Understanding the impact of the built environment mosaic on rainfall-runoff behaviour

1. INTRODUCTION

Increasing urbanisation of catchments is recognised to have a demonstrable effect on storm runoff characteristics, contributing to increased magnitude and frequency of urban flooding (McGrane 2016). The urban environment is often characterised by large surface areas of anthropogenic origin with hydrological characteristics that differ from natural surfaces in terms of reduced infiltration (e.g. Fletcher et al., 2013; Ragab et al., 2003; Redfern et al., 2016; Salt and Kjeldsen, 2019) and reduced lag-times (e.g. Leopold, 1991); the combined effect is a detectable increase in runoff volume and peak flow. These effects become evident when the fraction of urban landcover increases above 10%-15% of the total catchment area (Kjeldsen 2010; Miller et al. 2014), thereby making small catchments more susceptible to change.

To manage the resulting surface runoff within urban areas, hydraulically efficient surface water drainage systems that collect and route surface runoff to receiving water bodies are often constructed (Butler and Davies 2004); with major impacts to hydrological systems (Rose and Peters 2001). The urbanisation of previously natural land covers has potential negative downstream implications for flood risk management, geomorphology, hydro-ecology and water resources (DeFries and Eshleman 2004; Booth et al. 2016). However, despite the obvious importance of urban hydrology, there are surprisingly few experimental studies of observed flood events from high-resolution hydrological data in urban systems (Redfern et al., 2016). Thus, the relative importance of factors such as seemingly impervious surfaces, connectivity, and soil moisture are still not well-understood in the context of urban catchments (Jefferson et al. 2017). Current understanding of rainfall-runoff behaviour in urban areas is typically based on two key conceptual descriptions of the hydrological properties of urban surfaces:

(i) that anthropogenic surfaces such as roads, driveways and roofs are impervious to the infiltration of precipitation to the soil (Wiles and Sharp 2008); and,

(ii) that urban impervious surfaces are either connected or disconnected to a surface water drainage system (Arnold and Gibbons 1996).

These assumptions are used to derive descriptive statistics of urban development such as Percentage IMPervious area (PIMP) or Total Impervious Area (TIA) (Lu and Weng 2006; Sahoo and Sreeja 2016), or urban developments are described with categorical terms lacking physical detail e.g. residential, industrial, commercial (Herold et al. 2002). Aerial photographs, infrared imagery, satellite remote sensing and maps are analysed to produce estimates of the extent of impervious surfacing, combining areas covered by roofs, roads and other anthropogenic materials (Shahtahmassebi et al. 2016; Sørensen 2021). The hydrological properties of urban areas are examined by comparing rainfall-runoff data (where available) to geospatial data that describes the extent and features of urbanisation (O'Driscoll et al. 2010; Ferreira et al. 2016), or more typically where such data are limited, the hydrological behaviour of urban areas is estimated with hydrological models (Yin et al. 2016; Mei et al. 2020). Modelling techniques usually rely on the calibration of model parameters that link metrics describing urban development (e.g. PIMP) to rainfall-runoff behaviour, or, where such data are missing, model parameters are estimated, assumed or derived from previous work, e.g. Kjeldsen (2009) refers to Packman (1980) to estimate surface connectivity in the United Kingdom. Further, Vesuviano and Miller (2019) found substantial differences in the runoff patterns from three heavily urbanised catchments located close together, highlighting the importance of local scale effects. Although models can be calibrated to achieve a good performance between simulated and recorded rainfall-runoff data, model parameters at large scales are often abstract generalised mathematical representations of real-world processes and features, offering little understanding of how small-scale, local processes and physical features influence the generation of surface water runoff and pluvial flood risk.

It is well documented that not all rainfall falling onto urban surfaces is converted into direct runoff (Hollis and Ovenden 1988; Wiles and Sharp 2008; Awadalla et al. 2017), yet there is uncertainty about what causes losses from urban catchments and how to estimate these losses in lieu of monitored rainfall-runoff data. Not all surfaces are connected to the surface water drainage system and instead only a “Directly Connected Impervious Area” (DCIA) or “Effective Impervious Area” (EIA) has a hydraulic connection to a surface water drainage system (Carmen et al., 2016). The degree of connectivity between surface water drainage systems and surfaces has been found to play an important role in determining the rainfall-runoff properties of urban areas (Ebrahimian et al. 2016). Controlling and reducing connectivity of surfaces is cited (Walsh et al. 2005; Moore et al. 2012; Carmen et al. 2016) as a mechanism by which the impacts of urbanisation on hydrology could be reduced and determining accurate estimates of DCIA is acknowledged as an important factor in predicting urban hydrological behaviour (Beighley et al. 2009). However, without detailed ground assessments (e.g. Lee and Heaney, 2003), current methods for defining the connectivity of urban surfaces are based on estimates e.g. DCIA is equal to 70% of TIA (Packman 1980), or empirical equations (Sahoo and Sreeja 2016) that show poor performance when applied to areas outside of their original derivation (Lee and Heaney 2003).

Detailed studies have shown that the connectivity of urban surfaces to the surface water drainage system is dependent on small-scale features (such as road gullies), which are difficult to measure across large areas without intensive study (Ravagnani et al. 2009). Additionally, surface scale studies have shown that a direct connection to the surface water drainage system does not necessarily convert all rainfall into runoff upon impervious surfaces (Kidd and Lowing 1979; Hollis and Ovenden 1988) indicating that the rainfall-runoff properties of urban impervious surfaces are more complex than current theory allows for, e.g. urban surfaces can be considered impervious, converting a large fixed proportion of rainfall into runoff, or pervious converting little or no rainfall into runoff (Wiles and Sharp 2008; Law et al. 2009). The importance of the urban form and function on hydrological processes is predominantly based on modelled studies (e.g. Ogden et al. 2011), with few spatial empirical studies (Mejía and Moglen 2009; Miller et al. 2020a). In summary, there is a lack of detailed understanding of what features and processes affect the rainfall-runoff properties and connectivity of surfaces within the urban environment, with a greater need for understanding the role of spatial heterogeneity at different scales, from surface to flowpath to development (the present study) scales. Such information is critical for use in hydrological modelling and surface water management planning and therefore research and practical engineering decisions are often made on assumed or else uncertain model assumptions, parameters and outputs.

This study aims to better understand how the urban form (morphological land-use – e.g. relative land cover and spatial arrangement) and hydrological function (purpose and relationship to hydrological pathways - e.g. hydrological connectivity) of built environments in small urban catchments impacts hydrological response. Throughout this paper the relationship between what Van de Voorde et al. (2011) refers to as 'form and function' is shortened to 'urban mosaic' (Timms, 1971). The analysis of the hydrological response to urban form was achieved through the evaluation of high-resolution runoff data obtained from a monitoring campaign involving equipment installed in two neighbouring small (< 1ha) urban catchments (development scale) with differing densities of urban and green space (heterogeneity) in the town of Swindon in the South of England. The study compares key hydrological parameters observed during flood events, including runoff volume, lag-times and hydrograph shapes.

2. CASE STUDY

The town of Swindon is located 115km to the west of London and has experienced extensive development in peri-urban residential areas during the twentieth and twenty-first century. Originally a small village, Swindon's rapid development began during the latter part of the nineteenth century as a hub for construction and maintenance of the UK's rail network and related industries. The population grew in the post war era (1950s), as it was designated a “spill over” town for London, to reduce overcrowding (in central London) and aid in the supply of housing (Cullingworth 1961). Swindon also expanded rapidly during the period 1970-2000 as the central industrial core was re-developed into areas servicing commercial, financial, distribution and other service based economic activities (Brown et al. 2000). Housing developments constructed at different periods during the twentieth century accommodate a large proportion of the town’s population to the peri-urban north. Each development reflects the design and planning policy of its era of construction and thus forms a mosaic of differing surface types, housing layout, road design, green spaces and gardens. North Swindon is therefore characterised by several different residential areas with contrasting designs of land surface and the provision of surface water drainage. By selecting two different residential developments in north Swindon for study it is possible to control for a number of factors that may influence rainfall-runoff behaviour such as: climatic conditions, soils, geology and slope, thus isolating differences in design and layout of residential development – the subject of this study.

In selecting two study sites in close proximity (<1km apart) of comparable size, the influence of extrinsic variables in determining the rainfall-runoff behaviour of the two study sites is limited, with age and design being the predominant physical difference. The two study sites reflect two periods of urban expansion in much of Western Europe (including the UK and Swindon), during the post-war 1950s and 1990s. The two study catchments are of homogeneous residential land use and meet the following selection criteria:

(i) Each study sub-catchment is drained via separate surface water and foul/waste water drainage systems with no separate highway drains (i.e. roads drain to the surface water drainage system via road gullies).

(ii) The study areas are of a similar size (under 1ha), of similar slopes and with similar underlying soils and geology.

(iii) The potential to install and maintain hydrological monitoring equipment within the surface water drainage systems that serve each study sub-catchment with appropriate practical health and safety considerations.

After several field visits to the north Swindon area, two sites were selected for study: Arley Close (AC) and Winsley Close (WC; Figure 1a). WC was constructed in the post-World War II era of the 1950s, within the Penhill housing estate, and is built on the American Radburn principle, with houses grouped in small cul-de-sacs around areas of open vegetated space (Dunning et al. 1970). Access to each property is via shared pathways that link buildings to the road network, whilst few properties have private car parking spaces. Constructed as social housing following Swindon's designation as a spill over town for London in the 1950s, a time when car ownership was low and development planning favoured speed of construction over other considerations, such as transport links or proximity to employment (Cullingworth et al. 2014). In contrast, AC is part of the Abbey Meads housing development built during the 1990s, a period of increased car ownership (Dargay and Hanly 2007) and like WC (1950s) is arranged into a small cul-de-sac. However, there is no centrally shared open space, instead the road network constitutes the largest open shared space. Access to each property from the road network is via private pathways and driveways. Neither of the two developments contains any form of public green infrastructure (GI), whilst individual households may have installed water-butts, these were not evident during the data collection phase, as they are often situated in back gardens.

3. METHODS

3.1 Hydrological monitoring programme

A hydrological monitoring network was established to measure rainfall, runoff, and soil moisture within the study catchment areas between May 2014 and December 2015 (approximately 18 months). This is comparable to other studies, for example, Hollis and Ovenden (1988) and Gilbert and Clausen (2006) analyse data collected over a twelve-month period, Ragab et al., (2003) a fourteen-month period.

Flow monitoring: To monitor flow within the surface water drainage systems of AC and WC, two Stingray 2.0 (Greyline instruments) Ultrasonic Doppler Flow Monitoring (UDFM) devices are installed into the pipe network serving each study area (Figure 1b). The UDFM is a standard method for the measurement of flow within non-surcharged pipes and open channels (Blake and Packman 2008). Access is gained to each surface water drainage system via manholes within the roads serving each study catchment (Figure 2). To place the sensor in a position with known and constant geometry, metal plates were used to affix the sensor head onto the bottom of drainage pipes upstream of the access manhole. Data quality control and correction was undertaken on the data to ensure a stable and reliable velocity-depth relationship, with scatter in the velocity-depth data is ascribed to the following possible sources: (i) turbulence in flow conditions; (ii) debris within the pipe network, and; (iii) the backing up of flow under high flow conditions and potential instrument error.

