CRANFIELD UNIVERSITY

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Characterising urban catchments for explaining storm runoff and application in UK flood estimation

School of Water, Energy and Environment

PhD
Academic Year: 2013 - 2018

Supervisor: Prof. Tim Hess
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ABSTRACT

The impacts of urbanisation on catchment hydrology have been the focus of investigation over the last few decades, but quantifying and predicting the impacts remains an ongoing area of active research. One such area has been improving characterisation of urban land cover to predict urbanisation impacts whereby lumped catchment characterisation of urban land cover limits the ability of attribution and modelling methods to consider the spatial role of land cover in runoff response. This thesis evaluates the potential for spatially explicit characterisations of urban land cover based on landscape metrics, commonly employed in landscape ecology, to explain storm runoff in urban catchments and their application in UK flood estimation methods.

Rainfall and channel flow monitoring across two towns containing 18 variably urbanised sub-catchments were used to provide high-resolution time-series of rainfall and runoff and to identify storm events which were quantified using a range of hydrological metrics. Analysing storm runoff along a rural-urban gradient showed a lumped measure of urban extent can generally explain differences in the hydrological response between rural and urban catchments but not between more urbanised catchments in which soil moisture does not play a contributing role. Using high resolution geospatial data can improve the representation of the urban environment and landscape metrics can better represent the form and function of urban land cover, improving estimates of the index flood $QMED$ over lumped catchment descriptors. Regression analysis of hydrological metrics showed the potential of landscape metrics for explaining inter-catchment differences in rainfall-runoff and point to the importance of considering the location and connectivity of urban surfaces. Landscape metrics provide a workable means of overcoming the limitations inherent in using lumped characterisation of complex urban land cover and their ability to express connectivity, size and location of urban land cover promises potential applications in hydrological applications such as UK design flood estimation methods.

Keywords:

Landscape metrics, catchment descriptors, flood estimation handbook, impervious, urban extent, hydrological model

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
CEH	Centre for Ecology and Hydrology
DCIA	Directly Connected Impervious Area
DDF	Depth Duration Frequency
DEM	Digital Elevation Model
DPLBAR	Mean drainage path length
DPSBAR	Mean catchment slope
DR	Direct Runoff
EA	Environment Agency
EIA	Effective Impervious Area
FARL	Flood Attenuation from Rivers and Lakes
FEH	Flood Estimation Handbooks
GI	Green Infrastructure
HOST	Hydrology Of Soil Type
ISO	International Organisation for Standardisation
IUH	Instantaneous Unit Hydrograph
LCM	Land Cover Map
LCMGB	Land Cover Map Great Britain
LUC	Land Use Change
MORECS	UK Meteorological Office rainfall and evaporation system
NERC	Natural Environment Research Council
OSMM	Ordnance Survey Master Map
PR	Percentage Runoff
QMED	Median annual flood
ReFH	Revitalised Flood Hydrograph
SAAR	Standard Average Annual Rainfall
SIM	SuDS Infiltration Map
SMD	Soil Moisture Deficit
SuDS	Sustainable Urban Drainage Systems
TIA	Total Impervious Area
UAF	Urban Adjustment Factor
UDFM	Ultrasonic Doppler Flow Monitoring
UK	United Kingdom
URBEXT	Urban Extent

1 - INTRODUCTION

1.1 Background and rationale

The United Kingdom (UK) Government have highlighted flooding as one of the greatest natural hazards facing the UK (Cabinet Office, 2011) and paid particular attention to the impacts of nationwide flooding, such as the 2007 flood that cost the UK economy over £4 billion and led to a review of how to improve planning to reduce the risk of flooding (Pitt, 2008). The sources of such flooding can be pluvial, whereby exceedance of infiltration and drainage capacity reduces the ability for runoff to be routed away from impervious surfaces during a storm event, and/or fluvial, whereby the combined surface and sub-surface conveyance of runoff exceeds the carrying capacity of receiving watercourses. Within England and Wales the Environment Agency (EA) estimate around 2.4 million properties are at risk of flooding from rivers and the sea, with the majority located in urban areas (EA, 2009). The EA spent £930 million during 2014-2015 on flood and coastal erosion management, with a further £180 million spent on maintenance of existing defences (EA, 2014).

The EA has acknowledged that the combination of climate change and development pressures will bring about an increase in flood risk in the future (EA, 2009). The UK faces particular challenges through the combination of: i) rapid projected population growth, from 64.6 million in 2014 to 74.3 million by 2039 (15%) (Office for National Statistics, 2015), ii) over 80% of the population living in urban areas, and iii) being one of only ten countries worldwide with over 5% (5.7%) of total area occupied by cities (Angel et al., 2011). Climate change is predicted to bring about further challenges such as wetter winters (Murphy et al., 2010) and more intense summer storms (Kendon et al., 2014). Adaptation costs are expected to rise significantly, with Ashley et al. (2005) indicating potential increases in flood risk of almost 30 times over current levels. This will certainly raise the costs associated with flood management, with the Foresight Future Flooding report estimating that under certain emissions and management scenarios annual losses could reach to around £27 billion (Evans et al., 2004)

which are significantly greater than the current £1.0 billion expected annual damages estimated by Hall et al. (2005). The recent flooding of winter 2015-16 alone has resulted in an estimated cost of over £5 billion (Priestley, 2016).

Widespread growth of urban areas during the 20th century has led to significant urban expansion across all developed continents and such changes have altered the hydrological response of urbanised catchments through the replacement of pervious with impervious surfaces and replacing natural water pathways with artificial drainage (Leopold, 1968; Jacobson, 2011; Dams et al., 2013; Kim et al., 2016). The hydrological impacts of these changes include a decrease in infiltration and localized storage (Yang & Zhang, 2011), thereby increasing runoff volume (Arnell, 1982), which combined with more rapid conveyance of runoff (Burns et al., 2012) can result in a flashier response (Graf, 1977) with reduced baseflow (Braud et al., 2013) and overall increases in peak flow (Lee & Heaney, 2004 ; Konrad & Booth, 2005; Ogden et al., 2011; Miller et al., 2014; Prosdocimi et al., 2015). Antecedent soil moisture is known to have a role in influencing the rainfall-runoff process (Zehe & Bloschl, 2004), but its effect in urban areas is not well studied and generally deemed less important due to the high degree of soil-sealing and compaction (Bertier et al., 2004).

In urban hydrology it is perhaps understandable, given the complex nature of the urban hydrological cycle, and difficulties in obtaining empirical observations(McGrane, 2015), that imperviousness is used as a key indicator for modelling urban systems due to its ease of conceptual understanding (Lim, 2016). For lumped hydrological models and catchment-scale attribution methods this manifests in a reliance on using a catchment-scale summation of imperviousness or urban extent, with no spatial consideration of land cover. In such conceptual models there is no means to consider the complex interplays between soil and impervious area distribution that have been shown in modelling studies to drive inter-catchment differences in storm runoff behaviour in response to urbanisation (Zhang & Shuster, 2014; Mejía and Moglen, 2010a). Distributed modelling approaches have greatly improved the urban hydrologists' ability to represent and predict the spatial influences of land cover on the catchment outlet

hydrograph (Aronica & Cannarozzo, 2000). While Beven (2008) notes physically based distributed models are justified they also have particular limitations, including inappropriate process descriptions and grid scale parameterisation, validation issues arising from their uncertainty in model structure and spatial discretisation which limit their practical application. This is a particular issue for over-fitting, which is more likely in a complex distributed model with multiple parameters that spatially interact, and could lead to prediction errors related to calibration (Shaw et al, 2011). As such lumped approaches remain popular in urban hydrological modelling, Salvadore et al. (2015) finding more than 60% of urban modelling studies employ such an approach for practical applications, while also being easily applicable when data is scarce.

A particular area of modelling that employs a lumped catchment approach for practical purposes is estimating floods in ungauged catchments. Employing a purely empirical model that links hydrological response to catchment characteristics, normally using a regression framework, provides a means for predicting response variables such as percentage runoff and mean annual flood, and enables planning of storm water management for new developments or assessing potential flood risk. The UK government recommends using established flood estimation methods as set out in the Flood Estimation Handbook (FEH) (IH, 1999) and the Revitalised Flood Hydrograph (ReFH) model (Kjeldsen, 2007). The FEH details the widely used statistical method for estimating flood peaks of a particular return period and ReFH provides a rainfall-runoff modelling method that provides a design flood hydrograph. In ungauged catchments they use catchment descriptors that capture catchment properties to derive key hydrological variables. These catchment descriptors are derived from other geospatial data such as national land cover provided by the UK Land Cover Map (LCM) (Morton et al., 2011) or more hydrologically focused mapping such as soil hydrology (Boorman et al., 1995). In ungauged UK urban catchments both FEH and ReFH methods utilise LCM classifications of *Urban* or *Suburban* to derive an index of urban extent - *URBEXT* (Bayliss et al. 2006) - to predict the hydrological changes caused by urbanisation. *URBEXT* characterises

urbanisation impacts by providing a lumped catchment wide measure indicative of imperious surface coverage. It does not provide any characterisation of the spatial nature of the urbanised surfaces within a catchment. This has been noted as a specific limitation when used for estimating floods in small urban catchments (EA, 2012a) and studies have suggested the potential for improved catchment descriptors (Kjeldsen et al. 2008; Wan Jaafar & Han 2012) particularly in urban areas (Kjeldsen et al., 2013).

Landscape metrics, commonly used in landscape ecology (Turner, 2007), have been suggested as a means of capturing spatially explicit information for use in more detailed attribution of the spatial effects of urban land cover (Shuster et al., 2005). Landscape ecology utilises landscape pattern indictors – metrics – to provide measures of landscape structure that are used to explain the spatial pattern of organisms, populations and ecosystems which in turn shape dispersal and fluxes across the landscape (Kupfer, 2012). These metrics describe both compositional and spatial elements of landscape based on spatial data from maps and remote sensing. They comprise metrics for quantifying patch characterises such as size, shape and isolation, alongside those for mosaic properties such as connectivity or distribution of patches. Despite showing promise in certain hydrological applications (e.g. Yuan et al., 2015) landscape metrics have only recently been investigated for use in attribution of urban storm runoff (Oudin et al., 2018) and no evidence of use for flood estimation has been uncovered. Yet the limited evidence suggests landscape metrics could have great potential for quantifying the type of hydrological connectivity (Van Nieuwenhuyse et al., 2001) that has been shown, alongside imperviousness, so important to consider when predicting urban hydrological response at the catchment scale (Yang et al., 2011). As such they could provide a bridge between the spatially-limited lumped modelling and spatially-explicit distributed approaches which could lead to improvements in estimating floods for ungauged urban catchments.

This thesis evaluates the potential for explaining the impacts of urbanisation on storm runoff response using lumped catchment descriptors and spatially explicit

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landscape metrics and how this knowledge could be applied in design flood estimation in the UK. The focus is on urbanisation effects upon fluvial storm-runoff in receiving watercourses (stream, river, storm drain) and not pluvial flooding or flood risk in general.

1.2 Research gaps

A number of research gaps have been identified in the literature on the effects of urbanisation on storm runoff (Chapter 2) that if addressed could improve the ability to characterise urban land cover and explain storm runoff in small urban catchments:

1) Limited detailed empirical observations of hydrological response in small contemporary urban catchments
2) A reliance on using a lumped catchment measure of urban extent or imperviousness to explain storm runoff in attribution and lumped hydrological modelling
3) Limited investigation into the potential of using spatially explicit landscape metrics for attribution of spatial urban land cover effects on storm runoff
4) No research investigating the application of landscape metrics in flood estimation methods.

