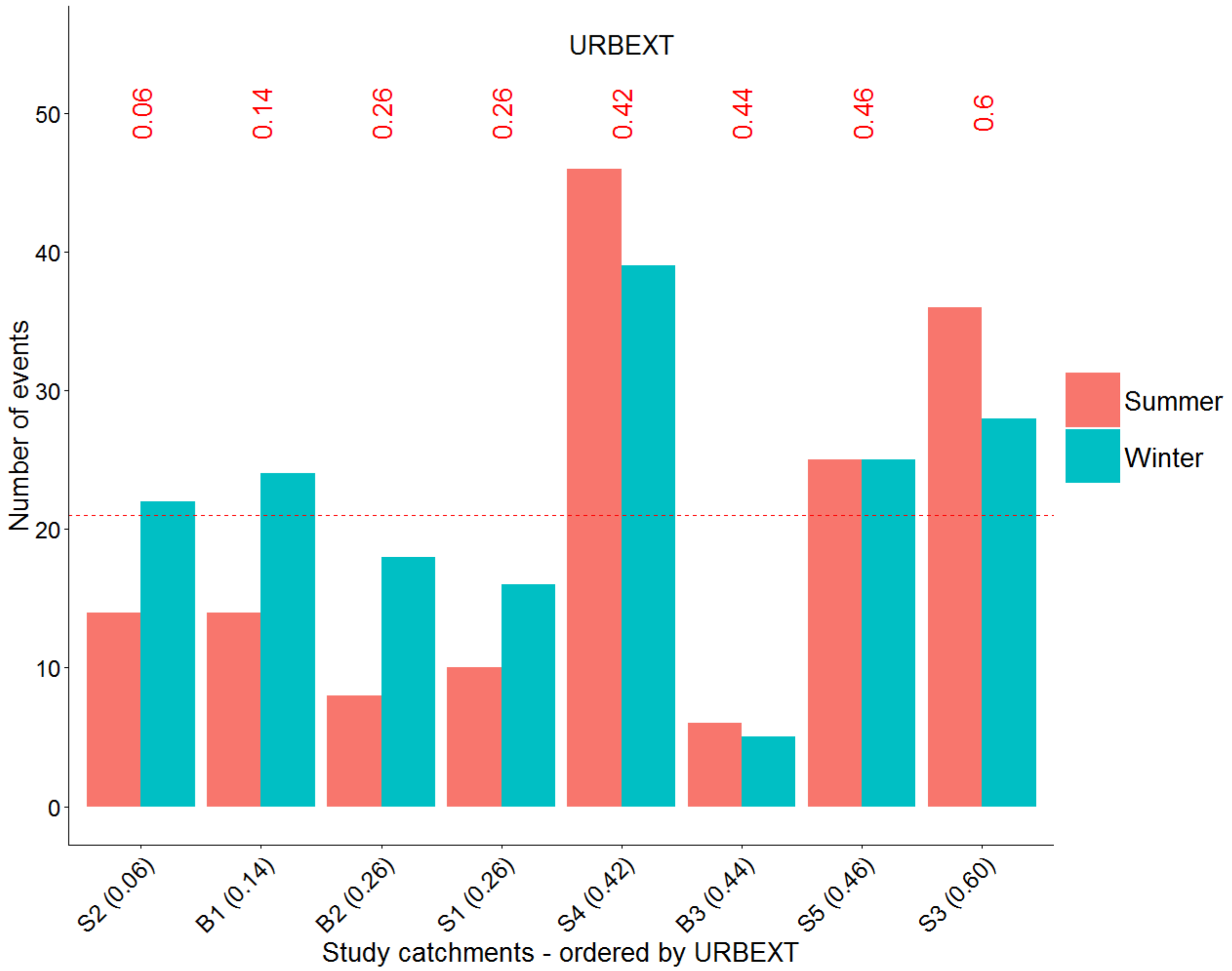


FIGURE 4: Histogram of storm events by site and season (summer defined as April to September) for each sub-catchment with mean frequency of all study catchments indicated by dashed red line.