Precipitation monitoring was undertaken by the Centre for Ecology and Hydrology (CEH) for the study monitoring period as part of a wider hydrological monitoring programme (Miller et al. 2014; Miller and Hutchins 2019). This data is used as it was not possible to place precipitation monitoring equipment directly within AC and WC given the lack of secure and suitable locations. Raw data collected by CEH was processed to determine estimates of precipitation at two-minute resolution (sensitive to 0.2 mm) for AC and WC. The three CEH precipitation stations at Vygon, Penhill and Pinhurst are all situated within 3 km or AC and WC (Figure 1a), however these stations represented less secure locations and as such suffered from intermittent vandalism and overgrowth of vegetation. Therefore, an Environment Agency tipping bucket rain-gauge at the Swindon treatment works to the southwest of Swindon was also used, this recorded at 15min intervals and is approximately 3km from both sites. To derive a complete rainfall series for AC and WC the rainfall time series from each of the CEH rain-gauges is compared to the data collected at the Environment

Agency gauge using double mass curves. Both Vygon and Penhill sites have periods of missing data, therefore analysis of the Pinehurst-EA gauge relationship using a Double Mass Curve (DMC) illustrates that there is a good correspondence between the two TBRs, with no discernible breaks/changes of slope, indicating a consistent relationship.

Soil moisture measurements were conducted at one location within each of the two study sites using a PR2 capacity-sensor based probe, converting soil electric permittivity to estimates of soil moisture at a depth of 100mm. Data is missing on a number of occasions throughout the PR2 soil moisture data as a result of malfunction caused by vandalism and rust, with infilling of periods of missing data a linear interpolation between two known points at either end of the missing data period. On 27th October 2015, the series of soil moisture measurements collected at AC falls within one hour by 14.5 m^3/m^3, caused by vandalism (the probe was lifted from the access tube). To correct this error an uplift of 14.5 m^3/m^3 is applied to data collected post 27th October 2015. After August 2015, the PR2 probe near WC records soil moisture readings at an increased variability and sensitivity compared to prior August 2015; the result of probe damage again caused by vandalism, therefore a DMC was established and the slope for the period August-December 2014 and August - December 2015 compared and examined by fitting a simple linear regression model using the Ordinary Least Squares method. The slope of the DMC during the period August-December 2015 is approximately 18% greater than the August-December 2014, therefore the later was adjusted to bring about an average reduction of DMC slope to match the August-December 2014 period. In addition, intermittent field monitoring was undertaken using a Field Scout TDR300 mobile soil moisture probe (Spectrum Technologies, Inc.) with GPS locator (Garmin 72H) to record surface soil moisture readings at 1-2 m spacing within the vegetated surfaces of the study catchments. Whilst the TDR300 soil moisture probe can be calibrated to site specific conditions, through comparison of data collected between the PR2 and TDR300, the PR2 data can be validated. It was found that during the summer months the TDR300 provided inaccurate and unreliable measurements, a function we believe of insufficient rod lengths penetrating below the vegetated horizon, with short rod length (76mm) selected to overcome earlier issues of rod deformation. However, the TDR300 data suggests limited variability in soil moisture across the two sites.

Event selection was based on a target set of characteristics defined a priori. The catchments in this study are comparatively small and heavily urbanised and the surface water drainage system at each site only drains the study area and do not contain drainage of non-urbanised or additional areas upstream. The hydrological response of the studied surface water drainage systems is highly sensitive to rainfall as they only contain flow when there is rain (i.e. the flow in the pipes is ephemeral). Therefore, minimal base flow removal is required, as it is unlikely that flow within the drainage system is derived from any source other than surface runoff (e.g. aquifers, groundwater or anthropogenic sources). Where there is flow within the drainage system prior to an event, this is assumed to be the contribution of local soil drainage from previous events. The following criteria were adopted to either include or exclude an event from analysis:

(i) Total event rainfall depth must be over 1mm.

(ii) Runoff response must have a defined single peak, with rising and falling limb. Fluctuations in hydrograph shape are allowed, however subsequent peaks must not be more than half of the peak runoff rate.

(iii) There must be rainfall, runoff and soil moisture data for the event at both AC and WC (this helped remove anomalous events, such as someone washing a car).

(iv) Runoff must return to pre-event conditions prior to the next event occurring.

By constraining analyses to events that meet these selection criteria, uncertainty in determining which rainfall input produces subsequent runoff output is reduced. A total of 34 individual events were identified. An average hydrograph is presented that was generated from the average normalized flow at each timestep. Of the 34 events, nine occur in winter (Dec, Jan, Feb), seven in spring (Mar, Apr, May), seven in summer (Jun, Aug) and eleven in autumn (Sep, Oct, Nov). Total event rainfall depth, maximum 10-minute rainfall intensity and event durations are plotted (Figure 3). This illustrates that event depth is positively associated with both rainfall intensity and duration. The events selected for analysis are predominantly sampled from relatively low values of depth, duration and intensity resulting in distributions that are skewed towards lower values of depth, duration and intensity (Figure 3). Seasonally there is little grouping in events, however there are no spring events over 2.0 mm/10-minute rainfall intensity and only one winter event (event 34). There are five summer and autumn events over 2.0 mm/10-minute rainfall intensity.

3.2 Assessing the urban mosaic

The impact of the urban mosaic on both peak flow and percentage runoff are assessed using multivariate linear regression. At each of the two study sites, the response variable (peak flow or percentage runoff) was modelled as a function of the explanatory variable listed in Table 3, which are derived from analysis of the observed rainfall and soil moisture data, representing rainfall characteristics and antecedent soil moisture conditions. To reduce co-linearity, an exploratory analysis of cross-correlations showing weak or no correlation between exploratory variables representing rainfall and antecedent soil moisture, respectively. Consequently, the explanatory variables are split into two groups defined as (1) rainfall characteristics and (2) antecedent conditions.

To assess the sensitivity of each study site the following procedure was adopted: First, one explanatory variable is selected from the antecedent group, one from the rainfall characteristics group. Next, a multiple linear regression model is fitted between either peak flow or percentage runoff (y) and a combination of one antecedence x_1 and one rainfall characteristics variable x_2, i.e.

$$y_i = \beta_0 + \beta_1 x_{1,i} + \beta_2 x_{2,i} + \varepsilon_i, \quad i = 1, \dots, 34 \tag{1}$$

where β_0, β_1 and β_2 are regression model parameters estimated using ordinary least square, and ε_i are normally distributed model residuals. The significance ($p<0.05$) of each regression model parameter is noted along with the adjusted R^2 value of the overall model fit.

The procedure is repeated for all possible combinations of antecedent and rainfall characteristics variables, and model outputs are used to determine the optimum model for analysis and interpretation, defined as the models where the regression model parameters for both explanatory variables are significant ($p<0.05$). Where more than one model is highlighted as having two significant explanatory variables, the model with the greatest adjusted R^2 value is chosen. Residual analysis is completed on optimum models to ensure conformity with the assumptions of linear regression modelling. If a model deviates from the assumptions of linear regression modelling, the modelling procedure is repeated following an appropriate transformation of the dependant or explanatory variables. Finally, the regression model parameters ($\beta_0, \cdots, \beta_p$) can be interpreted to understand how changes in values of the explanatory variables affect the response of the dependant variable.

4. CHARACTERISING THE URBAN MOSAIC

The catchment boundaries defined within AC and WC respectively and locations of key hydrological connections are illustrated in Figure 1b. An area to the west of WC was originally thought to be included within the catchment drained by the monitored surface water drainage system, however upon checking the connectivity of surfaces through a manual acoustic method, it was determined that this area connects downstream of the monitored point and was therefore omitted from the catchment boundary (hashed area, Figure 1b). The catchment area for AC is 4982 m^2 (0.4982 ha) and

6690 m^2 for WC (0.6690 ha). The average overall slope characteristics of the two catchments are compared by calculating the s1085 slope characteristic, derived from the LIDAR using the profile graph tool of the 3D Analyst ArcGIS Toolbar; with comparable results of 1.54% and 1.45% at AR and WC respectively.

The underlying soil characteristics are defined within Hydrology of Soil Types (Boorman et al. 1995). as soil type 2 at WC and as potential 2 and/or 25 at AC, with HOST 2 described as a 'Free draining permeable soils on 'brashy' or dolomitic limestone substrates with high permeability and moderate storage capacity', whilst HOST25 is a 'Slowly permeable, seasonally waterlogged soils over impermeable clay substrates with no storage capacity'. Analysis of the soil types indicates bulk density is comparable 0.86 g/cm^3 (AC) and 0.91 g/cm^3 (WC), the percentage organic matter differs, 7% and 19% respectively. Textural analysis of the sediments at both sites shows comparable percentages of sand, silt and clay, with classification of light silts and light loams. Therefore, whilst the HOST system may suggest differences in soil properties, the actual surface soil properties at both sites are similar and unlikely to generate notable different in hydrological response (Supplementary material S1).

Ordnance Survey Master Map data (OSMM), Light Detection and Ranging data (LiDAR) and aerial photography are combined in a GIS environment and site based Individual Parcel Assessments (IPA) are used to define surface cover and connectivity within AC and WC (Figure 4). The extra detail that is collected via the IPAs in roadside and domestic areas are compared to OSMM alone (Figure 4a- d). For both sites, the majority of surface cover is defined as General Surface within the OSMM (around 65%, Figure 4e-f), characterisation post IPA provides greater detail compared to OSMM alone. The OSMM data identifies the locations of buildings accurately in both areas and whilst roads are identified accurately within WC, in AC an area of road is incorrectly identified as general surface. All road surfacing is tarmac within WC, whilst AC contains 183 m2 (approximately 38% of total road surfacing) of brick paved surfacing, with cement mortar fill between brick elements (Table 1). No serious defects in surface condition are recorded in either area, although WC does contain some areas of minor cracking to road and pavement surfaces, likely a function of the increased age of surfaces within WC. AC contains a greater proportion of both private and roofed areas, whilst WC contains a greater proportion of public areas. The public areas within both study sites contain a majority of road related surfacing; AC contains 98% whilst WC contains 65%; as a consequence, 35% of public land within WC is vegetated compared to 2% at AC (Table 1). Both study areas have similar splits in the private areas between front and rear gardens in residential parcels (AC 62% and WC 64% rear gardens).