1.3 Aim and objectives

In view of the research gaps identified the overall aim of this thesis is:

To evaluate the potential of lumped and spatially explicit characterisations of urban land cover to explain storm runoff in urban catchments and their application in UK flood estimation methods.

To meet the overall aim of this thesis and to address the knowledge gaps that have been identified, a number of research objectives are set out:

1) To assess urbanisation impacts on storm runoff along a rural-urban gradient and determine the suitability of characterising urbanisation effects on storm runoff using the lumped catchment descriptor urban extent and the contributing role of soil moisture

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2) To evaluate the potential for using hydrologically relevant urban catchment descriptors and landscape metrics for estimating the index flood in small urbanised catchments

3) To evaluate the performance of urban catchment descriptors and landscape metrics for explaining inter-catchment variation in storm runoff.

1.4 Hypotheses

Three related hypotheses are presented here that considered together will facilitate an informed consideration of the aim:

H1 - Urbanisation causes changes in the hydrological response (storm hydrograph) of a catchment to storm events and these changes are directly proportional to the level of urban extent and affected by antecedent conditions.

H2 – Spatially explicit landscape metrics can improve characterisation of urban land-cover over lumped catchment descriptors and improve estimates of the index flood.

H3 - Urban runoff is controlled by the extent and layout of urban land cover and attribution of both the quantity and timing of storm runoff can be improved by characterising urban land-cover using spatially explicit landscape metrics, compared to lumped catchment descriptors.

1.5 Thesis format and research design

The thesis format and layout of chapters is illustrated in Figure 1.1, highlighting the general flow of research activities, with the relationships between chapters highlighted by dual arrows.

Chapter 2 comprises the literature review and summary of key knowledge gaps that have been identified to justify the aims and objectives.

Chapter 3 introduces the study areas and outlines the field monitoring campaign, data processing, quality control, and event selection methods used in the thesis. Appendix B provides additional detail on the field monitoring programme.

Chapter 4 (Objective 1) details the methods and metrics used to detect and quantify variable hydrological response along the rural-urban gradient of the monitored locations to storm events. This chapter tests whether a single measure of urbanisation, here using the FEH catchment descriptor *URBEXT*, can explain variation in storm runoff, defined by a number of hydrograph metrics, along a gradient of urbanisation. It is a version of a paper that has been published in the Journal of Hydrology (Miller and Hess, 2017).
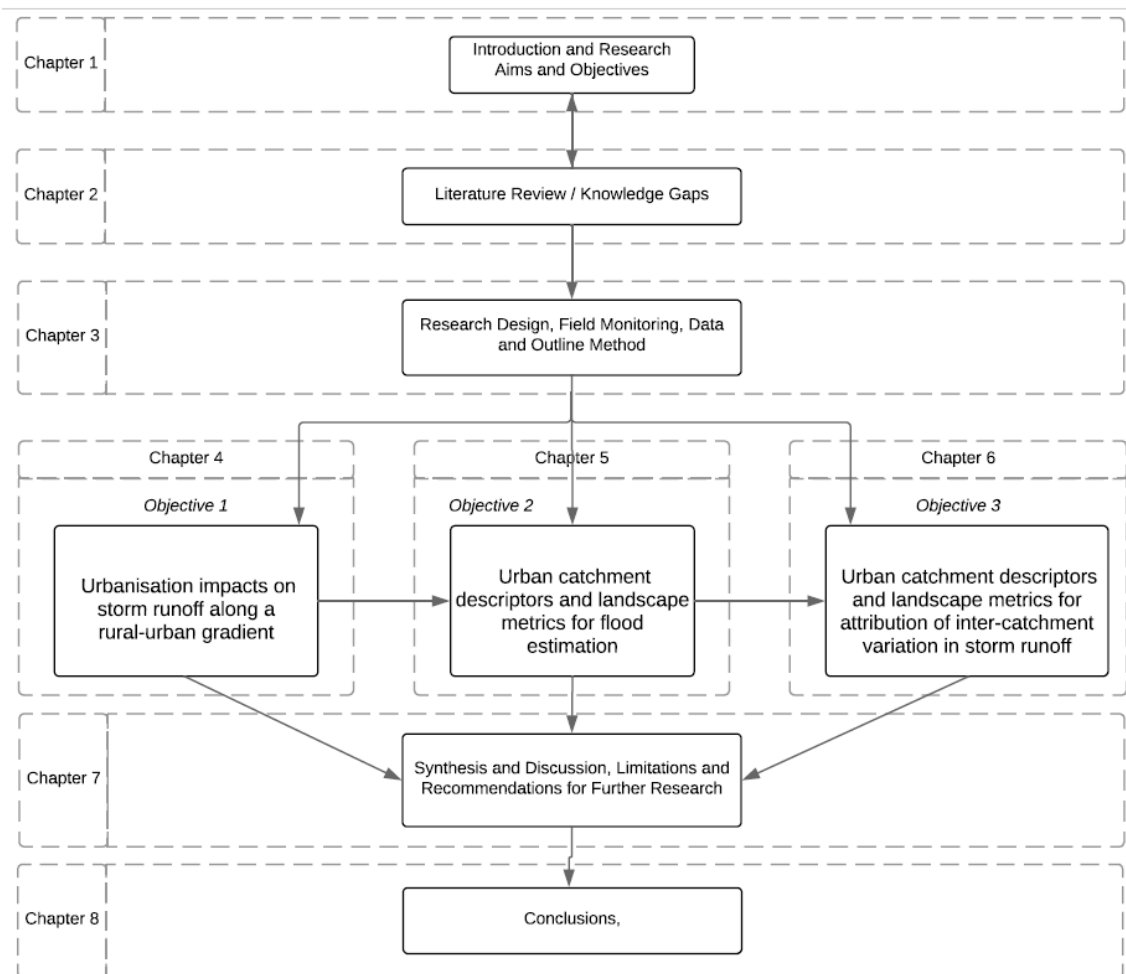
Figure 1.1: Schematic diagram of thesis structure. Arrows indicate the flow of information between chapters, with dual arrows representing an iterative process of development between activities and content of two related chapters.

Chapter 5 (Objective 2) details outlines the data and methods used to derive a number of hydrologically relevant and spatially explicit catchment descriptors, based on ecological landscape metrics, and to test their application in estimating

the median annual flood *QMED* through linear regression. This chapter assesses the performance of such refined descriptors for flood estimation compared to existing datasets and nationally based regressions, in order to determine if improvements in estimating *QMED* can be achieved. It is a version of a paper published in Landscape and Urban Planning (Miller and Brewer, 2018).

Chapter 6 (Objective 3) draws upon methods, data and findings from both Chapters 4 and 5. The chapter assesses the potential for landscape metrics for explaining inter-catchment variability in storm runoff and determines how enhanced descriptors and landscape metrics could be used to improve lumped modelling and attribution of storm runoff response in urban catchments. It has been formatted for submission to the Urban Water Journal as a co-authored paper (Miller JD, Stewart L, Hess T and Brewer T).

Chapter 7 provides a synthesis and discussion of the thesis objective findings with regard to the aim and hypotheses of the thesis. It considers the potential implications of findings with regard to flood estimation methods used in the UK. Potential limitations of the thesis with respect to conclusions made are discussed, and priorities for further work to address the limitations are identified

Chapter 8 provides a conclusion on the thesis aim.

A full list of symbols used in the thesis is included in Appendix A.

The monitoring network and the collection of data that were used in this thesis was part of the Pollcurb project (http://www.pollcurb.ceh.ac.uk/) which set out to improve understanding of the impacts of urbanisation on hydrology and water quality at various scales (Hutchins et al., 2016) and was funded by the Natural Environment Research Council (NERC UK) as part of the Changing Water Cycle program (NE/K002317/1). My role was to lead the design, installation and maintenance of hydro-meteorological monitoring to support other project work packages. The Pollcurb project integrated monitoring sites in Swindon that were installed under an earlier programme of monitoring used in the NERC funded peri-urban hydrological fluxes project (Ward et al., 2014; Miller et al., 2014).

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2 - LITERATURE REVIEW AND KNOWLEDGE GAPS

2.1 Introduction

The urbanised catchment is an artificial environment where many natural hydrological processes have been modified through urban land use and installation of significant hydraulic engineering to service the needs of the urban population. To understand and predict the effects of urbanisation requires determining hydrological changes attributable to catchment properties.

This chapter provides a literature review of research on the impacts of urbanisation on storm runoff and the methods used to characterise urban land cover and attribute urbanisation impacts. It introduces landscape ecology and associated landscape metrics, reviewing how they have been utilised in field of hydrology. The review identifies research gaps and provides the justification of the research undertaken in the thesis. Literature on UK flood estimation methods are reviewed with regard to limitations in small urban catchments.

2.2 Evidence of impacts of urbanisation on hydrological response

The hydrological impacts of urban development derive from a loss of pervious surfaces and vegetation and replacement with impervious surfaces that acts to reduce infiltration to soils and increase surface runoff (Jacobson, 2011; Redfern et al., 2016). Additionally the introduction of artificial drainage structures replaces natural pathways of water movement through the catchment and connects impervious surfaces to natural channels, increasing hydraulic efficiency (Shuster et al., 2005). The combined hydrological impacts have been shown to include: faster response to rainfall (Huang et al., 2008) raised river flows (Hawley and Bledsoe, 2011) more frequent small floods (Hollis, 1975; Braud et al. 2013) reduced baseflow and groundwater recharge (Simmons & Reynolds, 1982). While there is some uncertainty at defining the level of urbanisation at which such hydrological changes become manifest the literature suggests that the effects become apparent when urbanisation reaches between 5 and 10% of catchment

cover (Salvadore et al., 2015). Shuster et al. (2005) however, point out that it is not possible to set a single threshold of cover that predicts hydrological impacts across all catchment and urbanisation types.

The loss of pervious surfaces is also generally considered to reduce the importance of antecedent soil moisture (Shuster et al., 2005) which can be a key predictor of hydrologic response for certain soil types (Boorman et al., 1995; Zehe & Bloschl, 2004). Booth et al. (2002) surmised a reduction in soil water storage potential with increased impervious area correspondingly decreases the importance of antecedent soil moisture in runoff. However, as noted by Bertier et al. (2004) this is not well researched and their own modelling results showed that soil plays a significant role in runoff generation in small urban catchments. Conversely, Smith et al. (2013), analysing observed data for nine small urbanised basins, found soil moisture to have no significant impact on the storm response of either the urban or nonurban basis tested. This lack of agreement and overall lack of empirical data on soil moisture and runoff in small urbanised catchments points to the need to consider the role of antecedent soil moisture when analysing urbanisation impacts on storm runoff.

Modified hydrology also results from the complex array of hydraulic infrastructure for managing water transfers and flood mitigation/defence. The water balance of the catchment is altered by importing water and wastewater discharges from sewage treatment works (Lerner, 2002). Substantial artificial drainage alters the natural hydrological catchment area (Miller et al., 2014). Ponds provide flood alleviation by attenuating storm runoff and delaying the runoff peak (Ciria, 2014). Sustainable Urban Drainage Systems (SuDS) represent a range of soft engineering measures, also known as green infrastructure (GI) (Golden and Hoghooghi, 2017) that aim to increase infiltration to soils and attenuate local runoff. They include, along with ponds and wetlands, features such as green roofs, butts, soakaways, permeable paving, and swales (Ciria, 2014). Modelling and monitoring of features such as green roofs has shown the potential for mitigating storm runoff rates and volumes (Vesuviano et al., 2014; Stovin et al., 2012). Such features are increasingly important in the UK as the Flood and Water

Management Act (2010) introduced new responsibilities for local authorities on implementing SuDS.