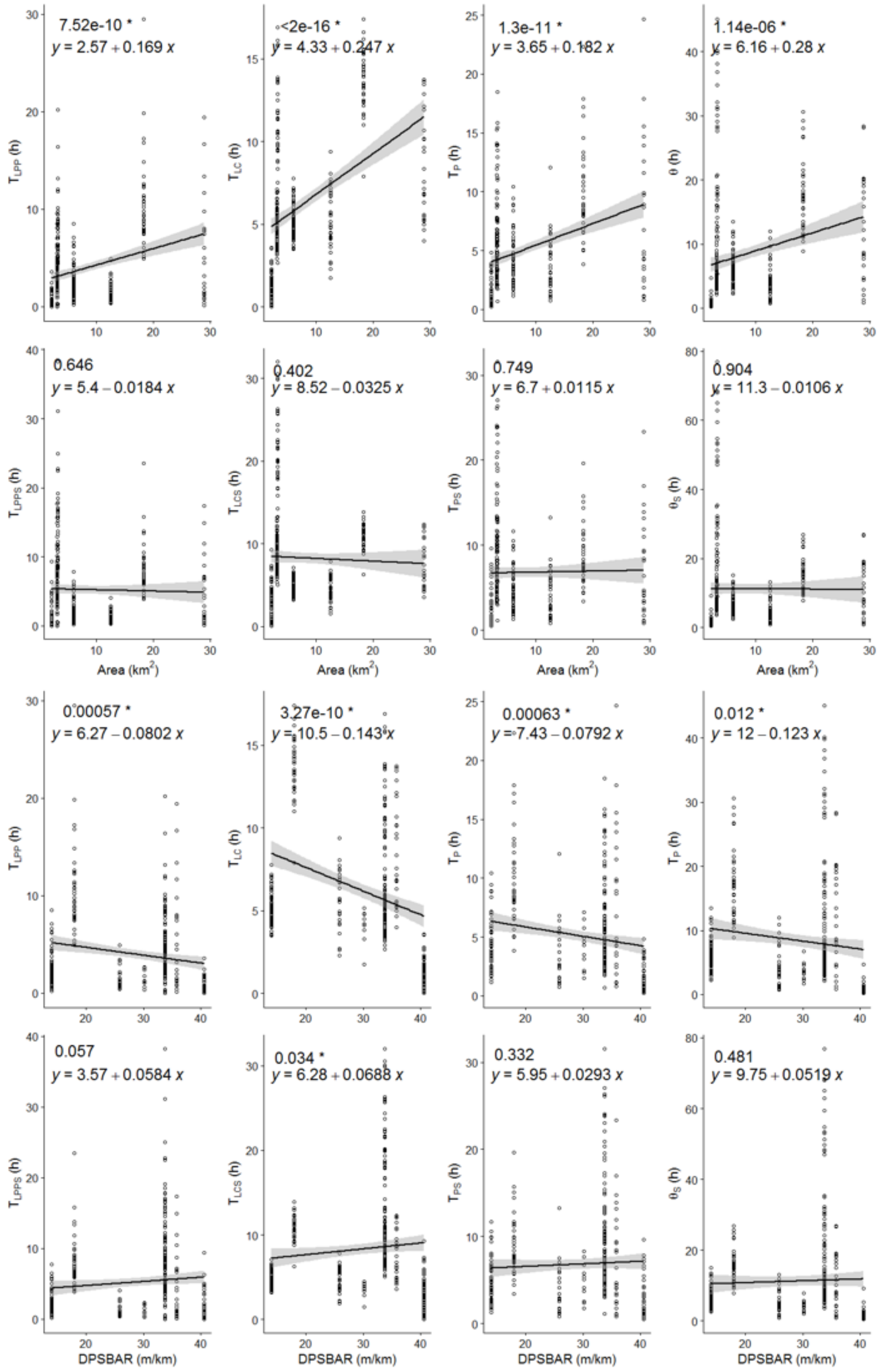