There is uncertainty in both AC and WC as to whether rear garden non-vegetated surfaces are impervious or semi-impervious cover and therefore the total impervious area in each study area is calculated under the three assumed states:

(i) that all non-vegetated rear garden surfaces are impervious, (High Estimate)

(ii) that 50% of non-vegetated rear garden surfaces are impervious, (Medium Estimate)

(iii) that all non-vegetated rear garden surfaces are semi-impervious, (Low Estimate)

AC contains a larger PIMP in comparison to WC for all three methodological assumptions tested. The variation in estimated imperviousness is greatest at WC where there is a larger area of rear garden non-vegetated surfaces (Table 1). However, AC has a greater impervious cover ranging from 54% to 71% vs 43% to 64% compared to WC respectively. In both sites roofs constitute the largest component of directly connected impervious surfacing 1156 m^2 (AC) and 992 m^2 (WC), being directly connected via guttering and downpipes to the surface water system, typical of the age and type of development (i.e. no soakaways identified).

Within AC and WC the position and type of hydraulic connections between urban surfaces and the surface water drainage system is determined through site based IPA (Figure 1b). The number of road drainage gullies, roof downpipes and linear drainage features were recorded in each study area, AC

(11) has nearly three times the number of drainage gullies in comparison to WC (4), with gullies located on both private and public surfaces in AC. In comparison, WC only has drainage gullies upon public surfaces, meaning that there are no gullies draining private driveways or paths, therefore hydrological connectivity at AC is much greater than at WC, with mean drainage areas of 60m^2 compared to 219m^2 and average drainage distances of 15.7 compared to 27m respectively (Supplementary materials S2a-b). The combination of an increased number of gullies, draining smaller surface areas with reduced drainage distances creates a greater connection efficiency in AC than WC (Supplementary materials S2c-d).

5. IMPACT OF URBANISATION ON PEAK FLOW AND PERCENTAGE RUNOFF

Comparison of the 34 hydrographs at AC and WC indicates that flows are, in general, greater in magnitude at AC compared to WC. In addition, for certain storm events, flows at AC start at zero before quickly reaching peak flow rates, while at WC, flows are non-zero at the onset of these storms. Combined, these results indicate that AC has a more rapid response to rainfall that at WC. The average hydrograph shape is similar for both sites (red lines, Figure 5), though the height of the average hydrograph and the steepness of the rising and falling limbs are greatest at AC. There is a considerable amount of variability in hydrograph shape at both sites, with AC having the greatest hydrograph shape variability.

For each of the 34 events from AC and WC, a set of descriptive metrics (explanatory variables) are derived through the analysis of the rainfall and soil moisture data collected during the monitoring campaign. Table 2 details these descriptive metrics, their definition, and units. The metrics are split into two categories, describing either the characteristics of the rainfall event, or the antecedent wetness of the catchments prior to a rainfall event. Those metrics within the antecedent conditions grouping are derived either from an analysis of the rainfall or soil moisture time-series of data (for example the pre-event 1hr rainfall depth), or else require the use of previously published equations to derive descriptive metrics that are shown to correlate to urban rainfall runoff behaviour (API5, SMD and UCWI, Kidd and Lowing (1979). By deriving these descriptive metrics of each event, it is possible to investigate the sensitivity of the urban rainfall-runoff process within AC and WC and how this sensitivity may be influenced by their respective designs through multiple linear regression.

Each of the 34 rainfall-runoff events is processed to determine the peak flow rate (QMAX) and percentage runoff value (PR); with each event (QMAX and PR) at WC plotted against those from AC (Figure 6a-b). All but two QMAX events plot to the right, with comparable findings for PR; however, deviation from the 1:1 relationship into the WC side of the plots is small. AC therefore has a consistently greater rainfall-runoff response in terms of peak flow and percentage runoff across studied rainfall-runoff events. Both median peak flow at AC and median percentage runoff values are more than double those at WC (median normalised AQMAX = 0.0016 mm/s, median normalised WQMAX = 0.0006 mm/s, median APR= 60%, median WPR = 25%; Figure 6c-d). Little seasonal patterning within the QMAX or PR data is evident, however there are more spring events for AC than WC, whilst winter, summer and autumn events show similar levels of variability. The difference in mean normalised QMAX and PR values between the two sites is significantly different ($p<0.05$; Mann Whitney non-parametric test).

5.1 IMPACT OF URBANISATION ON PEAK FLOW

Initial exploratory data analysis based on the regression models defined in Eq. (1) demonstrated that using non-log transformed values of peak flow result in violations of the linear regression assumptions (namely homoscedasticity). The regression modelling of peak flow (QMAX) therefore progresses using log-transformed values of peak flow as the dependent variable (y).

Based on the results in Table 3, the strongest link between peak flow and rainfall and antecedent soil moisture for AC and WC, respectively, are the maximum average 10min intensity (10MinMaxIn) at both sites, the total rainfall one-hour prior to the event (Pre1hr) at AC, and the five-day antecedent rainfall (API5) at WC. The resulting regression equations are:

Arley Close:

$$\ln y = 1.36 + 0.53x_1 + 0.34x_2$$
$$x_1 = 10MaxInt10 \qquad (2)$$
$$x_2 = Pre1HR$$

Winsley Close:

$$\ln y = -0.03 + 0.87x_1 + 0.14x_2$$
$$x_1 = 10MaxInt10 \qquad (3)$$
$$x_2 = API5$$

The log-level regression coefficients are interpreted as follows: For a unit increase of x_1, the percentage increase in y is given by:

$$\%\ \text{change in Y} = [100]\ (e^{\beta p}-1) \qquad (4)$$

This rule applies to all explanatory model variables (x_1, x_2) and their corresponding model coefficient values (β_1, β_2), where it is assumed that all other explanatory variables are held constant (Wooldridge, 2009).

The log-level structure of Eqs. (2) and (3) indicate a non-linear relationship between peak flow and the independent variables. Interpreting the regression coefficients contained within the models in Eqs.(2) and (3) using Eq.(4), an increase of one unit of 10 minute rainfall intensity leads to a 69% increase of peak flow rate at AC and a 138% increase at WC. A one unit increase of Pre1HR rainfall total leads to a 40% increase in peak flow at AC, whilst a one unit increase of API5 increase peak flow rates at WC by 15%.

The model for AC contains the Pre1HR rainfall total as the antecedent condition variable, whereas the model for WC (Eq. 3) contains API5. This indicates that the peak flow rates at AC are sensitive to short term variability in antecedent conditions, whereas peak flow rates at WC are more sensitive to antecedent conditions over the preceding five days prior to a rainfall event.

5.2 IMPACT OF URBANISATION ON PERCENTAGE RUNOFF

In contrast to peak flow, no significant regression relationships could be identified between percentage runoff, rainfall and antecedent soil moisture at AC. However, for WC two models contain significant model parameters and have the same adjusted R^2 values. The results of the exploratory analysis are shown in Table 3 and the significant models summarised in Eqs. (5) and (6).

Winsley Close:

$$y = 7.6 + 5.1x_1 + 4.1x_2$$
$$x_1 = RainDepth$$
$$x_2 = API5 \tag{5}$$

Winsley Close:

$$y = 9.6 + 7.56x_1 + 3.82x_2$$
$$x_1 = MaxInt10$$
$$x_2 = API5 \tag{6}$$

The models in Eq. (5) and (6) differ in terms of whether rain depth or 10-minute intensity is included along with API5. In Eq. (4), a per unit increase of rain depth and API5 produce an increase in percentage runoff values of 4.1 and 5.1 (percentage runoff units e.g. %). Eq. (6), however, suggests that the per unit increase in percentage runoff attributable to rainfall intensity is 7.56%, whilst per unit increases of percentage runoff attributed to API5 is 3.82%. Overall, the multiple linear regression modelling methodology applied to percentage runoff values for the 34 studied events in AC and WC is unable to provide a coherent understanding of the sensitivity of percentage runoff behaviour. In AC, regression modelling provides no models with greater explanatory power than the mean value alone, whilst at WC the variable selection methodology is unable to determine which variables PR values are sensitive to. Whilst the regression model parameters in Eqs. (5) and (6) are statistically significant ($p < 0.05$) the adjusted R^2 values are low demonstrating that a large proportion of variability in PR values is unexplained by the regression models.

6. DISCUSSION

Experimental rainfall-runoff results obtained from a paired catchment study involving two small urban catchments (< 1ha; AC and WC) located in close geographical proximity (~1km), characterised by different types of urban development, generally representative of the time of construction have been analysed. WC was constructed in the 1950s and is characterised by more green and open space than AC which was constructed in the 1990s. Analysis of the hydrographs from the selected 34 events recorded in both catchments demonstrates considerable differences in the observed hydrological response (Figure 5). First, it is observed that the hydrographs at AC are generally characterised by shorter time-to-rise and higher peak flow values than corresponding hydrographs observed at WC. This is consistent with the hypothesis that increasing urbanisation (PIMP surfaces) generally results in reduced lag-time in catchment response, with median peak flow rate and percentage runoff values at AC more than double those at WC (Figure 6). Differences in rainfall-runoff behaviour exhibited between AC and WC are likely a function of increased imperviousness of AC and increased connection efficiency between surface water drainage system and urban surface combining to reduce losses and provide a more efficient drainage system (decreased time to peak). The results are in line with observations and modelling results from larger (~ 5km^2) urbanised catchments within Swindon examined by Miller et al. (2014) and highlight that significant variability in responses can occur.

Peak flow rates at both AC and WC are highly sensitive to 10-minute rainfall intensity, whilst similar to that reported by other authors (Lloyd-Davies 1906; Schilling 1991), the results reported here indicate that the relationship between peak flow rates and rainfall intensity are non-linear following a log-linear response. QMAX values at AC are sensitive to depth of rainfall within one hour prior to an event, whilst at WC QMAX values are sensitive to the antecedent 5-day precipitation index (API5), indicating that different urban mosaics influence variability of peak flow behaviour (Table 3). This suggests that at AC less storage capacity exists compared to WC, where the large open vegetated surfaces and reduced connection efficiency has created a rainfall-runoff behaviour that is sensitive to longer duration changes in antecedence, thus WC has greater storage capacity.

Percentage runoff is difficult to model, with multiple linear regression at AC and WC failing to identify significant (P= 0.05) explanatory variables, consequently regression modelling is not able to produce a model with greater descriptive efficacy than the mean value alone (Table 3). Specifically, for AC, none of the tested variables were significant. The lack of significant regression coefficients could suggest that PR values at AC are static, insensitive to changes in physical conditions. This is unlikely, given variability in PR values observed. Instead, the lack of significant regression coefficients could suggest that at AC PR is (a) insensitive to tested explanatory variables, or (b) non-linearly related to the explanatory variables. A less rigid model structure applied to PR could improve descriptive and predictive power, however this is undesirable given the difficulties of physical interpretation of low-bias/high-variance model structures e.g. a tree based model (James et al. 2013). At WC, multiple linear regression of PR is uncertain, given that two models produce significant explanatory variable coefficients and low (0.18; Table 3) values of the adjusted coefficient of determination (R^2), indicating large proportions of variation in PR values are unexplained by the regression models [5,6]. Percentage runoff is an important variable used in hydrological models and engineering design calculations (Kidd and Lowing 1979; Woods Ballard et al. 2015), we have demonstrated here that it is challenging to capture a clear relationship, as such greater consideration should be given to percentage runoff assumptions in current hydrological modelling given analysis of field observation data is inconclusive.