Early empirical studies during the 1960's to 1980's tended to confirm the conventional hydrological theories concerning increases in runoff and peak flows, and reductions in lag time and flood duration (Leopold 1968; Jacobson, 2011). Limited early studies in the UK found urbanisation results in a decrease in lag-time between rainfall and runoff peak (Hall, 1977) increased flood flows (Hollis & Luckett, 1976) with small floods being particularly affected (Hollis, 1975) and that percentage runoff from impervious surfaces can vary seasonally (Hollis & Ovenden, 1988). While more recent examples of empirical urban research exist (e.g. Mcmahon et al., 2004; Baker et al., 2004; Braud et al., 2013) a review by Miller & Hutchins (2016) found contemporary studies generally rely on using hydrological models to develop and test new theories and that uncertainty remains on the catchment scale effects of contemporary urbanisation. Hydrological models have become the de-facto method for investigating complex hydrological questions as they enable conceptualization of water fluxes and testing of theories (Salvadore et al., 2015). While distributed models using spatial data are increasingly used to investigate and represent factors such as the spatial layout of urban areas (Zhang & Shuster, 2014), lumped approaches remain limited as they are not capable of describing spatially-variable processes. Likewise, statistical methods that rely on lumped catchment characteristics for attributing hydrological response in ungauged catchments cannot consider such spatially explicit effects. Despite this, where only catchment discharge is required, lumped approaches can be more accurate as they require less parameterisation (Krebs et al., 2014).

Reviewing current understanding of hydrological processes on common urban surfaces, Redfern et al. (2016) suggest further research into the linkages between urban surfaces and hydrological behaviour will improve the representation of urban landscapes within hydrological models and result in improved performance. This observation is in agreement with the view of Bahremand, (2015) that a determined effort is required to shift the focus of modelling studies

away from parameter optimization towards a deeper attention to process modelling and reconsideration of underlying conceptual models. The growing availability of high resolution monitoring technologies is enabling better identification of the key physical process (Hutchins et al., 2016) but there is a related need to suitably characterise urban catchment properties in order to test methods used to attribute hydrological changes to properties of the urban system.

2.3 Investigating urbanisation impacts on storm runoff

2.3.1 Characterising urban catchments for hydrological applications

2.3.1.1 Typologies and urban land-use classification

Typology refers to a classification according to general type and involves classifying geospatial features into distinct suitable groups for use in further analysis. The 1970s saw significant advances in defining and mapping urban ecological typologies, from descriptive terms such as forest, park, gardens, to resource feature maps including air, water, land and life (Turner et al., 2001). Brady et al. (1979) proposed a typology that described natural, physical and structural elements of urban areas in regard to their ecological properties, integrating land use types and subtypes to a wider biogeographical hierarchy in order to better study ecosystem dynamics. Here each typology was differentiated by its fauna and flora, its hydrology, its soils, management and productivity.

Urban typologies can be simple or highly complex and be presented at a range of scales. The European Commission has defined a simple system of urban/rural typologies with three levels of classification based on population distribution and units from grids to regions – Urban, Intermediate, and Rural (Castellano et al., 2010). More complicated systems exist and can have be given their own descriptor, such as the mapping of urban morphology types undertaken by Gill et al. (2008) where categories such as transport and residential are broken down further into roads or rail and low to high density respectively. The level of complexity will ultimately be determined by the application and also the limitations of the underlying spatial data.

2.3.1.2 **Urban land cover mapping and urban areas in the UK**

The Land Cover Map of Great Britain (Edmundson et al., 1999) - known as LCMGB for approximately 1990 - was the first complete map of land cover of Great Britain produced since the 1960s and was produced using remote sensing imagery (Fuller *et* al., 2002). Here urban surfaces were represented as either and-use that was a mix of green and developed (Suburban) or mainly developed (Urban). While such mapping is used in FEH methods the development of LCM products was more focused on providing ecologically relevant information to the Countryside Survey.

The pioneering use of satellite imagery used in LCMGB was further developed in the enhanced LCM2000 (year 2000) where land cover was mapped using spectral segmentation of image data in vector land parcels derived from the spectral segmentation of images (Fuller et al., 2002). The most recent incarnations of the LCM (LCM2007, LCM2015) are based on a Ordnance Survey Master Map (OSMM) topography layer combined with 34 multi-date summer-winter satellite images, dramatically improving the spatial and thematic accuracy of mapping (Morton et al., 2011; https://www.ceh.ac.uk/services/land-cover-map-2015). These improvements have improved mapping of land cover but limitations are that they do not enable a comparison of land use change (LUC) between periods due to the different methods and data used (Morton et al. 2011) and simplify urban land cover (Miller and Grebby, 2014).

Detailed mapping of urban land cover and LUC bas become increasingly possible with access to improved technology and frequently updated high resolution satellite/aerial imagery. Research into using multispectral sequences of interferometric coherence data undertaken by Grey et al. (2003) demonstrated the potential to map urban change but clearly identified the difficulty in detecting small scale changes and need to incorporate survey data. Such small scale changes in urban land-use – termed 'urban creep' - were mapped across five UK urban areas by Allitt & Tewkesbury (2009) by incorporating additional survey data with remote sensing imagery. The UK Government use OSMM to derive

national land use change statistics (Government, 2015) and this has opened up opportunities for urban mapping that have not been widely utilised for hydrological attribution.

2.3.1.3 Mapping impervious cover

Impervious cover was identified in the 1990s as a key environmental indicator for use in environmental research and urban planning (Arnold & Gibbons, 1996). The increasing availability of high-resolution remote sensing imagery and aerial photography, and the clear limitations of simplified land-use descriptors that cannot be universally applied, has led to a growth in research into the mapping of impervious cover since the year 2000 (Weng, 2012). The possibility to produce detailed comparable datasets on the location and degree of soil sealing has had particular relevance and application for catchment hydrological modelling (Jacobson, 2011). It has been integrated with products such as the OSMM polygons to measure sealed areas in urban environments (Kampouraki et al., 2004) and the availability of consistently updated medium-resolution satellite imagery such as Landsat, ASTER and SPOT now provides the basis for most LUC modelling in urban areas (e.g. Dams et al., 2013; Verbeiren et al., 2013). Changes at the smallest scale, typified by urban creep, require higher resolution imagery such as aerial photography. Perry & Nawaz (2008) combined aerial photography with Google earth imagery and OSMM to provide detailed estimates of changes in particular features of urban sprawl over a small catchment (1.16 km^2) and highlighted the large contribution that such small local changes can make to estates of total catchment impervious area. To date however there has not been national scale mapping of impervious cover across the UK (Miller and Grebby, 2014) and only localised examples of urban creep being mapped (e.g. Allit & Tewksbury, 2009).

2.3.1.4 Catchment descriptors for lumped hydrological applications

Distributed hydrological models can directly utilise suitable spatial land cover but lumped catchment hydrological applications such as the FEH statistical method require catchment scale properties that characterises hydrological relevant

properties such as the land cover or soils. This may be based on information that relates to some form of summation of land-use typologies mapped within a catchment, this is the method used in the FEH (IH, 1999). This could be categorical, taking the dominant land use, as applied by Gallo et al. (2013) whereby 5 dominant land uses were identified – low, medium, and high density residential, mixed, and commercial. Descriptors can also be quantitative, such as taking the total impervious area (TIA) (Lee and Heaney, 2004). There is also growing interest in measuring the effectiveness and connectivity of such surfaces for conveying runoff, producing indicators such as directly connected impervious area (DCIA) (Roy and Shuster, 2009) or effective impervious area (EIA) (Janke et al., 2011). There remain limitations however in providing universal methods to map such detail and at catchment scales such detail may not add value to measurements of impervious area (Shuster et al., 2005).

Catchment descriptors underpin the ability to estimate flood peaks and hydrographs in ungauged catchments in FEH methods. They provide a method and means for quantifying the physical and climatological properties of a catchment. The catchment descriptors used in FEH flood estimation methods and are detailed in Volume 5 of the FEH (Bayliss, 1999) and additional descriptors have been developed and tested for use in the statistical method (Kjeldsen et al., 2008). They are derived from a combination of mapping and digital geospatial data and have generally not been updated since their original computation in the 1990s. One exception, and the most important descriptor with regards to this thesis, is the indexing of catchment urbanisation in terms of urban extent - *URBEXT*. *URBEXT* is a weighted sum of *Urban* and *Suburban* LCM classes (IH, 1999: Eq. 2-1). It is computed for a selected period for which LCM data are available; for LCM2000 the derived urban extent is $URBEXT_{2000}$.

$$URBEXT = Urban + 0.5\,Suburban \qquad\qquad \textbf{(2-1)}$$

URBEXT has been shown to provide relatively robust means of representing catchment imperviousness, even for small urban catchments below 1 km^2 (Miller & Grebby, 2014). One limitation however is that such a lumped urban catchment descriptor does not provide characterisation of the spatial effects of layout and connectivity identified by Zhang & Shuster (2014) as being important factors for urban runoff. There was development of potential spatially explicit urban catchment descriptors in the FEH - *URBLOC* (a location index) and *URBCONC* (an index of concentration) (Bayliss, 1996), but these were not subsequently employed in any further regression analysis. In the most recent update to ReFH methods Kjeldsen et al. (2013) point to the possibilities that a geometric representation of urban land cover could offer over a lumped value such as *URBEXT*.

Wan Jaafar & Han (2012) have shown that alternative descriptors can be developed from freely available geo-spatial data and that they have potential for more reliable regression models, and provide a wider range of morphometric feature descriptors that include more information on drainage and relief. Such hydrologically relevant catchment descriptors have been developed to represent the hydrological form and function of a catchment (Van de Voorde et al., 2011) or to provide a measure of density and form of drainage networks (Meierdiercks et al., 2010). Such descriptors have also been shown by Ogden et al. (2011) to be more important than impervious cover in affecting peak flows during rare events. While more hydrologically relevant for an urban catchment they still do not provide spatially explicit representation of urban land cover or its connectivity.

2.3.2 Attribution of hydrological response to urbanisation

Attribution of hydrological response is achieved by investigating the relationship between hydrological variables that quantify response and catchment characteristics. Here a brief review is provided of the various methods used in urban hydrological studies.

The simplest form of investigation is to compare the hydrological response of catchments and to attribute differences in response to differences in catchments

characteristics. In urban studies this usually takes the form of comparing an urban and rural catchment, or a range of development types, and testing for statistically significant differences in response. This approach has been utilised to demonstrate the expected differences between rural and urban catchments (Sheeder, Ross and Carlson, 2003) and also more nuanced differences in response between traditional urban development and more modern approaches that utilise SuDS or related systems (Hood et al.,2007). While such studies are useful for validating broad theories they are limited in the number of catchments used and the selection of broadly different catchments. Further, for the purposes of using their findings to determine hydrological changes attributable to land cover differences, they do not provide a means for determining the relationship between urban catchment characteristics and hydrological response.