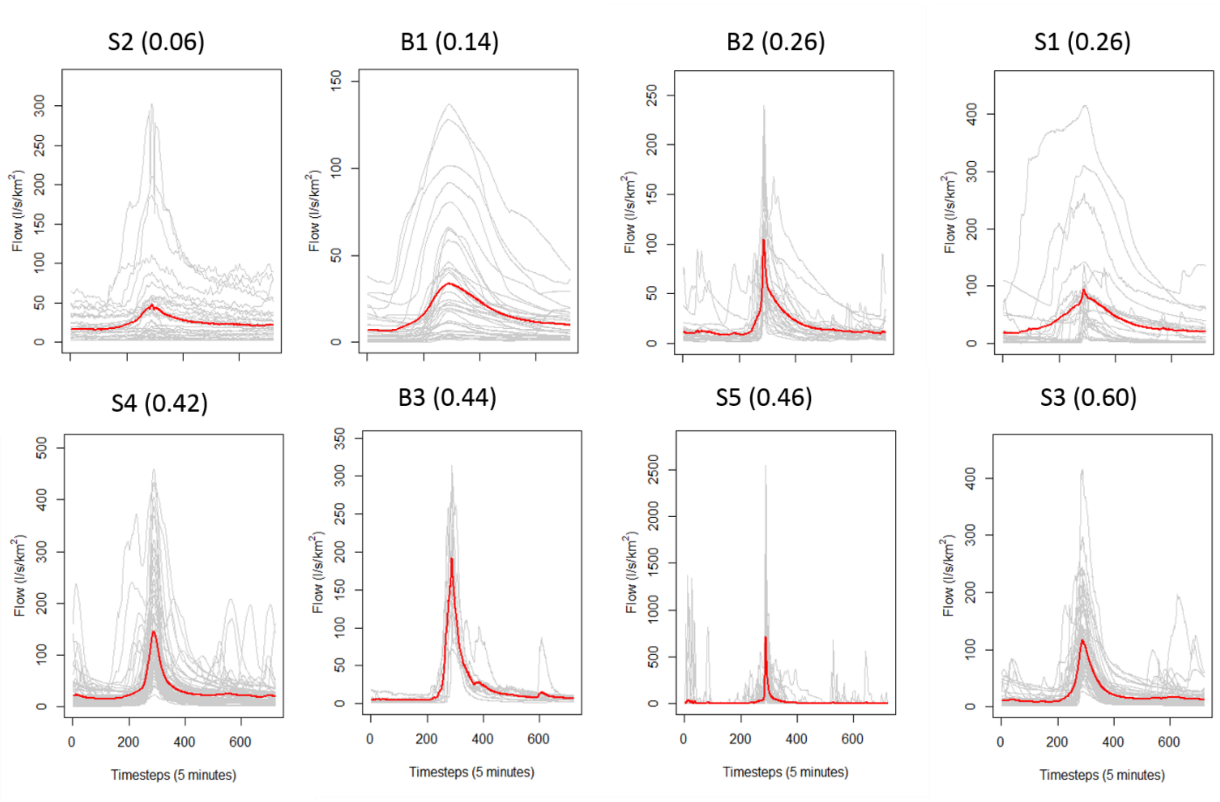