At the study catchment scale, AC and WC are similar in terms of proportion of surface under impervious and non-impervious cover (Table 1). Therefore, hydrological models that link total imperviousness to hydrological response would likely estimate that the two sites have similar rainfall-runoff properties unless locally calibrated (Valeo and Moin 2000; Verbeiren et al. 2012; Dixon and Earls 2012); which would be inaccurate given the results reported here. The results indicate a greater sensitivity is required of how surface water drainage systems connect hydraulically to the urban surface and to small-scale variations in surfacing. Assessing surface connectivity requires detailed data of surface types and hydraulic entry points to the surface water drainage system (i.e. drain gully or down pipe). A lack of relevant data concerning individual surfaces and urban surface water drainage systems and connectivity at small-scales within urban settings has previously limited the inclusion of such fine scale detail on the urban environment within hydrological models (Han and Burian 2009). Instead, connectivity is typically estimated or defined as a function of land use or total imperviousness across large urban areas (Lee and Heaney 2003). However, as demonstrated, connectivity of impervious areas and land cover characteristics vary even within a single residential land use area (Table 1; Figure 4) and it is likely that hydrological characterisation based on simple descriptors that group areas based on generalised properties (e.g. land use, imperviousness) would be inaccurate when applied to the study catchments (Figure 4e-h). A further consideration is that pervious surfaces may respond differently to precipitation events, reflecting storm intensity and antecedent conditions, with the potential of pervious surfaces to generate runoff, thereby presenting new flow paths and increasing connectivity. As Sytsma et al. (2020) notes, moving away from the inherent limitation of directly connected impervious areas as binary and static (connected or not) is necessary, to accurately reflect the complexity and dynamic nature of hydrological processes. This study provides comparable results to Miller et al. (2020) that indicate more spatially refined metrics for quantifying urban land cover are required to improve peak flow estimates in small urbanised catchments. Advances in remote sensing and LIDAR offer opportunities for finer resolution understanding of urban environment surfaces, particularly for inaccessible areas, helping to identify small scale interventions that may modify connectivity and runoff relationships (e.g. water butts). The results from this study offer the opportunity to re-evaluate the performance of the most common approaches to urban surface representation, the importance of accurate surface representation at such refined (catchment/plot) scales, to identify inaccuracies and improvements based on the greater detail of understanding between the urban mosaic and rainfall-runoff behaviour generated.

It has been claimed that representing the complexity of the urban mosaic within hydrological models and surface water management planning is unnecessary, given that not all hydrological processes at all scales need accounting for (Beven, 2012). However, where deficiencies in understanding and knowledge of heterogeneity of surface and scale may cause inaccurate rainfall-runoff modelling that limits evidence-based surface water management planning, thus reducing the efficacy of hydrological management (Borowski and Hare 2007), further detail and information are required. To date there is a dearth of observation studies examining the rainfall-runoff relationship in urban environments, as such the complexity of such systems remains poorly quantified and understood. Therefore, understanding what level of detail is required to accurately represent the urban surface within hydrological theory, and at what scale certain physical features and processes produce significant effects on hydrological behaviour remains a research priority (Blöschl and Sivapalan 1995;

Leandro et al. 2016; Ichiba et al. 2018); within this study we contribute to this discussion at the development/plot scale.

7. CONCLUSION

The hydrological properties of urban surfaces are complex and sensitive to a number of different hydrological processes that respond to variations in the materials of construction, slope, age, condition and connectivity to the surface water drainage system (Redfern et al. 2016). The rainfall-runoff behaviour of the two small urban catchments studied is influenced by the urban mosaic, this study demonstrating how residential layout and hydraulic connections influence rainfall-runoff behaviour. To improve residential design with a focus on reducing runoff generation, an understanding of how the number and locations of hydraulic connection features affects the connectivity of urban surfaces and thus rainfall-runoff behaviour is a priority. In particular, untangling the relationships between urban imperviousness, surface water flood risk, the design of surface connectivity and runoff generation to downstream areas is needed, as reducing surface connectivity may reduce the generation of runoff to downstream areas (Walsh et al. 2005); whilst this could increase local surface water ponding and thus flooding (Maksimović et al. 2009). Limiting gully positions to only public surfaces may reduce direct surface connections, however ensuring that important transport infrastructure remains clear of surface water remains crucial (Fryd et al. 2013). Private land would therefore need landscaping to accommodate runoff generated on private impervious surfaces. This is possible, given that no flooding incidents are reported in WC during the study period, despite its reduced number of hydraulic connection points in comparison to AC. We demonstrate that complex, non-linear rainfall-runoff processes within small-scale urban settings may not currently be fully accounted for within current hydrological theory, indicating that improved understanding of urban rainfall-runoff process is required that accounts for, and is adaptive to, the urban mosaic. The rainfall-runoff regression models fail reproduce the rainfall-runoff characteristics at the two study catchments consistently, indicating that greater complexity exists than previously identified. An understanding of hydrological processes in urban areas and parameter uncertainty, has a direct impact on potential modelling outcomes and thus the surface water management design and planning process. Given the importance of percentage runoff values, it is important that the efficacy of rainfall-runoff models for predicting PR are assessed against monitored data, as uncertain regression results reported here imply that variability in PR is difficult to predict by hydrologically derived parameters and therefore there is considerable opportunity for uncertainty in current model parameterisation based on current assumptions.

Acknowledgements: The work reported in this paper was undertaken by Thomas Redfern as part of a NERC Centre for Ecology and Hydrology-University of Liverpool PhD studentship (NEC05015) 2013-2016, supervised by NM, TRK and JM. We would also like to thank the two anonymous reviewers for provided detailed and thoughtful comments on the manuscript.

References

Arnold CL, Gibbons & CJ (1996) Impervious Surface Coverage: The Emergence of a Key Environmental Indicator. J Am Plan Assoc 62:243–258. doi: 10.1080/01944369608975688

Awadalla M, Abd El Halim AO, Hassan Y, et al (2017) Field and laboratory permeability of asphalt concrete pavements. Can J Civ Eng 44:233–243. doi: 10.1139/cjce-2016-0143

Beighley RE, Kargar M, He Y (2009) Effects of Impervious Area Estimation Methods on Simulated Peak Discharges. J Hydrol Eng 14:388–398. doi: 10.1061/(asce)1084-0699(2009)14:4(388)

Beven K J (2012) Rainfall-Runoff Modelling: The Primer, 2nd Edition | Wiley, 2nd edn. Wiley-Blackwell, London

Blake JR, Packman JC (2008) Identification and correction of water velocity measurement errors associated with ultrasonic Doppler flow monitoring. Water Environ J 22:155–167. doi: 10.1111/j.1747-6593.2007.00089.x

Blöschl G, Sivapalan M (1995) Scale issues in hydrological modelling: A review. Hydrol Process 9:251–290. doi: 10.1002/hyp.3360090305

Boorman DB, Hollist JM, Lilly A (1995) Hydrology of soil types: a hydrologically-based classification of the soils of the United Kingdom

Booth DB, Roy AH, Smith B, Capps KA (2016) Global perspectives on the urban stream syndrome. Freshw. Sci. 35:412–420

Borowski I, Hare M (2007) Exploring the gap between water managers and researchers: Difficulties of model-based tools to support practical water management. Water Resour Manag 21:1049–1074. doi: 10.1007/s11269-006-9098-z

Brown FE, Rickaby PA, Bruhns HR, Steadman P (2000) Surveys of Nondomestic Buildings in Four English Towns. Environ Plan B Plan Des 27:11–24. doi: 10.1068/b2571

Butler D, Davies JW (2004) Urban Drainage, 2nd Edition. Spon Press, London

Carmen NB, Hunt WF, Anderson AR (2016) Volume Reduction Provided by Eight Residential Disconnected Downspouts in Durham, North Carolina. J Environ Eng 142:05016002. doi: 10.1061/(asce)ee.1943-7870.0001107

Cullingworth B, Nadin V, Hart T, et al (2014) Town and Country Planning in the UK, 15th ed. Routledge, London

Cullingworth JB (1961) The Swindon Social Survey: A Second Report on the Social Implications of Overspill. Sociol Rev 9:151–166. doi: 10.1111/j.1467-954X.1961.tb01091.x

Dargay J, Hanly M (2007) Volatility of car ownership, commuting mode and time in the UK. Transp Res Part A Policy Pract 41:934–948. doi: 10.1016/j.tra.2007.05.003

DeFries R, Eshleman KN (2004) Land-use change and hydrologic processes: a major focus for the future. Hydrol Process 18:2183–2186. doi: 10.1002/hyp.5584

Dixon B, Earls J (2012) Effects of urbanization on streamflow using SWAT with real and simulated meteorological data. Appl Geogr 35:174–190. doi: 10.1016/j.apgeog.2012.06.010

Dunning RW, Rogers K H, Spalding P A, et al (1970) Swindon: Growth of the town. A History of the County of Wiltshire. In: Crittall E (ed) Victoria County History - Wiltshire. Victoria County History, London

Ebrahimian A, Gulliver JS, Wilson BN (2016) Effective impervious area for runoff in urban watersheds. Hydrol Process 30:3717–3729. doi: 10.1002/hyp.10839

Ferreira CSS, Walsh RPD, Nunes JPC, et al (2016) Impact of urban development on streamflow regime of a Portuguese peri-urban Mediterranean catchment. J Soils Sediments 16:2580–2593. doi: 10.1007/s11368-016-1386-5

Fletcher TD, Andrieu H, Hamel P (2013) Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. Adv Water Resour 51:261–279. doi: 10.1016/j.advwatres.2012.09.001

Fryd O, Backhaus A, Birch H, et al (2013) Water sensitive urban design retrofits in Copenhagen - 40% to the sewer, 60% to the city. Water Sci Technol 67:1945–1952. doi: 10.2166/wst.2013.073

Gilbert JK, Clausen JC (2006) Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut. Water Res 40:826–832. doi: 10.1016/j.watres.2005.12.006

Han WS, Burian SJ (2009) Determining Effective Impervious Area for Urban Hydrologic Modeling. J Hydrol Eng 14:111–120. doi: 10.1061/(asce)1084-0699(2009)14:2(111)

Herold M, Scepan J, Clarke KC (2002) The Use of Remote Sensing and Landscape Metrics to Describe Structures and Changes in Urban Land Uses. Environ Plan A Econ Sp 34:1443–1458. doi: 10.1068/a3496

Hollis GE, Ovenden JC (1988) The quantity of stormwater runoff from ten stretches of road, a car park and eight roofs in Hertfordshire, England during 1983. Hydrol Process 2:227–243. doi: 10.1002/hyp.3360020304

Ichiba A, Gires A, Tchiguirinskaia I, et al (2018) Scale effect challenges in urban hydrology highlighted with a distributed hydrological model. Hydrol Earth Syst Sci 22:331–350. doi: 10.5194/hess-22-331-2018