The majority of studies investigating the relationship between urbanisation and hydrological response utilise hydrological data from a number of catchments and attribute response to derived catchment characteristics using a statistical regression. An early example is the work of Hollis & Ovenden (1988) to relate land cover types to the percentage runoff and peak runoff, and other independent variables such as soil moisture deficit. They used regression analysis to attempt to attribute various hydrological measures of response and found that while percentage runoff from roads could not be explained satisfactorily by land use, seasonal variables were important, and antecedent conditions were not, overturning expectations. This highlights the value of having multiple explanatory variables and hydrological measures available during any statistical attribution. Certain studies have chosen to attribute the instantaneous unit hydrograph (IUH) shape to catchment properties, and while the relationship with imperviousness has been demonstrated (Rao & Delleur, 1974; Cheng 2011), it must be considered that the IUH itself is modelled, and thus does not directly constitute empirical data.

Research that has focused upon utilising peak flow values from relatively large gauged sites (e.g. FEH: IH, 1999) has indicated that even with this single measure of response it can be problematic to relate LUC and urbanisation to

increases in peak flows (Kjeldsen et al., 2013) or to attribute urbanisation effects on flood extremes using nonstationary flood-frequency models (Prosdocimi et al., 2015). Regression model performance in urban catchments is generally found to be much greater in smaller catchments with higher resolution hydrological data, a range of hydrological variables, and more detailed information on land-use for explanatory variables (e.g. Valtanen et al. 2013; Gallo et al. 2013).

Common across all studies investigating urbanisation impacts, from local studies comparing a limited number of small localised catchments with clear differences (Graf, 1977) up to national assessments that seek to provide nationally applicable statistical regressions (Driver & Troutman 1989), is using some measure of urban development to characterise urban impacts. In general this involves a measure of catchment imperviousness, which alongside catchment area, has often been shown to be the primary driver of inter-catchment variability in response (e.g. Rao & Delleur, 1974; Sillanpää & Koivusalo, 2015). Reviewing the literature on the hydrological impacts of imperviousness Jacobson (2011) identifies that while earlier research (1960's – 1990's) confirmed conventional hydrological theory that runoff and peak flow increases with urbanisation and is governed by the impervious area, more recent studies have investigated the relationship with other facets of hydrological response like lag time and flashiness. Flashiness, for example, has been shown to linked to imperviousness and to be a fundamental change that occurs with urbanisation (Mcmahon et al., 2004). This direct measure of soil sealing has also been investigated regarding specific hydrological metrics such as peak flows (Smith et al., 2005), flood duration (Braud et al., 2013), low and slow flows (Smith et al., 2013) among others.

Another more recent area of research has been considering the influence of distribution and connectivity of impervious surfaces. Studies relating urban land use to hydrological variables do not normally consider location (Jacobson, 2011; Alberti et al., 2007) but there has been limited research linking drainage network characteristics and storm water management to hydrological variables (Smith et al. 2005; Meierdiercks et al. 2010). Additional factors that interact with imperviousness to affect runoff response include rainfall intensity (Gallo et al.,

2013) season (Valtanen et al., 2013) soil condition (Ferreira et al., 2013) and soil moisture (Nied et al., 2016).

No urban catchments were considered by Nash (1960) for attributing the IUH but other studies have assessed IUH in urban basins. Rao & Delleur (1974) undertook a comprehensive IUH attribution assessment of rainfall-runoff for eight urban and five rural basins in Indiana, Texas, at a range of catchment scales using impervious cover percentage as the urban physiographic characteristic. They were able to relate basin and storm characteristics to peak discharge and time lag between rainfall and runoff and found that regression relationships using only area and an urbanisation factor were sufficient to override natural characteristics such as stream length and slope (Rao and Delleur, 1974).

2.3.3 Landscape metrics

Landscape ecology has become a vital element of ecological research and focuses on the interaction between spatial patterns in the landscape and ecological processes. It is a branch of ecology that combines the spatial element of geography with the functional approach of a geographer (Forman and Godron, 1986) to explore the fundamental concept that spatial patterns and ecological processes are coupled (Wu and Hobbs, 2002). Landscape can be considered at various scales but key to this concept is that the landscape typology can be classified, and that heterogeneity in landscape can further be summarised at the landscape or class level, and further that individual patches of a similar class type can be identified. From such data the spatial arrangement of landscape can be quantified.

Turner et al (2001) present three broad categories of metrics used to quantify landscape: metrics of landscape composition; measures of spatial configuration; and fractals. Metrics for landscape composition indicate what is present and the quantity, and are not normally spatially explicit (e.g. percentage of landscape – PLAND – the percentage taken up by a given class (class level). Configuration refers to the spatial arrangement of habitat types and can be at a landscape level (e.g. contagion – which identifies the degree of clumping) or patch-based (e.g.

connectivity – such as the average distance between patches). Fractals are commonly used as a metric of landscape complexity and for comparing different landscapes and scales (e.g. fractal dimension of a patch – an indicator of shape complexity as a function of perimeter and area). To aid in the quantification of such landscape metrics specific software such as FRAGSTATS (McGarial, 2015) provide spatial analysis programs that process spatial datasets and are able to compute a suite of landscape metrics.

The important role that spatial distribution, location and connectivity of urban surfaces can have on runoff has been explored using models and points to the important role such factors can have on storm runoff. Zhang & Shuster (2014) demonstrated the importance of considering the location of impervious areas relative to the outlet and interplays between spatial distribution and catchment shape. Likewise, Mejía & Moglen (2010) find the impervious pattern influences hydrological response and recommend accounting for spatial variability in imperviousness when determining the response of an urbanising catchment.

Spatially explicit landscape metrics were highlighted by Herold et al. (2003) as valuable for improving the analysis and modelling of urban growth and LUC and can improve representations of urban dynamics. Recent studies have demonstrated such potential applications by using landscape metrics for explaining hydrological processes in a lotic wetland (Yuan et al., 2015), or for conveying hydrological connectivity (Van Nieuwenhuyse et al., 2011). Yuan et al (2015) highlighted few studies utilising such metrics despite the importance of testing and developing metrics to link landscape pattern to hydrological function, and found no studies explicitly accounting for hydrological connectivity. Van Nieuwenhuyse et al. (2011) had specifically sought to relate a suite of landscape metrics to functional hydrological connectivity, however the study was solely conceptual in its framework. Only very recently have studies begun to acknowledge the limitations of lumped measures of imperviousness for attribution of hydrological impacts, with Oudin et al. (2018) employing landscape metrics for assessing hydrological impacts at the catchment scale. This is evidence of the infancy of this potentially useful area of research.

Given the spatial limitations of using lumped catchment measures of urbanisation identified in the literature regarding hydrological modelling (e.g. Salvadore et al., 2015) and flood estimation (Vesuviano and Miller, 2018) it is interesting that there is no specific literature exploring this potential fusion between landscape ecology and hydrological prediction. The value of applying landscape metrics in lumped catchment scale applications comes from their unique ability to convey spatially explicit information on landscape connectivity, location and fragmentation, but in single catchment values. Oudin et al. (2018) explored the use of landscape metrics to explain modelled hydrological impacts of urbanisation at the catchment scale and found fragmentation mitigates urbanisation impacts and that certain metrics better link catchment imperviousness to high flows. The limited number of studies exploring hydrological applications, and limitations identified in current attribution and flood estimation methods certainly suggests potential applications in hydrological modelling. To date, however, there has however been no empirical study attempting to evaluate the use of landscape metrics for explaining the hydrological response of urban catchments to storm events, or for use in flood estimation.

2.4 Flood estimation in the UK

2.4.1 UK flood estimation methods

In countries where flood peak data are available across a range of catchments, statistical flood frequency analysis can be used to establish a relationship between flood magnitude and the frequency of occurrence – this is the case for most of Europe (Castellarin et al., 2012). The flood frequency curve is obtained by scaling the growth curve by the index flood. The growth curve relates flood-size to flood-rarity. In the UK the statistical method for estimating peak flows is based on the generalised logistic distribution and the index flood is the median annual maximum flood – $QMED$ – being the flood that is exceeded on average every other year (IH, 1999). $QMED$ is most accurately estimated from observed data, using annual maxima or peak-over-threshold data from gauged flow records, but in ungauged sites, another approach is required. In such cases

QMED is estimated from a number of catchment properties based on a derived regression linking catchment descriptors to observed *QMED* (Kjeldsen et al., 2008).

In cases such as the design of hydraulic infrastructure a more detailed picture of potential future flooding is required which can be provided by modelling a design storm hydrograph. Event-based rainfall-runoff models play a vital role for the design of hydraulic infrastructure such as bridges or flood defence along rivers. These include the Soil Conservation Method (Huang et al., 2008) that is internationally widely used, and in the UK, the Revitalised FSR/FEH rainfall-runoff method (ReFH) (Kjeldsen, 2007). ReFH is an event-based rainfall-runoff method used to model a design flood hydrograph. Much like methods for flood peak estimates, the ReFH model is best parameterised using data from a gauged site, but for ungauged sites relies on regressions between catchment descriptors and observed peak flow data to estimate these parameters. This has been recently updated to include an urban component (Kjeldsen et al., 2013) and is currently available as the ReFH2 software package (WHS, 2015).

2.4.2 Accounting for urbanisation in FEH methods

Applying the FEH statistical index flood method in urban catchments requires taking a nationally derived regression between catchment descriptors and observed *QMED* for rural catchments and applying an urban adjustment factor (UAF) to account for the proportional increase in *QMED* resulting from urbanisation (IH, 1999). This improved performance over the rural model when applied in urban ($URBEXT_{1990}$>0.025) catchments but model residuals were still larger than the spread in predicted values and incurred a high uncertainty, with the urban effect predicted by the UAF found to be much lower than values reported in field based measurements such as Hollis (1975). It was concluded of the UAF model that local variations in the degree and type of flood management are an important factor determining the flood peaks and that uncertainty arises from local variations in the type, age and nature of the urbanisation that cannot be generally characterised through available digital information (IH, 1999). With

such information Kjeldsen et al. (2008) noted the potential for updated *URBEXT* descriptors to improve performance of FEH statistical methods in urban catchments but to date the most recent remains *URBEXT*$_{2000}$.

The impact of urbanisation is explicitly considered in the routing and loss model parameters of the updated ReFH2 method (Kjeldsen, 2013). The routing parameter is the time-to-peak (*Tp*) of the IUH and is determined to be directly influenced by urban extent. The *Tp* parameter value for the urban area is expressed as a ratio of the larger (longer) *Tp* for the rural area (WHS, 2015). The loss model parameter is the percentage runoff (*PR*) for urban areas of the catchment which is estimated using an assumption of 30% imperviousness for urban areas and information on urban extent (*URBEXT*).

Various sources have noted the limitations of relying on the lumped catchment descriptor *URBEXT* to explain the effects of urbanisation and pointed to the potential for using a more spatially explicit approach that considers the distribution of urban areas within a catchment (Kjeldsen et al., 2013; Vesuviano and Miller, 2018). There are however no studies that have sought to use landscape metrics as a means of resolving the lumped approach while providing a more geometric representation of urban land cover.

2.4.3 FEH performance in urban catchments

While the FEH methods represent the most suitable flood estimation techniques in small (<25 km^2) and urban (*URBEXT* ≥ 0.03) catchments (Environment Agency, 2012b) a number of specific limitations have been identified. These limitations include: i) small urban catchments are not well represented in the data used to calibrate regression formulae, ii) a need to develop and test improved catchment descriptors, and iii) and a requirement to improve methods to support application in small urban catchments (Kjeldsen et al., 2006; Faulkner et al., 2012; Wan Jaafar and Han, 2012; Environment Agency, 2012a; Kjeldsen et al., 2013; Vesuviano and Miller, 2018). It should however be noted that limitations aimed at the ReFH model have to some degree been addressed in the updated ReFH2 model (Kjeldsen et al., 2013) which has been shown by Vesuviano and

Miller (2018) to perform resonably well in small highly urbansied catchments, but to have limitations where signficant storm drainage is present.