FIGURE 5: Time-based hydrograph metrics (Table 4) against AREA and DPSBAR before (a, b) and after (a_S, b_S) scaling (eqs. 4 – 7). Data are fitted with a linear model fitted with significance (p) of fitted model slope (* denotes $p < 0.05$) and model equation reported. Grey shading shows the 95% confidence interval.



S2 (0.06)

B1 (0.14)

B2 (0.26)

S1 (0.26)

S4 (0.42)

B3 (0.44)

S5 (0.46)

S3 (0.60)

FIGURE 6: Comparison of area weighted event hydrographs (grey) and mean hydrograph (red) among study catchments (Table 1, Fig. 1) with catchment UREBEXT in brackets (ordered top left to bottom right by URBEXT)

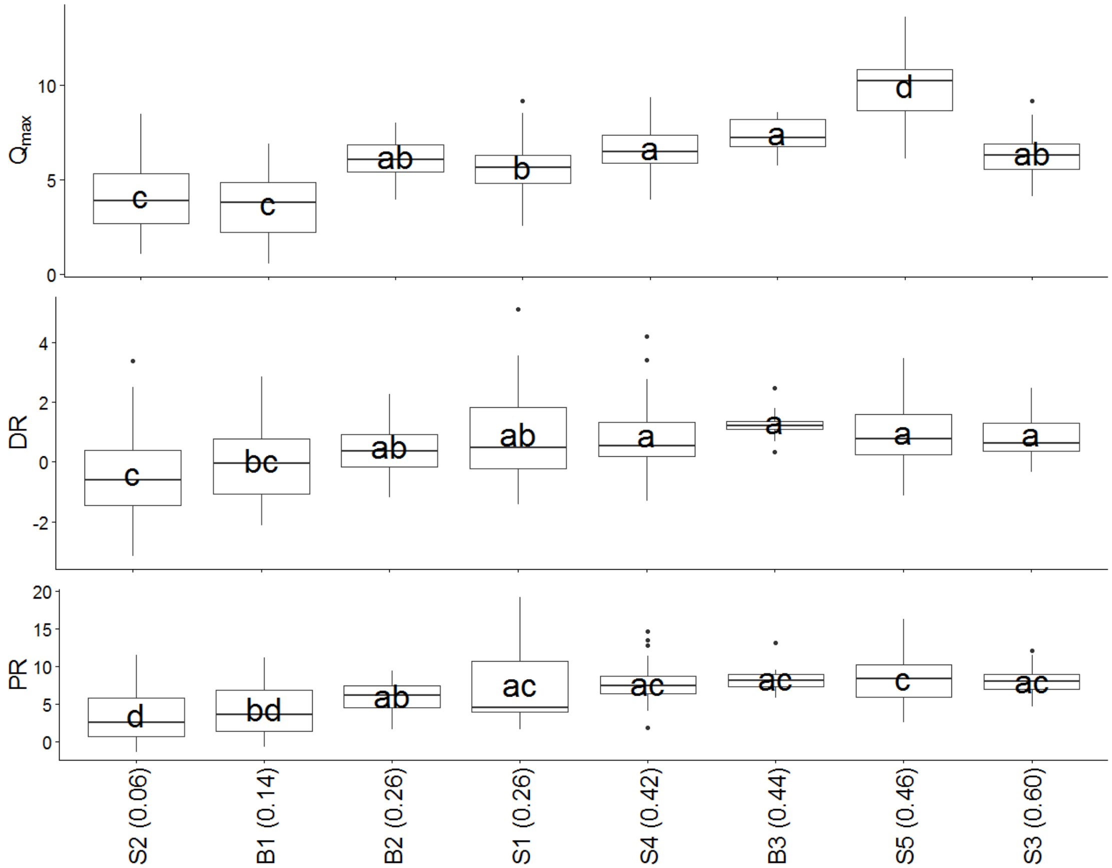


FIGURE 7: Boxplots of normalised peak flow (Q_{max}), storm runoff (DR), and percentage runoff (PR) across the study catchments – URBEXT in brackets. Box-plots sharing the same letter have means that are not significantly different.