James G, Witten D, Hastie T, Tibshirani R (2013) An introduction to Statistical Learning. Springer, New York

Jefferson AJ, Bhaskar AS, Hopkins KG, et al (2017) Stormwater management network effectiveness and implications for urban watershed function: A critical review. Hydrol Process 31:4056–4080. doi: 10.1002/hyp.11347

Kidd CHR, Lowing MJ (1979) The Wallingford urban subcatchment model

Kjeldsen TR (2009) Modelling the impact of urbanisation on flood runoff volume. Proc Inst Civ Eng - Water Manag 162:329–336. doi: 10.1680/wama.2009.162.5.329

Kjeldsen TR (2010) Modelling the impact of urbanization on flood frequency relationships in the UK. Hydrol Res 41:391–405. doi: 10.2166/nh.2010.056

Law NL, Cappiella K, Novotney ME (2009) The Need for Improved Pervious Land Cover Characterization in Urban Watersheds. J Hydrol Eng 14:305–308. doi: 10.1061/(asce)1084-0699(2009)14:4(305)

Leandro J, Schumann A, Pfister A (2016) A step towards considering the spatial heterogeneity of urban key features in urban hydrology flood modelling. J Hydrol 535:356–365. doi: 10.1016/j.jhydrol.2016.01.060

Lee JG, Heaney JP (2003) Estimation of Urban Imperviousness and its Impacts on Storm Water

Systems. J Water Resour Plan Manag 129:419–426. doi: 10.1061/(asce)0733-9496(2003)129:5(419)

Lemon J. (2006) Plotrix: a package in the red light district of R. R-News 8–12

Leopold LB (1991) Lag times for small drainage basins. Catena 18:157–171. doi: 10.1016/0341-8162(91)90014-O

Ligges U, Mächler M (2003) Scatterplot3d - An R package for visualizing multivariate data. J Stat Softw 8:1–20. doi: 10.18637/jss.v008.i11

Lloyd-Davies DE (1906) The elimination of storm water from sewage systems. Minutes Proc Inst Civ Eng 164:41–67. doi: 10.1680/imotp.1906.16637

Lu D, Weng Q (2006) Use of impervious surface in urban land-use classification. Remote Sens Environ 102:146–160. doi: 10.1016/j.rse.2006.02.010

Maksimović Č, Prodanović D, Boonya-Aroonnet S, et al (2009) Overland flow and pathway analysis for modelling of urban pluvial flooding. J Hydraul Res 47:512–523. doi: 10.1080/00221686.2009.9522027

McGrane SJ (2016) Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrol Sci J 61:2295–2311. doi: 10.1080/02626667.2015.1128084

Mei C, Liu JH, Wang H, et al (2020) Urban flood inundation and damage assessment based on numerical simulations of design rainstorms with different characteristics. Sci China Technol Sci 63:2292–2304. doi: 10.1007/s11431-019-1523-2

Mejía AI, Moglen GE (2009) Spatial Patterns of Urban Development from Optimization of Flood Peaks and Imperviousness-Based Measures. J Hydrol Eng 14:416–424. doi: 10.1061/(ASCE)1084-0699(2009)14:4(416)

Miller J, Hutchins M (2019) Thames catchment hydrometric and water quality data 2013-17

Miller JD, Kim H, Kjeldsen TR, et al (2014) Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. J Hydrol 515:59–70. doi: 10.1016/j.jhydrol.2014.04.011

Miller JD, Stewart E, Hess T, Brewer T (2020a) Evaluating landscape metrics for characterising hydrological response to storm events in urbanised catchments. https://doi.org/101080/1573062X20201760320 17:247–258. doi: 10.1080/1573062X.2020.1760320

Miller JD, Stewart E, Hess T, Brewer T (2020b) Evaluating landscape metrics for characterising hydrological response to storm events in urbanised catchments. Urban Water J 17:247–258. doi: 10.1080/1573062X.2020.1760320

Moore SL, Stovin VR, Wall M, Ashley RM (2012) A GIS-based methodology for selecting stormwater disconnection opportunities. Water Sci Technol 66:275–283. doi: 10.2166/wst.2012.172

O'Driscoll M, Clinton S, Jefferson A, et al (2010) Urbanization Effects on Watershed Hydrology and In-Stream Processes in the Southern United States. Water 2:605–648. doi: 10.3390/w2030605

Ogden FL, Pradhan NR, Downer CW, Zahner JA (2011) Relative importance of impervious area, drainage density, width function, and subsurface storm drainage on flood runoff from an urbanized catchment. Water Resour Res 47:12503. doi: 10.1029/2011WR010550

Packman JC (1980) The effects of urbanisation on flood magnitude and frequency

Ragab R, Rosier P, Dixon A, et al (2003) Experimental study of water fluxes in a residential area: 2. Road infiltration, runoff and evaporation. Hydrol Process 17:2423–2437. doi: 10.1002/hyp.1251

Ravagnani F, Pellegrinelli A, Franchini M (2009) Estimation of urban impervious fraction from satellite images and its impact on peak discharge entering a storm sewer system. Water Resour Manag 23:1893–1915. doi: 10.1007/s11269-008-9359-0

Redfern TW, Macdonald N, Kjeldsen TR, et al (2016) Current understanding of hydrological processes on common urban surfaces. Prog Phys Geogr 40:699–713. doi: 10.1177/0309133316652819

Rose S, Peters NE (2001) Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. Hydrol Process 15:1441–1457. doi: 10.1002/hyp.218

Sahoo SN, Sreeja P (2016) Determination of Effective Impervious Area for an Urban Indian Catchment. J Hydrol Eng 21:05016004. doi: 10.1061/(asce)he.1943-5584.0001346

Salt C, Kjeldsen TR (2019) Infiltration capacity of cracked pavements. Proc Inst Civ Eng - Water Manag 172:291–300. doi: 10.1680/jwama.18.00001

Schilling W (1991) Rainfall data for urban hydrology: what do we need? Atmos Res 27:5–21

Shahtahmassebi AR, Song J, Zheng Q, et al (2016) Remote sensing of impervious surface growth: A framework for quantifying urban expansion and re-densification mechanisms. Int J Appl Earth Obs Geoinf 46:94–112. doi: 10.1016/j.jag.2015.11.007

Sørensen BL (2021) Urban Drainage Modelling for Management of Urban Surface Water. In: Air Pollution Sources, Statistics and Health Effects. pp 229–236

Sytsma A, Bell C, Eisenstein W, et al (2020) A geospatial approach for estimating hydrological connectivity of impervious surfaces. J Hydrol 591:125545. doi: 10.1016/J.JHYDROL.2020.125545

Timms D (1971) The Urban Mosaic. Cambridge University Press

Valeo C, Moin SMA (2000) Grid-resolution effects on a model for integrating urban and rural areas. Hydrol Process 14:2505–2525. doi: 10.1002/1099-1085(20001015)14:14<2505::AID-HYP111>3.0.CO;2-3

Verbeiren B, Van De Voorde T, Canters F, et al (2012) Assessing urbanisation effects on rainfall-runoff using a remote sensing supported modelling strategy. Int J Appl Earth Obs Geoinf 21:92–102. doi: 10.1016/j.jag.2012.08.011

Vesuviano G, Miller JD (2019) Design flood estimation and utility of high-resolution calibration data in small, heavily urbanised catchments. J Flood Risk Manag 12:e12464. doi: 10.1111/jfr3.12464

Walsh CJ, Fletcher TD, Ladson AR (2005) Stream restoration in urban catchments through redesigning stormwater systems: Looking to the catchment to save the stream. In: Journal of the North American Benthological Society. North American Benthological Society, pp 690–705

Wiles TJ, Sharp JM (2008) The secondary permeability of impervious cover. Environ Eng Geosci 14:251–265. doi: 10.2113/gseegeosci.14.4.251

Woods Ballard B, Wilson S, Udale-Clarke H, et al (2015) The SuDS Manual (C753F). London

Yin J, Yu D, Yin Z, et al (2016) Evaluating the impact and risk of pluvial flash flood on intra-urban road network: A case study in the city center of Shanghai, China. J Hydrol 537:138–145. doi:

10.1016/j.jhydrol.2016.03.037

Figure and Table captions

Figure 1: (A) Locations of precipitation stations used in the study relative to Arley Close and Winsley Close; (B) location of connectivity points in Arley close (left) and Winsley Close (right). The hatched area for Winsley Close was removed based on manual investigation of connectivity.

Figure 2: Installation of Stingray 2.0 UDFM equipment in surface water drainage manholes; (left) the installation of the sensor within the pipe upstream of the manhole; (right) the storage of cabling and data logging box.

Figure 3: Rainfall event characteristics for 34 studied events. Points are coloured by season. Histograms of rainfall characteristics are plotted underneath. Drawn with the R 3dscatterplot package (Ligges and Mächler 2003).

Figure 4: Catchment maps with (A,B) OSMM data and (C,D) more detailed surface definitions following IPAs and associated surface cover comparisons between Arley Close (A,C,E,G) and Winsley Close (B,D,F,H). Plots E and F are defined from OSMM data alone whilst plots G and H contain data from IPAs. Note that in plots G and H, domestic impervious includes both impervious and semi-impervious surface definitions.

Figure 5: Selected event (34) hydrographs plotted on single axis, for Arley Close and Winsley Close, with average hydrograph for each site (bold red). The x axis has been centred to a 20-minute window around the time of peak flow for each event. Flow ordinates are normalised by catchment area to allow for direct comparison between study catchments.

Figure 6: (a) QMAX and (b) PR values at Winsley Close plotted against those at Arley Close. Any points to the right of 1:1 line indicates that QMAX or PR at Arley Close are greater than those at Winsley Close, while the opposite is true of points left of the 1:1 line. The axes have been normalised by catchment area to allow for direct comparison between catchments. (c) Comparison of QMAX and (d) PR values between study catchments.

Table 1: Calculation of total impervious area and PIMP for Arley Close and Winsley Close under three assumptions of the imperviousness of rear garden non-vegetated surfaces.

Table 2: Descriptive metrics for rainfall-runoff events sampled from Arley Close and Winsley Close. Metrics are split into rainfall characteristics and antecedent conditions groupings.

Table 3: Regression model table for log(QMAX) and PR values. + = variable is significant at 0.05 level. - = not significant. Left hand symbol relates to antecedent condition, right hand symbol is rainfall characteristic variable. Numbers are the model adjusted R^2 value. Yellow highlighter with bold is a model with two significant regression coefficients, Red is the optimum model where the model has two significant regression coefficients and the greatest value of the adjusted R^2.

Supplementary Materials S1: Soil grain size analysis for surface soil samples taken from Arley Close and Winsley Close (drawn using the Plotrix R package, Lemon J., 2006).

Supplementary Materials S2: Gully drainage areas and maximum drainage distance for gullies in the two study catchments. A) Gully drainage areas, B) Gully area drainage distances, C) The area of connected impervious surface plotted against the distance from a drainage gulley (WC - black, AC - dashed red), D) The area connected expressed as a percentage of total catchment area plotted against distance from a gully.