2.5 Knowledge gaps

This review has identified a number of knowledge gaps that relate to empirical evidence on the impacts of urbanisation on storm runoff that if addressed could contribute to potential improvements to the FEH methods required to overcome limitations identified for small urban catchments:

1) Limited detailed empirical observations of hydrological response in small contemporary urban catchments

2) A reliance on using a lumped catchment measure of urban extent or imperviousness to explain storm runoff in attribution and lumped hydrological modelling

3) Limited investigation into the potential of using spatially explicit landscape metrics for attribution of spatial urban land cover effects on storm runoff

4) No research investigating the application of landscape metrics in flood estimation methods.

2.6 References

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3 - FIELD MONITORING, DATA AND METHODS

This chapter provides an overview of the field monitoring, data and methods used in this thesis. Sections 3.1 introduces the study catchments. Section 3.2 provides an overview of the field monitoring programme and hydro-meteorological data processing employed to provide the material to meet Objective 1 of the thesis. Additional detail on the field monitoring, data and methods is provided in Chapter 4 and in Appendix B. Section 3.3 provides an overview of the data and methods used to characterise urban catchment properties, with more detail provided in Chapter 5.

3.1 Study areas – Swindon and Bracknell: Thames Basin

The river Thames is the longest river in England, with a maximum length of 354 km. The Thames basin contains major urban centres, including London, Swindon, Oxford, Slough, Maidenhead and Reading, and houses approximately a fifth of the UK population. The geographical scope of the monitoring was focused within two urbanised catchments within the Thames basin that contain the towns Swindon and Bracknell (Figure 3.1).

Bracknell has grown from a small village and since being designated a new town in 1949 has grown rapidly to a population of 120,000 (2015). Bracknell was designed with consideration of water management, utilizing a number of flood storage tanks and ponds to mitigate flooding and reduce sediment delivery to downstream areas (Packman and Hewitt, 1998). Swindon was a small 19th century industrial town that has grown into an area of mixed peri-urban development and commerce with a population now exceeding 215,000 (2015). Only minor localised flood storage infrastructure exists but development in recent years has required localized flood management to adapt to increased flooding in certain dense areas of housing (Miller et al., 2014).
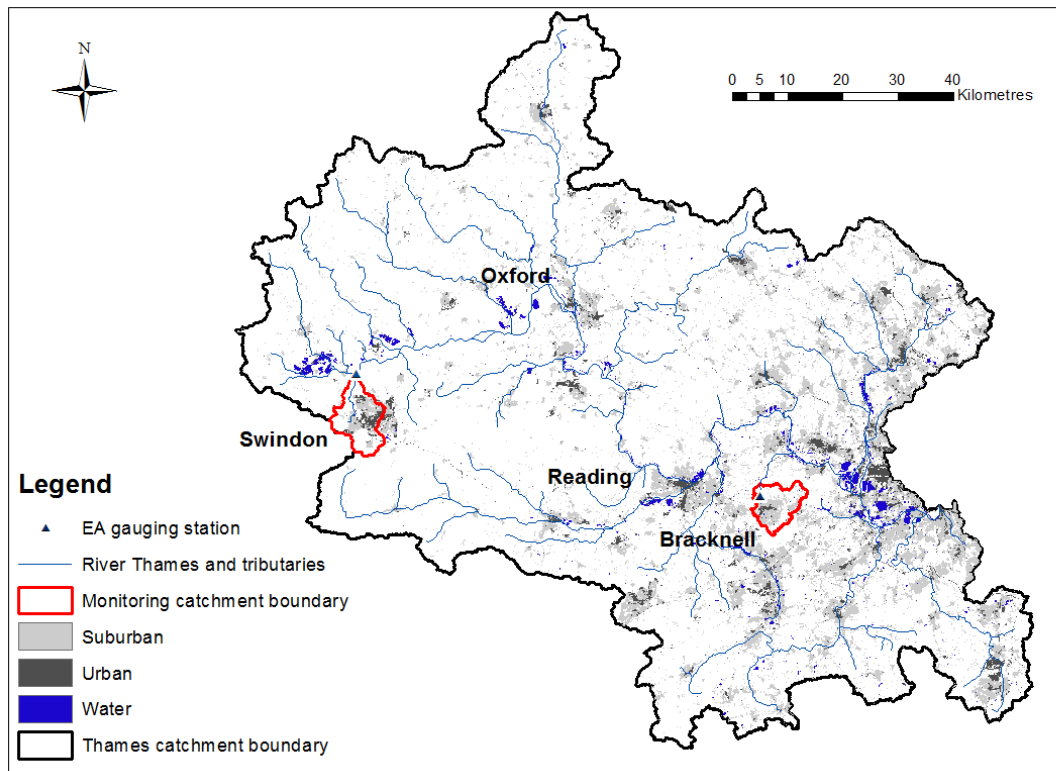
Figure 3.1: Locations of study towns Swindon and Bracknell within the Thames basin – showing areas of urban development and EA gauging stations used in this thesis.

Swindon and Bracknell were specifically selected due to a number of considerations listed below that relate to the geographical location shown in Figure 3.1 and FEH catchment descriptors listed in Table 3.1:

1. Hydrological location – sites not located on a 'major' river, but on source tributaries of Thames and within catchments monitored by the EA. This focuses monitoring of responses due to local urban land-use issues and not to capture issues of the wider catchments. The two catchments containing the towns are: Binfield station (39052), for Bracknell; and Water Eaton station (39087), for Swindon. Herein these stations are refereed to EA_39052 and EA_39087 to indicate their both being EA stations, and not a flow gauging locations set-up in the monitoring network deployed.

2. Level of urbanisation – both Swindon and Bracknell are similar types and age of town, and the degree of urbanisation, as measured using urban extent in 2015 (*URBEXT$_{2015}$*), is of a similar level (0.24-0.26).

3. Climate – standard average annual rainfall (*SAAR*) totals are similar and indicative that both sites are subject to a similar climate. However, other climate related variables (RMED-1H, PROPWET) indicate Bracknell is subject to more high intensity storms that Swindon.

4. Underlying catchment hydrology - both locations are located at similar altitude (*ALTBAR*) with similar slope (*DPSBAR*) on similar geology and hydrological soil type (*BFIHOST, SPRHOST*). However, Bracknell does have a greater degree of attenuation from rivers and lakes (*FARL*), indicating it has a greater number and coverage of retention ponds to mitigate urban effects.

Table 3.1: FEH catchment descriptors for the EA gauging stations at Bracknell (EA_39052) and Swindon (EA_39087)

	Bracknell EA_39052	Swindon EA_39087
AREA (km^2)	51.96	82.5
Year start	1957	1974
ALTBAR - Mean catchment altitude (mASL)	75	109
BFIHOST - Base flow index derived from HOST	0.36	0.39
SPRHOST - Standard HOST* percentage runoff	41.5	42.6
DPLBAR - Mean drainage path length (km)	7.46	9.31
Length - Maximum catchment length from outlet (km)	8.56	15.03
DPSBAR - Catchment steepness (m/km)	24.7	27.4
FARL - Index of flood attenuation from reservoirs and lakes	0.94	0.99
PROPWET - Index of proportion of time soils are wet	0.29	0.34
RMED-1H - Median annual max 1 hour rainfall (mm)	12.6	9.6
SAAR - 1961-90 standard-period average annual rainfall (mm)	676	698
URBEXT$_{2015}$ - Fractional urban extent in 2015	0.24	0.26

3.2 Flow and rainfall monitoring

Flow and rainfall data are required for characterising the hydrological response of a catchment to storm events. In small urban areas it is also important to have high-resolution monitoring of rainfall and runoff as response times and the duration of flood events are short. An outline of the monitoring programme and data used for characterising hydrological response are provided.

3.2.1 Flow monitoring

3.2.1.1 Site selection

The selection of sub-catchments within the two towns and within the boundaries of two gauging stations involved applying a number of criteria. Primarily there was an intention to capture rainfall-runoff responses across a range of sub-catchments at varying levels of urbanisation, from predominantly rural to highly urban. Second was identifying sites suitable for the installation of flow gauging equipment. Suitability and design of site installations was based on international organisation for standardisation (ISO) guidance (ISO15769: ISO, 2010). This involved finding culverted section or bridges through which watercourses of interest passed through that would provide a suitable base for fixing the equipment and a regular cross-sectional profile that was stable and would not change over time and in a location that was not subject to backing up or blockage during storm flows. Additionally it was important that the sites could be easily accessed and that there was a suitable location for fixing the associated battery and box well above levels that could be inundated during storm flows.

3.2.1.2 Equipment and locations

Across the two towns 16 sites were identified that met the site selection criteria for installation of flow monitoring equipment. The locations of the equipment and the hydrological sub-catchments that were monitored are illustrated in Figure 3.2, alongside the locations of the two EA flow gauging stations.
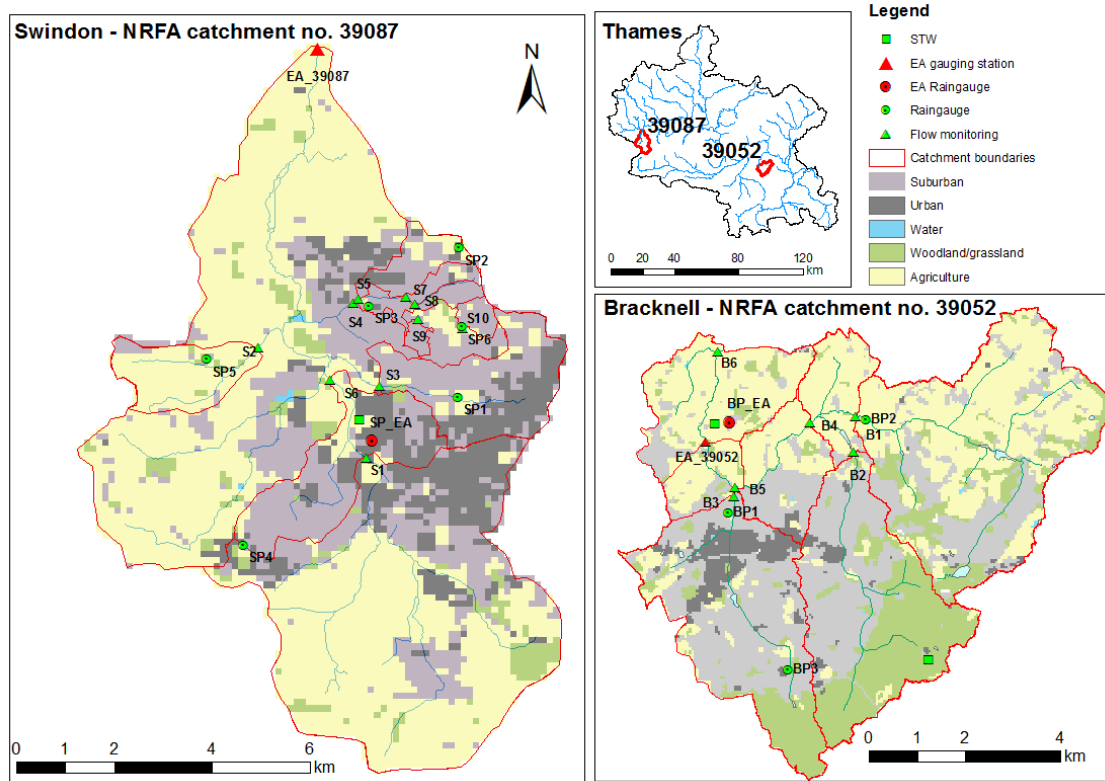
Figure 3.2: Monitoring locations and hydrological sub-catchments

Velocity and depth data were obtained using ultrasonic Doppler shift flow meters, also known as acoustic velocity meters, mounted to the bed of the suitable hydraulic structures. Key guidance was followed regarding bed-mounted ultrasonic Doppler and echo correlation devices (ISO, 2010). Figure 3.3 shows the equipment being installed, how it is cited on the stream bed, and a typical monitoring set-up with the data-box accessible for download of data and changing of battery. Ultrasonic Doppler flow monitoring (UDFM) is a standard technique for measuring flow in pipes, culverts and open channels and is often employed to study flows in urban environments and storm drain systems (Herschy, 1995; Blake & Packman, 2008). Water velocity is measured using the ultrasonic Doppler principle, whereby velocity is measured acoustically by recording the Doppler shift of particles and bubbles carried in flowing water (Unidata, 2008). Unless the channel is very small such devices only measure velocity in part of the channel cross section and requires calibration using a velocity-index rating, as detailed in ISO15769 (ISO, 2010). Water depth above the instrument is

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measured using a pressure transducer that records the hydrostatic water pressure. Flow is then derived from this monitoring data using information on the cross section of the site, whereby flow is equal to velocity multiplied by the cross sectional area of flow at the measured depth. Detail on the equipment is provided in Appendix B.1.