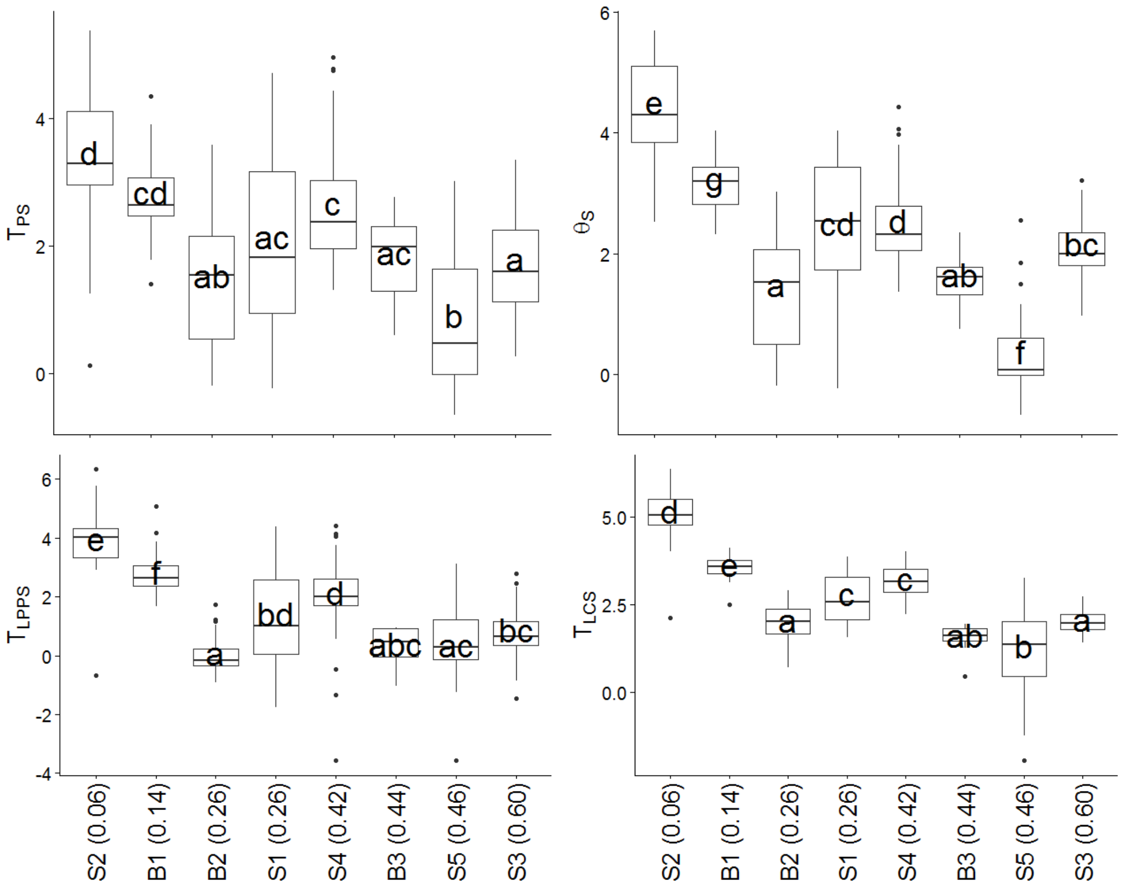


FIGURE 8: Box-plots of scaled and normalised time-to-peak (T_{PS}), flood duration (Θ_S), time lag-to-peak (T_{LPPS}), and time lag-to-centroid (T_{LCS}) across study catchments – URBEXT in brackets. Box-plots sharing the same letter have means that are not significantly different.

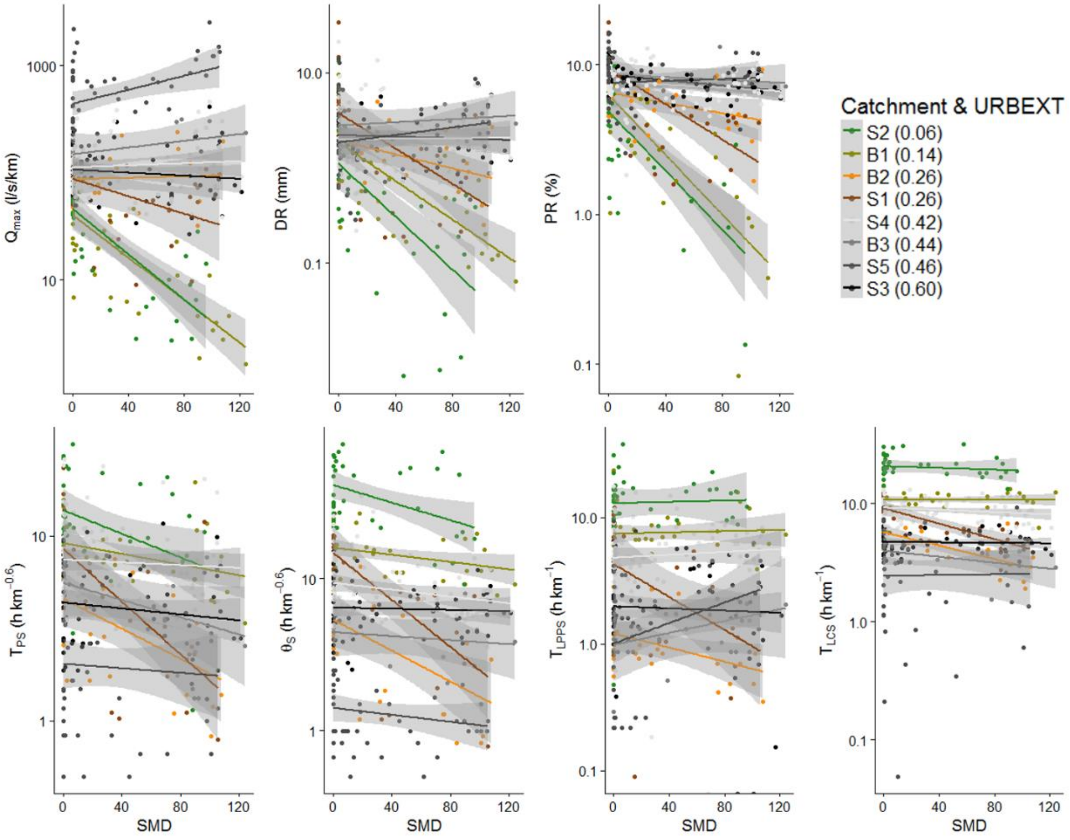


FIGURE 9: Change in metrics (Table 4) with SMD by catchment with linear fit and 95% confidence intervals shown in grey. (Y axis is log scale)