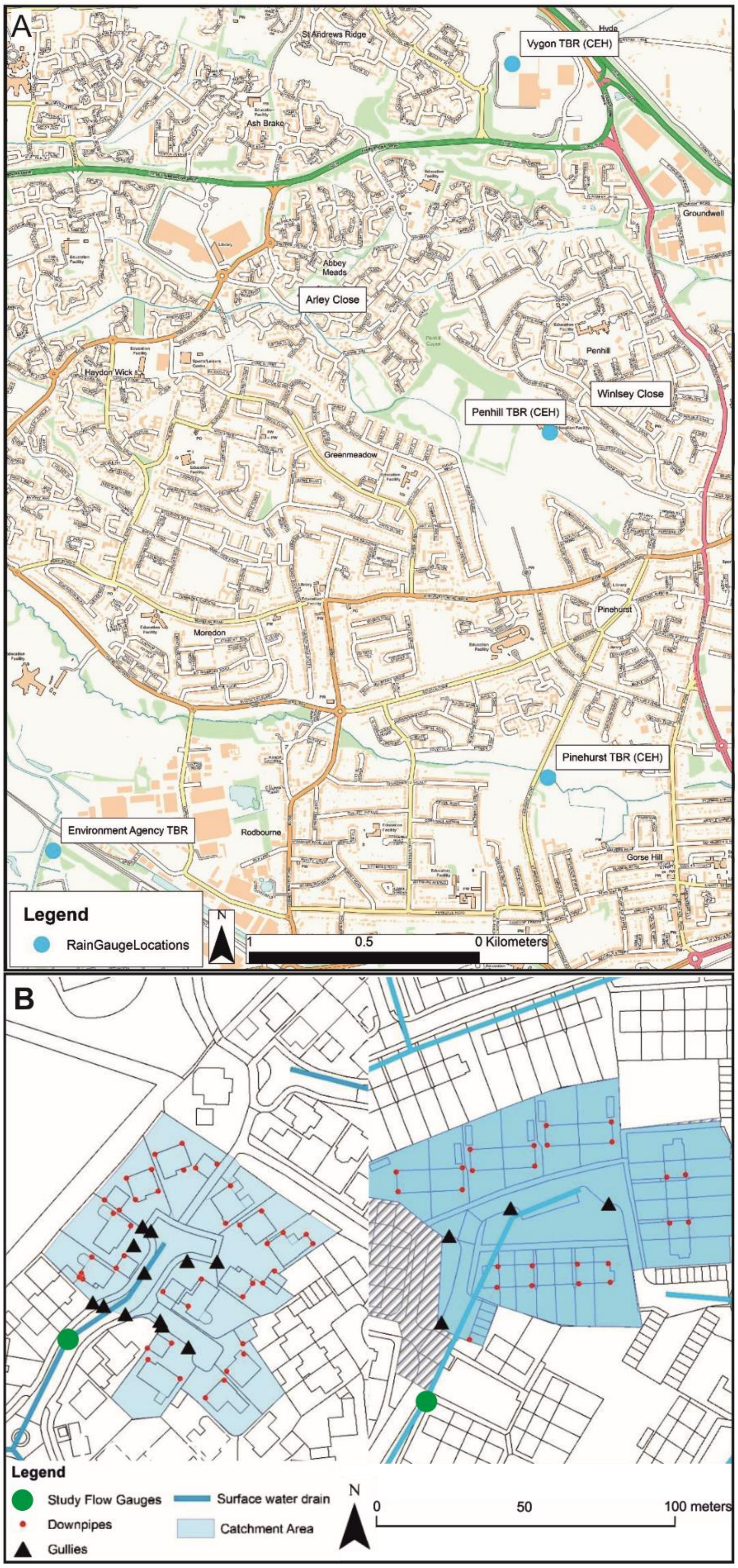


Figure 1: (A) Locations of precipitation stations used in the study relative to Arley Close and Winsley Close; (B) location of connectivity points in Arley Close (left) and Winsley Close (right). The hatched area for Winsley Close was removed based on manual investigation of connectivity.

Figure 2: Installation of Stingray 2.0 UDFM equipment in surface water drainage manholes; (left) the installation of the sensor within the pipe upstream of the manhole; (right) the storage of cabling and data logging box.

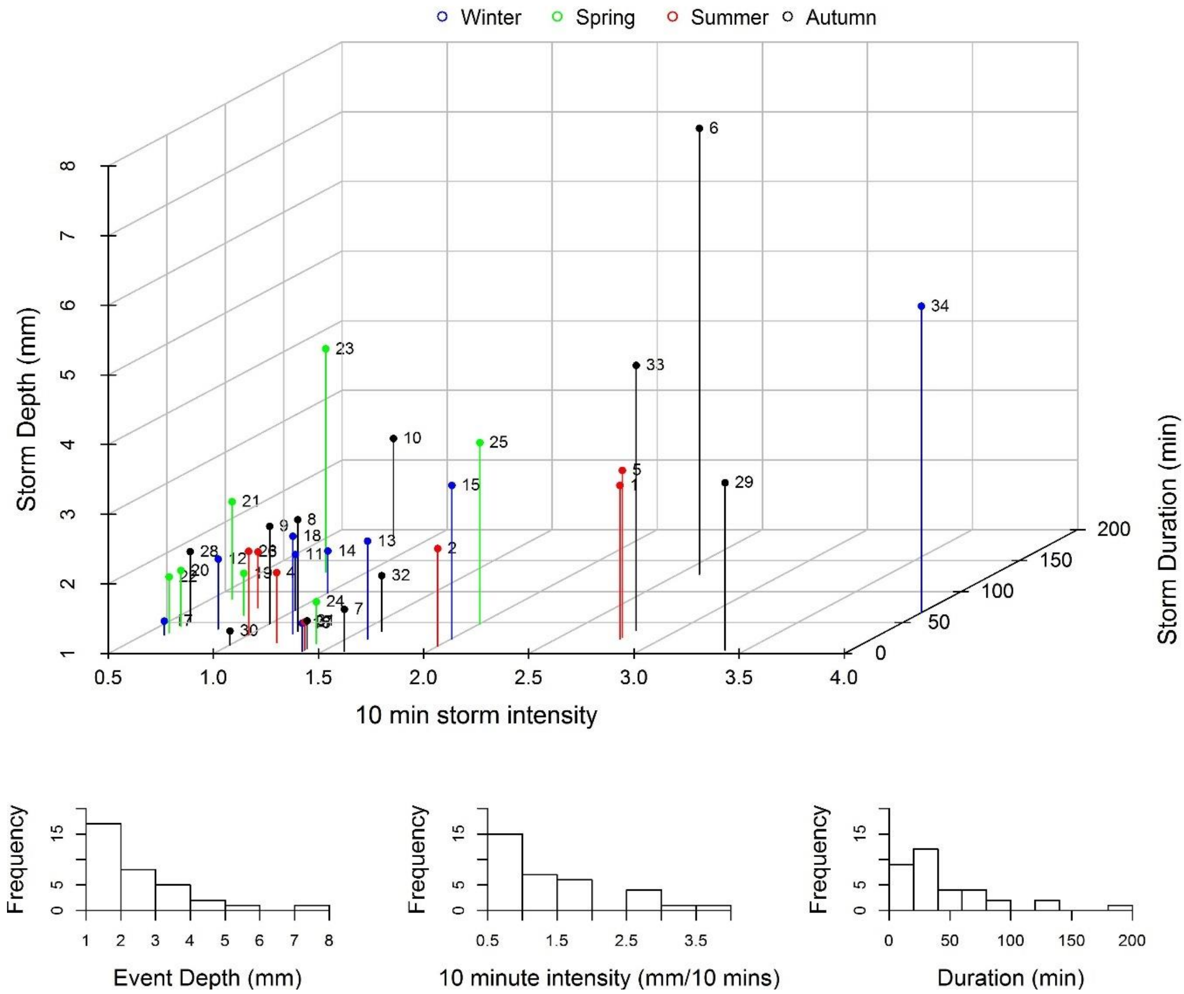


Figure 3: Rainfall event characteristics for 34 studied events. Points are coloured by season. Histograms of rainfall characteristics are plotted underneath. Drawn with the R 3dscatterplot package (Ligges and Mächler 2003).

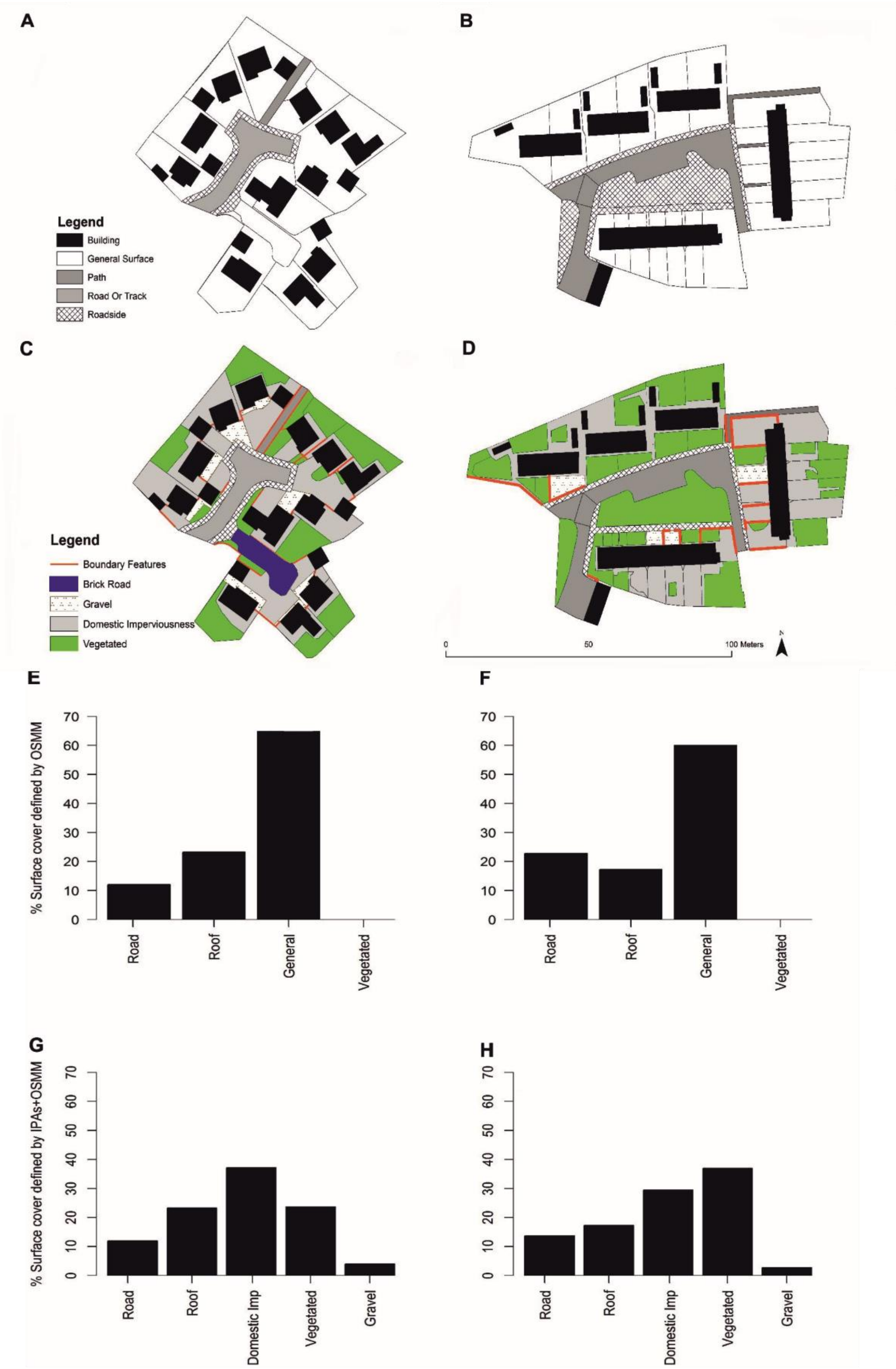


Figure 4: Catchment maps with (A,B) OSMM data and (C,D) more detailed surface definitions following IPAs and associated surface cover comparisons between Arley Close (A,C,E,G) and Winsley Close (B,D,F,H). Plots E and F are defined from OSMM data alone, whilst plots G and H contain data from IPAs. Note that in plots G and H, domestic impervious includes both impervious and semi-impervious surface definitions.