Figure 3.3: Installation of flow monitoring equipment on stream bed in urban culverts.

Final site selections are shown in photographs of both Bracknell (Figure 3.4) and Swindon (Figure 3.5), with specific locations shown in Figure 3.2. Culverts were selected as the ideal locations in most cases as they provided a stable surface for mounting and a controlled structure in which channel form would remain stable. Where stable bed surfaces were not available the flow meters were mounted onto a concrete slab and sunk into the sediment to a level matching the bed substrate (e.g. B1 in Figure 3.4). In Swindon a number of storm drain sites

were used (S5, S7, S9, S10: Figure 3.5), whereby access was via a manhole cover and the flow meter was set within the storm drain below. Access to such sites required confined space training and specialist equipment such as gas meters and winches to ensure safety, along with agreement from Thames Water who own and maintain the drainage systems.

B1

B2

B3

B4

B5

B6

Figure 3.4: Flow monitoring locations for Bracknell - photos of site cross section

The sampling period was set to 5 seconds and the recording frequency to 5 minutes. This was deemed a suitable frequency to capture the hydrological response of the selected sites and to allow for a maximum 50 days between downloads. Thus an approximate monthly duration of sampling and download was followed during the monitoring programme. Each site visit required download of the existing data, notation of current readings, site measurements of water level and conditions, and finally change of battery and starting a new log. Data from the two EA gauging stations was available as a time series of flow data at a 15min resolution.

Figure 3.5: Flow monitoring locations Swindon - photos of cross sections

Figure 3.6: Spot gauging of flow using Flow-Tracker

Additional spot-measurements of depth and flow at each site were regularly taken to provide calibration data for the instruments. Depth was routinely measured during most visits using a 1m steel ruler and recorded on a site visit sheet along with information about the conditions and any equipment issues. Flow was measured across a range of conditions to provide calibration information on velocity and flow using a portable UDFM 'Flow-Tracker' (SonTek, 2007). This involved the user entering the watercourse to record depth and velocity across a transect to compute an average flow profile for the channel (Figure 3.6). The ability to compute an average profile was important as it allowed calibration of the installed instruments, which could only sample a portion of the channel.

3.2.2 Rainfall monitoring

Rainfall was monitored at eight locations across the Swindon and Bracknell study catchments (Figure 3.2) using tipping bucket rain gauges. Sites were selected to provide good spatial coverage over the two towns relative to the sub-catchments being monitored. Ideally a rain gauge would be located in each sub-catchment but due to resource constraint's this was not viable.

The tipping bucket rain gauges used are comprised of a housing and funnel that directs water into a 2mm tipping bucket mechanism that tips when full, and each tip is recorded by a count logger, here a TinyTag Plus Re-Ed logger set to record number of tips at a 2min interval (Figure 3.7). Gauges were located at each site using guidelines set out by WMO (1994) whereby gauges were set level using spirit levels and sufficient space was provided for precipitation to not be affected by surrounding vegetation or buildings. Each gauge was visited on a monthly

basis for download and cleaning of equipment, necessary as the gauge inlet can become blocked by debris such as grass seeds and leaves. Data from the two EA rain gauges was similarly collected using tipping bucket rain gauges and was provided as a 15min resolution time series of rainfall.

3.2.3 Processing, storage and quality control of data

Much of the data collected were considered raw data that required some form of processing and quality control for use in detailed hydro-meteorological analysis. Following Blake & Packman (2008), hydrological data processing comprised:

1) Identification of UDFM velocity errors
2) Analysis of cleaned data to define depth-velocity relationships
3) Correction of UFDM errors

Additional steps required in this thesis relate to the wide diversity and number of sites that required site specific processing and the use of donor sites for infill if missing data and validation of values between upstream and downstream sites – such as checking for mass balance. Appendix B.2 details the processing steps applied (Table_APX B-1).

Figure 3.7: Precipitation measurement using a tipping bucket rain gauge (left) located in an open area (centre) with data collected using a reed logger (right) (photo of rain gauge courtesy of Casellasolutions.com, photo of reed logger courtesy of geminidataloggers.com)

Precipitation data for each site were quality controlled and reformatted to a 15min resolution using observed rainfall totals recorded at the most localised EA rain gauge. Each EA rain gauge has data collected and managed under British standards guidance (BSI, 2012a; BSI, 2014). The same guiding principles of data were followed in the collection and subsequent processing and storage of precipitation data obtained in this research. Catchment areal rainfall was derived using British standards guidance (BSI, 2012b). Appendix B.3 details the processing steps applied.

3.2.4 Storm event data

The focus of the thesis is on relating catchment characteristics to the hydrological response of the monitored streams/storm-drains/rivers to rainfall during storm events. The approach used to process the time-series data collected into suitable event based data was to isolate storm events that occurred in the observation record across all sites over the variable monitoring periods and from these to select only independent storm events of good data quality. From these events a

number of storm event hydrological metrics were derived that described the rainfall-runoff response and shape of the storm hydrograph. These values were subsequently saved into a database of storm event hydrological metrics that formed the basis of subsequent data analysis. The method, metrics and process used for this are detailed in Chapter 4.

3.3 Characterising urban catchment properties

Geo-spatial data were required for capturing land cover and hydrological features in the catchments and for characterising catchment hydrological properties. A brief introduction to the underlying methods is provided here while Chapter 5 provides a full list of the geospatial datasets used in this thesis and details the methods used to map urban land cover, and to derive catchment descriptors and landscape metrics.

3.3.1 Catchment descriptors

Catchment descriptors are used in FEH methods to quantify the physical and climatological properties of a catchment and play an essential role in flood estimation methods for ungauged sites. They are derived using gridded spatial data and the FEH has a suite of catchment descriptors which are available for any UK river catchment via the FEH Web Service (https:\\fehweb.ceh.ac.uk). A full list and explanation of the catchment descriptors used in this thesis is provided in Appendix A. For urban sites, the Urban, Suburban and Rural LCM classes are used to derive the catchment descriptor for urban extent – *URBEXT. URBEXT* is essentially a proxy for impervious cover within a catchment, based on a weighting of the two classes with respect to their relative level of development (Eq. (3-1) Bayliss et al., 2006). In FEH methods catchments are categorised according the urban extent for the period of interest (Table 3.2). This key descriptor will be used in Chapter 4 to compare catchments hydrological response and to assess if response follows a gradient of urbanisation using a suite of statistical tools. Chapters 5 and 6 test the performance of *URBEXT* for explaining storm runoff compared to landscape metrics derived.

$$URBEXT = Urban + 0.5\,Suburban \hspace{2cm} \textbf{(3-1)}$$

Table 3.2: Categories of catchment urbanisation used in FEH (Bayliss et al., 2006)

Category	$URBEXT_{2000}$
Essentially rural	$0.00 \leq URBEXT_{2000} < 0.03$
Slightly urbanised	$0.03 \leq URBEXT_{2000} < 0.06$
Moderately urbanised	$0.06 \leq URBEXT_{2000} < 0.15$
Heavily urbanised	$0.15 \leq URBEXT_{2000} < 0.30$
Very heavily urbanised	$0.30 \leq URBEXT_{2000} < 0.60$
Extremely heavily urbanised	$0.60 \leq URBEXT_{2000} < 1.00$

3.3.2 Landscape metrics

Landscape metrics are automatically derived from suitable geo-spatial land cover data using a software package that converts the spatial data into a range of selected landscape metrics. The software package FRAGSTATS (McGarigal and Marks, 1994) is employed in this thesis to derive a suite of landscape metrics using the gridded land-cover data. The methods and data used, including a full list of landscape metrics used, are covered in Chapter 5.

3.4 References

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4 – URBANISATION IMPACTS ON STORM RUNOFF ALONG A RURAL-URBAN GRADIENT

This chapter addresses Objective 1 of the thesis, namely: to assess urbanisation impacts on storm runoff along a rural-urban gradient and determine the suitability of characterising urbanisation effects on storm runoff using the lumped catchment descriptor urban extent and the contributing role of soil moisture

A version of the material presented here has been published in 2017 in the Journal of Hydrology.

Miller JD and Hess T (2017) Urbanisation impacts on storm runoff along a rural-urban gradient. *Journal of Hydrology* 552: 474–489. Available from: http://dx.doi.org/10.1016/j.jhydrol.2017.06.025

4.1 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 & Boorman, 1993) and volume (Kjeldsen et al., 2013), reduction in baseflows (Simmons & 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 & 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., 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 & 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.

4.2 Study sites and experimental design

The Thames basin in southern England (Figure 4.1) 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 (Figure 4.1; Table 4.1). The selection of catchments was based upon sampling across a range of variously urbanised catchments to provide rainfall-runoff event data along a rural-urban gradient. Sites were chosen that met this key design criteria along with suitability for access, and importantly, suitability for measuring the environmental variable.

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Table 4.1: 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.
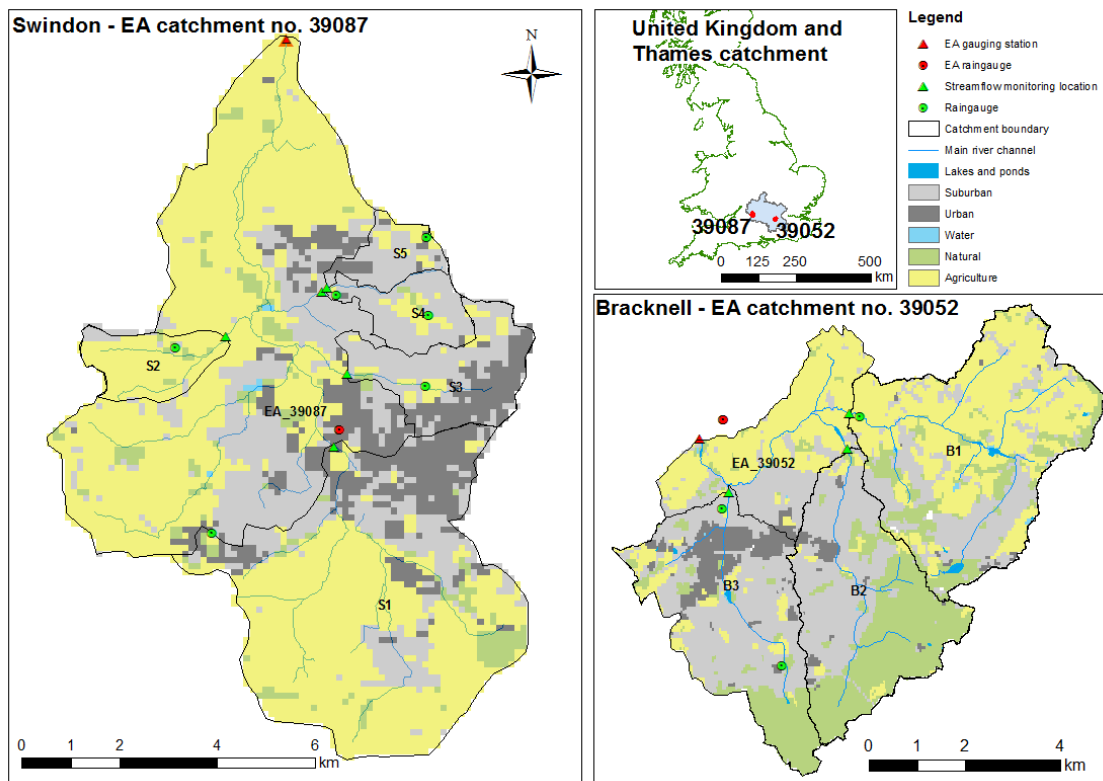
Figure 4.1: EA catchments at Swindon and Bracknell, showing study catchments, monitoring locations and land cover. Inset shows EA catchment locations within Thames basin and the United Kingdom.

4.3 Data and methods

This section provides an overview of the hydro-metrological monitoring and data and processing used to extract storm events and quantify storm response. Detail is provided in Chapter 3.

4.3.1 Hydro-meteorological urban monitoring networks

Precipitation was monitored at 8 locations (shown as Raingauge in Figure 4.1) at a 15 min resolution with tipping bucket rain gauges (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 rain gauges located within the

catchment at Swindon (R249744) and close to the catchment boundary at Bracknell (R274918), were provided by the EA (shown as EA rain gauge in Figure 4.1). 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 rain gauge 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 & Hashino, 2000), was found suitable for Swindon due to the distribution of monitoring rain gauges 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 Figure 4.1) 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-gauging 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: Figure 4.1) were provided by the EA.

4.3.2 Hydrological response along a rural-urban gradient

4.3.2.1 Catchment characterization

Catchment descriptors (Table 4.2) 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: Appendix A*), they are all valuesgreater than 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.(4-1) 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, such as rural developed areas and peri-urban developments, while "Urban" areas contain near continuous development with few green spaces, such as dense residential urban or commercial and industrial areas (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 (S2: Table 4.2) to 0.60 for a well-developed town centre study catchment containing mixed urban land cover (S3: Table 4.2).

$$URBEXT = Urban + 0.5\,Suburban \qquad \textbf{(4-1)}$$

4.3.2.2 **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 4.2) using a set of pre-defined criteria applied in sequence (Table 4.3). Hydrograph separation, event window definitions and time-based metric definitions are shown in Figure 4.2. 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.

	EA_39052	B1	B2	B3	EA_39087	S1	S2	S3	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 hour rainfall (mm)	12.6	12.6	12.7	12.6	9.6	9.6	9.7	9.4	9.6	9.6
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 4.2: Catchment flow data records and FEH catchment descriptors (* HOST refers to the Hydrology Of Soil Type classification used in the UK (Boorman, Hollis and Lilly, 1995), ** indicates derived values; catchment descriptor equations in Appendix A)

Table 4.3: Event selection criteria (Illustrated in Figure 4.2)

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

Figure 4.2: Hydrograph separation with event instants used to select independent events and time instants used to derive time-based metrics of storm events

4.3.2.3 **Metrics of hydrological response**

A number of hydrological response metrics were identified to be important in quantifying storm runoff in urban catchments. Correlation analysis between potential metrics was undertaken in R using the Pearson correlation parametric test to select independent metrics for quantifying rainfall-runoff response. Following correlation analysis seven, independent, volume- and time-based hydrograph metrics were selected (Table 4.4). 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.

Table 4.4: Selected volume- and time-based hydrograph metrics used to quantifying storm runoff

Hydrograph metric	Description	Reference application
Volume-based		
Q_{max} (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		
TP (h)	Time to peak flow from start of storm runoff	Gallo et al. (2013); IH (1999)
Ө (h)	Flood duration of event hydrograph corresponding to $Q/Q_{max} = 0.5$ 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)

Peak flow (Q_{max}) 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 (*TP*), also known as time-of-rise, indicates catchment responsiveness on the rising limb of the observed hydrograph (Mcdonnell et al., 1990). Flood duration (Ө) 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) (Figure 4.2). As study catchments varied by both area and to a lesser degree slope (Table 4.1) 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 as both catchment length and slope play a contributing role. 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 the unit hydrograph scaling parameter parameter T_P, being the time-to-peak measurement in the ReFH unit hydrograph model:

$$\theta = 2.99\, T_P{}^{0.77} \tag{4-2}$$

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

$$T_P = PROPWET^{-1.09}DPLBAR^{0.6}(1 + URBEXT)^{-3.34}DPSBAR^{-0.28} \tag{4-3}$$

While T_P is the unit hydrograph time-to-peak it is sufficiently similar in context for considering how to scale the observed hydrograph time-to-peak TP and flood duration θ. The descriptor $PROPWET$ does not differ significantly between catchments and $URBEXT$ is used to define the urban gradient, leaving the remaining parameters $DPLBAR$ and $DPSBAR$ to scale TP and θ for each catchment so that standardised values (T_{PS} and θ_s) are available for direct comparison:

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

$$\theta_S = \frac{\Theta}{DPLBAR^{0.60} \; DPSBAR^{-0.28}} \qquad \text{(4-5)}$$

Catchment lag-time is related to the ratio L/√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. Scaled T_{LC} and T_{LPP} are thus standardised to T_{LCS} and T_{LPPS}:

$$T_{LCS=}\frac{T_{LC}}{L/\sqrt{S}} \qquad \text{(4-6)}$$

$$T_{LPPS=}\frac{T_{LPP}}{L/\sqrt{S}} \qquad \text{(4-7)}$$

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 in data normality. 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 at improving data normality. 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 soil moisture deficit 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.

4.3.2.4 **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 water required for a soil to reach field capacity and provides an indication of antecedent soil moisture, shown to affect high flow generation (Michele & 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 & 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 4.2). 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.

4.4 Results

4.4.1 Hydrological response along a rural-urban gradient

4.4.1.1 Hydrological summary

Rainfall data obtained from the met stations over this period highlight two important periods (Figure 4.3). 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, Hannaford & Parry, 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 from gauging stations 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 (Figure 4.3) during summer 2014 due to a recording malfunction.
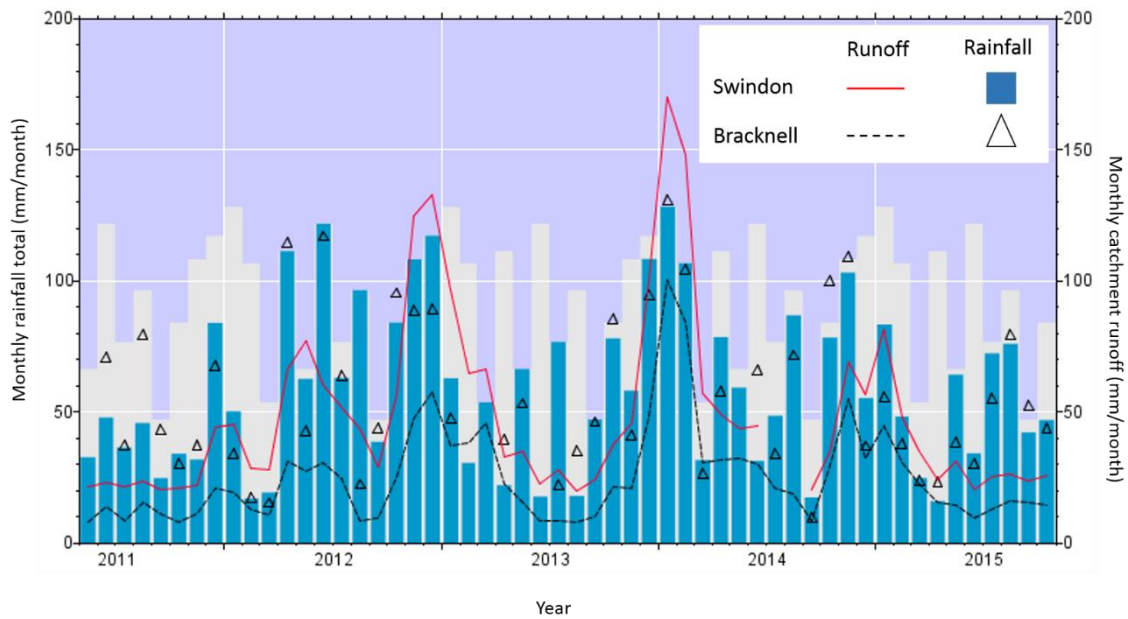
Figure 4.3: Monthly rainfall (bars) and flow (lines) for Environment Agency rainfall and gauging stations at Swindon (39087) and Bracknell (39052). The blue upper envelope marks the long-term maximum monthly rainfall for Swindon.

4.4.1.2 Selected events

Figure 4.4 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 ($URBEXT \leq$ 0.26) exhibit more winter than summer events compared to the study catchments with higher urbanisation levels where summer events are dominant.
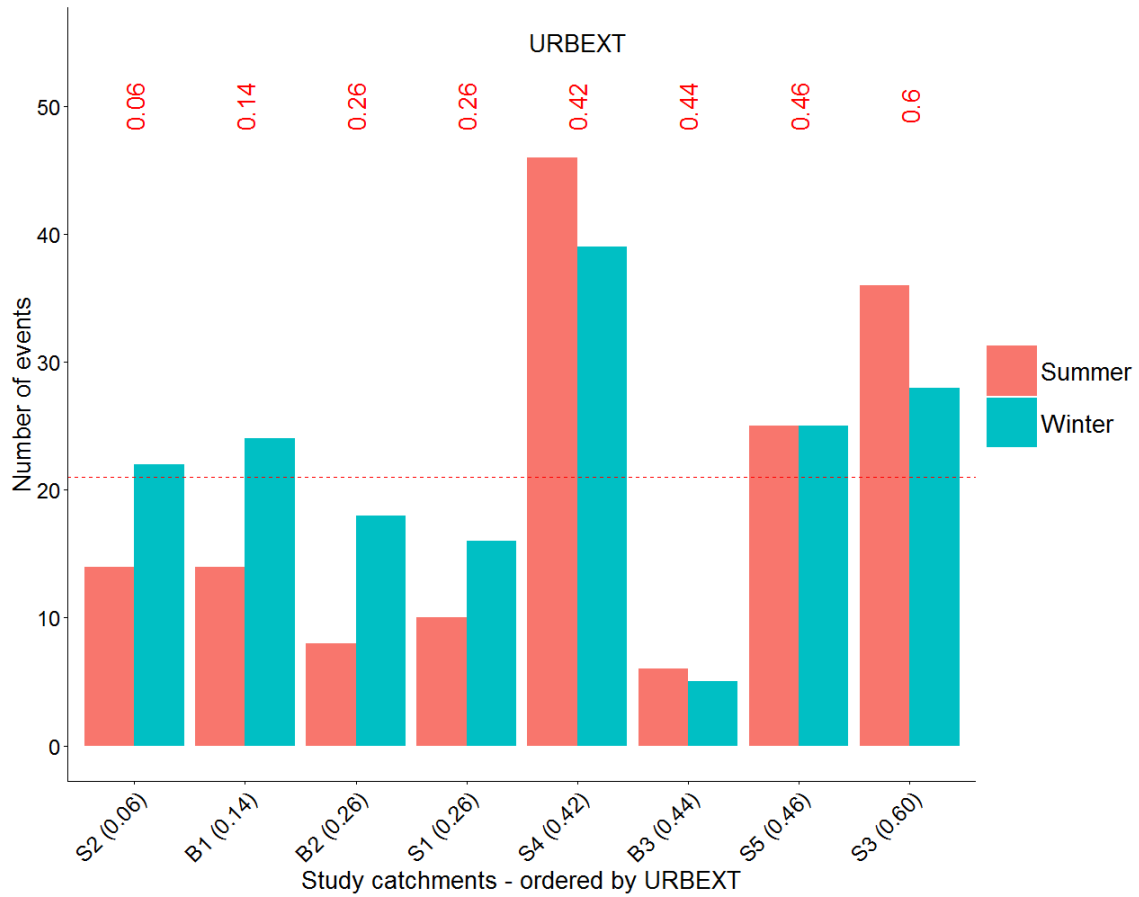
Figure 4.4: Histogram of storm events by site and season (summer defined as April to September) for each sub-catchment with mean frequency of all study catchments indicated by dashed red line.