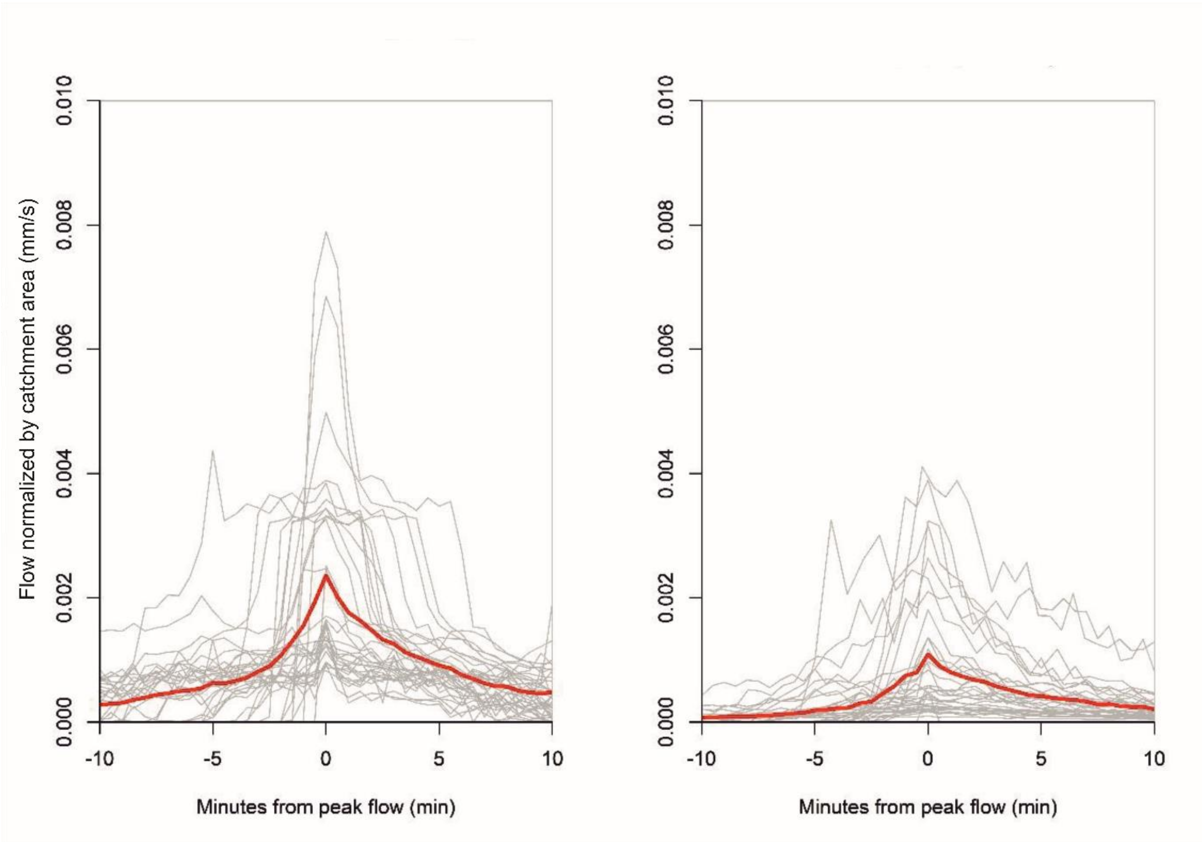


Figure 5: Selected event (34) hydrographs plotted on single axis, for Arley Close and Winsley Close, with average hydrograph for each site (bold red). The x axis has been centred to a 20-minute window around the time of peak flow for each event. Flow ordinates are normalized by catchment area to allow for direct comparison between study catchments.

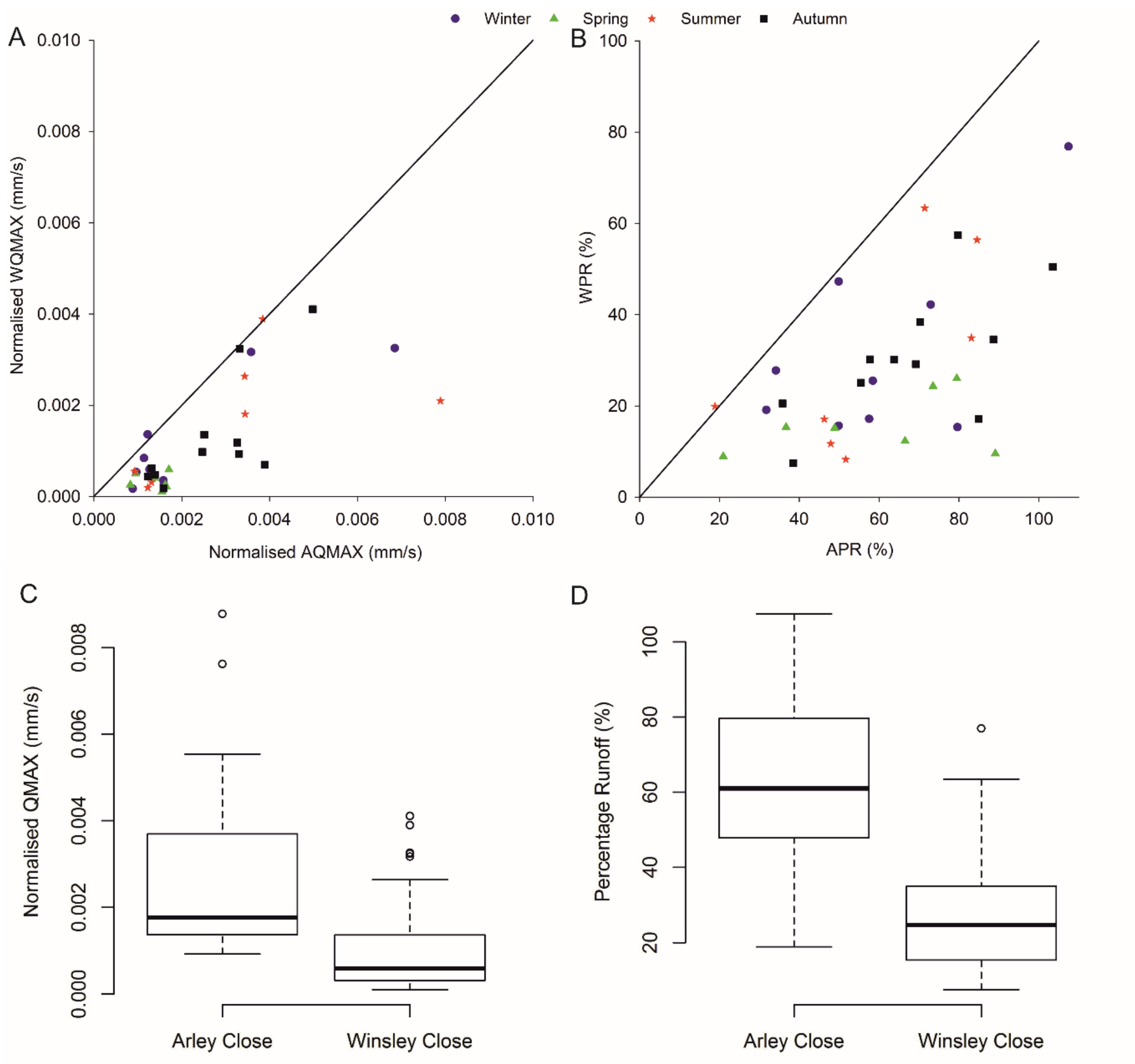


Figure 6: (A) QMAX and (B) PR values at Winsley Close plotted against those at Arley Close. Any points to the right of 1:1 line indicates that QMAX or PR at Arley Close are greater than those at Winsley Close, while the opposite is true of points left of the 1:1 line. The axes have been normalised by catchment area to allow for direct comparison between catchments. (C) Comparison of QMAX and (D) PR values between study catchments.

Table 1: Calculation of total impervious area and PIMP for Arley Close and Winsley Close under three assumptions of the imperviousness of rear garden non-vegetated surfaces.

	HIGH Area (m2)	**MEDIUM** Area (m2)	**LOW** Area (m2)
Arley Close			
Roofs	1156	1156	1156
Road related	782	782	782
Domestic Impervious (front garden)	753	753	753
Domestic Impervious (rear garden)	862	431	
Sum (PIMP)	3553, (71%)	3122, (63%)	2691, (54%)
Winsley Close			
Roofs	1150	1150	1150
Road related	1218	1218	1218
Domestic Impervious (front garden)	540	540	540
Domestic Impervious (rear garden)	1389	695	
Sum (PIMP)	4297, (64%)	3603, (54%)	2908, (43%)

Table 2: Descriptive metrics for rainfall-runoff events sampled from Arley Close and Winsley Close. Metrics are split into rainfall characteristics and antecedent conditions groupings.

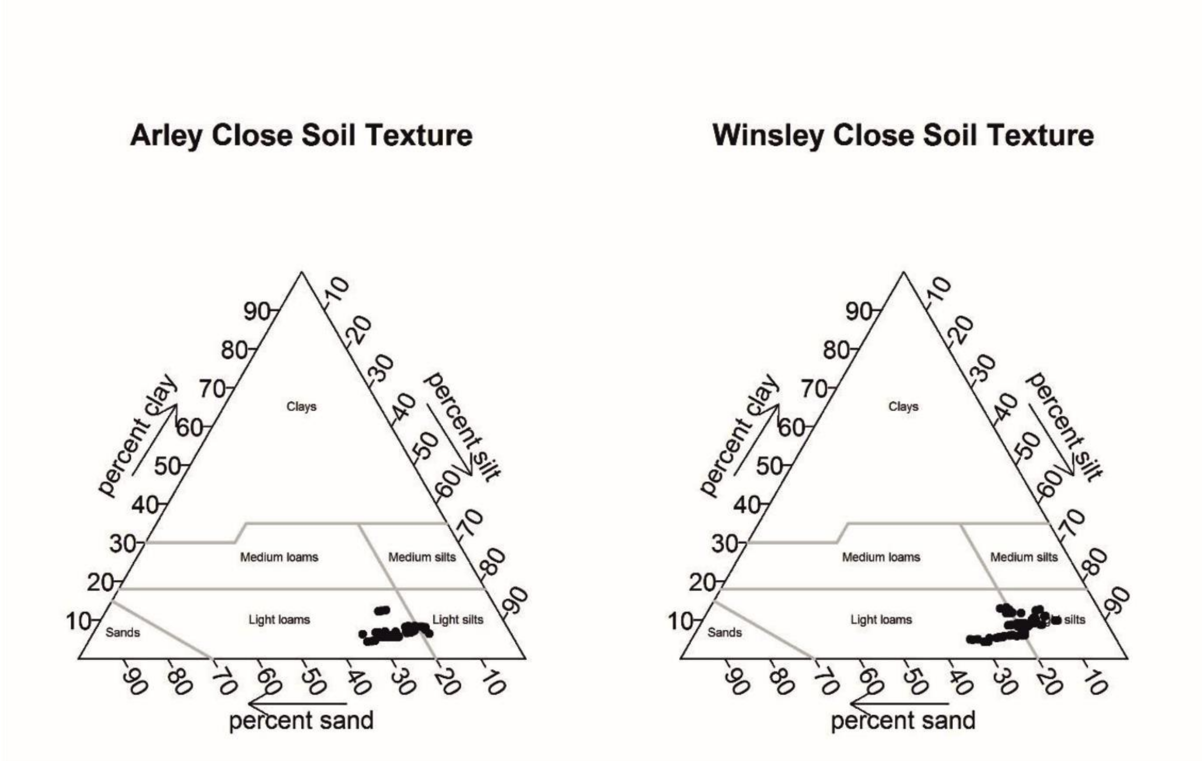
	Variable Name	Definition	Units
Rainfall Characteristics	**Depth**	Total event rainfall depth	mm
	Duration	Total event duration	Minutes
	2MinMaxInt	Maximum 2 minute rainfall intensity	mm/2minutes
	10MinMaxInt	Maximum 10 minute rainfall intensity	mm/10minutes
Antecedent Conditions	**API5**	Antecedent (5 day) Precipitation Index	mm
	SMD	Soil Moisture Deficit	mm
	UCWI	Urban Catchment Wetness Index	mm
	Pre1HR	Pre event 1 hour rainfall depth	mm
	Pre2HR	Pre event 2 hour rainfall depth	mm
	Pre6HR	Pre event 6 hour rainfall depth	mm
	ASM/WSM	Soil moisture recorded by PR2 probes, ASM = Arley Close, WSM = Winsley Close.	m^3/m^3

Table 3: Regression model table for log(QMAX) and PR values. + = variable is significant at 0.05 level. - = not significant. Left hand symbol relates to antecedent condition, right hand symbol is rainfall characteristic variable. Numbers are the model adjusted R^2 value. * indicates a model with two significant regression coefficients, ** is the optimum model where the model has two significant regression coefficients and the greatest value of the adjusted R^2.

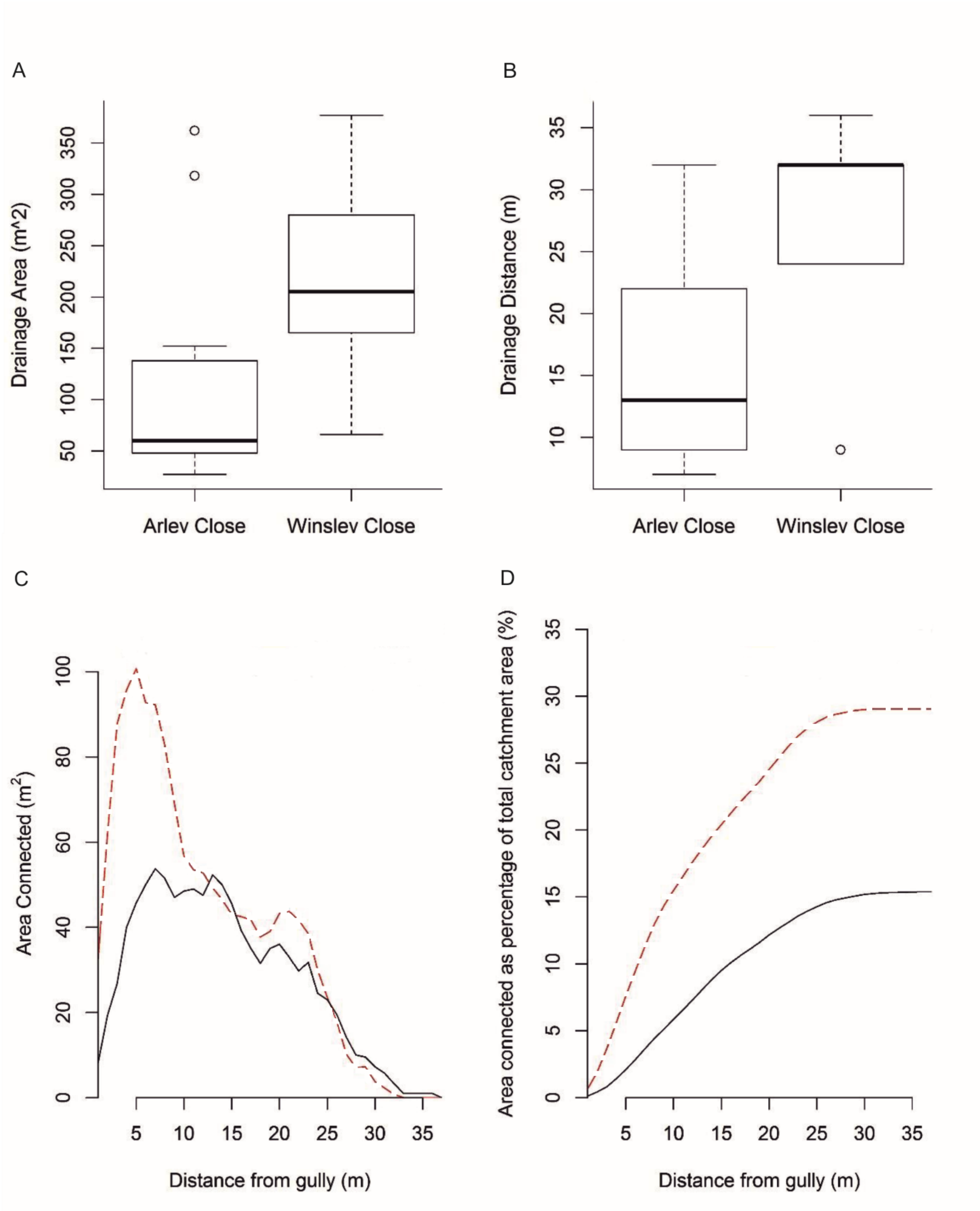
		Rainfall Characteristics			
Site	**Ant. soil m.**	**Depth**	**Duration**	**2MinMaxInt**	**10MinMaxInt**
logQMAX (Discharge)					
AC	**UCWI**	-/+,0.23	-/-,-0.02	-/+,0.45	-/+,0.50
WC		-/+,0.22	-/-,-0.06	-/+,0.37	-/+,0.43
AC	**SMD**	-/+,0.23	-/-,-0.04	-/+,0.45	-/+,0.50
WC		-/+,0.21	-/-,-0.05	-/+,0.37	-/+,0.41
AC	**Pre1Hr**	-/+,0.31	-/-,-0.04	-/+,0.45	+/+,0.56**
WC		-/+,0.29	-/-,-0.03	-/+,0.38	-/+,0.48
AC	**Pre2HR**	-/+,0.28	-/-,-0.02	-/+,0.45	-/+,0.51
WC		-/+,0.24	-/-,-0.04	-/+,0.37	-/+,0.42
AC	**Pre6HR**	+/+,0.33*	-/-,-0.02	-/+,0.45	+/+,0.5*
WC		-/+,0.23	-/-,-0.05	-/+,0.37	-/+,0.42
AC	**ASM**	-/+,0.23	-/-,-0.06	-/+,0.45	-/+,0.45
WC	**WSM**	-/+0.29	-/-,-0.01	-/+,0.37	-/+,0.38
AC	**API5**	-/+,0.23	-/-,-0.03	-/+,0.44	-/+,0.50
WC		-/+,0.28	-/-,0.05	-//+,0.39	+/+,0.49**
Percentage Runoff (PR)					
AC	**UCWI**	-/-, -0.04	-/-, -0.04	-/-, -0.01	-/-, .0.03
WC		+/-, 0.12	-/-, 0.01	-/-, 0.11	+/+, 0.13*
AC	**SMD**	-/-,-0.04	-/-, -0.04	-/-, -0.02	-/-, -0.02
WC		-/-, 0.04	-/-, 0.03	-/-, 0.05	-/-, 0.06
AC	**Pre1Hr**	-/-, -0.02	-/-, -0.02	-/-, 0.01	-/-, -0.004
WC		-/-, 0.1	-/+, 0.14	-/-, 0.08	-/-, 0.11
AC	**Pre2HR**	-/-, -0.05	-/-, -0.05	-/-, -0.2	-/-, -0.03
WC		-/-, 0.04	-/-, 0.02	-/-, 0.04	-/-, 0.004
AC	**Pre6HR**	-/-, -.0.04	-/-, -0.04	-/-, -0.001	-/-, -0.004
WC		-/-, 0.02	-/+, 0.04	-/-, 0.02	-/-, 0.01
AC	**ASM**	-/-, 0.03	-/-, -0.03	-/-, -0.003	-/-, -0.001
WC	**WSM**	+/-, 0.19	+/-, 0.10	+/-, 0.15	+/-, 0.15
AC	**API5**	-/-, -0.06	-/-, -0.06	-/-, -0.04	-/-, -0.04
WC		+/+, 0.18*	-/-, 0.04	+/-, 0.15	+/+, 0.18*

Please see Table 2 for definitions of acronyms.

Supplementary Materials



Supplementary Materials S1: Soil grain size analysis for surface soil samples taken from Arley Close and Winsley Close (drawn using the Plotrix R package, Lemon J., 2006).



Supplementary Materials S2: Gully drainage areas and maximum drainage distance for gullies in the two study catchments. A) Gully drainage areas, B) Gully area drainage distances, C) The area of connected impervious surface plotted against the distance from a drainage gulley (WC - black, AC - dashed red), D) The area connected expressed as a percentage of total catchment area plotted against distance from a gully.