4.4.1.3 **Standardising time-based metrics**

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 Figure 4.5. Figure 4.5 illustrates the relationship between the derived values for the four time-based metrics against the standard catchment descriptor values for area (a) and slope (b) for the eight catchments. It also illustrates the effect of applying the scaling equations (Eqs 4-4 – 4-7) to remove the effects of area (a$_S$) and slope (b$_S$).

Prior to scaling, the clear relationship between *AREA* and time–based metrics is evident (Figure 4.5a), with the relationship being both positive and significant ($p < 0.05$). Following scaling (Figure 4.5a$_S$) 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 ($p < 0.05$) (Figure 4.5a) however the relationship is negative. Scaling (Figure 4.5b$_S$) 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.
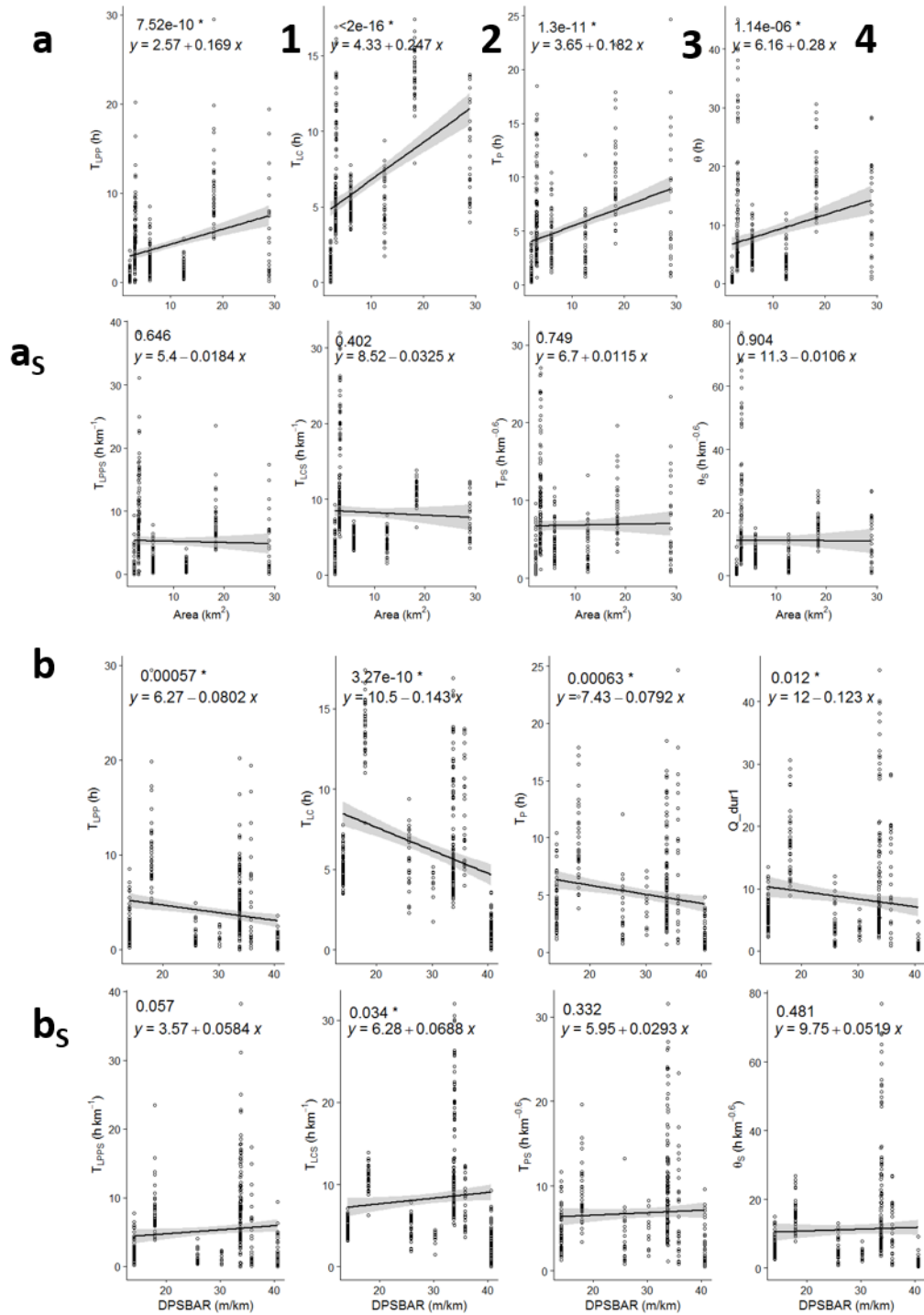
Figure 4.5: Time-based hydrograph metrics (T_{LPP} (1), T_{LC} (2), TP (3), Θ (4)) against *AREA (a)* and *DPSBAR (b)* before (a, b) and after (a_S, b_S) scaling (eqs. 4.4 – 4.7). Data are fitted with a linear model fitted with significance (p) of fitted model slope (* denotes $p < 0.05$) and model equation reported. Grey shading shows the 95% confidence interval.

4.4.1.4 **Analysis of storm hydrographs along rural-urban gradient**

The variability in response among study catchments along the rural-urban gradient is illustrated in Figure 4.6, 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 (S2, B1), and while it generally drops with increasing urbanisation, there is clear inter-catchment variability This is evinced in the differences between the highly urban S5, with zero baseflow outside events, and S3, where baseflow is considerable and prolonged in flow recession.

- Variability in hydrograph shape across the selected events (grey) compared to the mean (red) is indicative of seasonal and soil moisture influences. This generally decreases with urbanisation, excepting the most urban catchment S3 that has high variability, and is at a minimum in the storm drain dominated catchments (B3, S5).

- The mean hydrograph peak is significantly lower than the largest event, particularly in the more rural catchments (S2, B1: *URBEXT* ≤ 0.14).

- For study catchments with *URBEXT* ≥ 0.26 the hydrograph becomes peakier in shape (flashier – and indicative of urbanisation impacts) but there is clear inter-catchment variability that does not follow the urban gradient. This is evident in the two of the urban catchments (S4, S3) being less flashy than catchments with less urbanisation (B2, S5).

While the hydrographs in Figure 4.6 demonstrate some of the generalised observations that are applied to urban catchments reported in the literature such as increased urbanisation leading to an increase in runoff and reduction in response time, they also indicate that there are inter-catchment differences that do not fit such generalizations. Table 4.5 and Figure 4.7 and Figure 4.8 outline statistical analyses of how the metrics vary along the urban gradient of catchments studied, using ANNOVA and Tukeys HSD (4.2.2.3) to identify

significant differences in the geometric means between study catchments and along the urban gradient utilised.
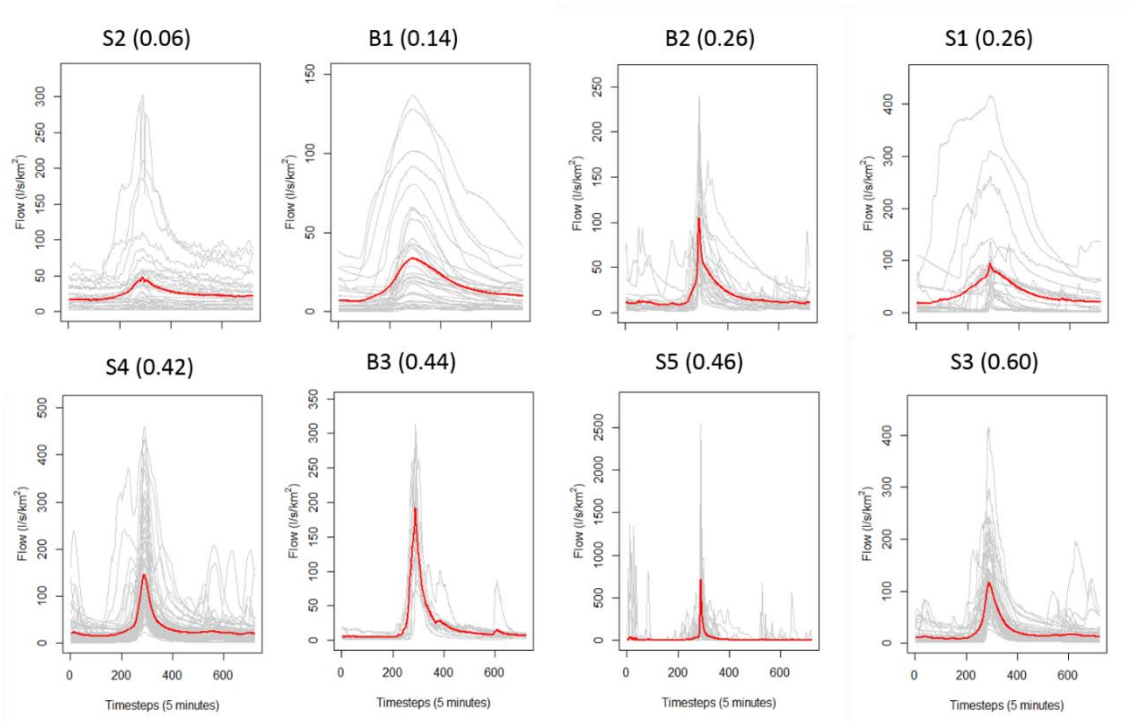
Figure 4.6: Comparison of area weighted event hydrographs (grey) and mean hydrograph (red) among study catchments (Table 4.1, Figure 4.1) with catchment *URBEXT* in brackets (ordered top left to bottom right by *URBEXT*)

An analysis of the volume-based metrics (Figure 4.7) 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 4.5), 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 significant difference observed is a higher Q_{max} at S5.

The time-based metrics (Figure 4.8) 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 ($URBEXT \geq 0.26$). 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 4.5) 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 from the expected diminution in response time with increasing urbanisation. These could be hydraulic features that act to either speed up conveyance of flow, related to the spatial layout of land cover, or affected by groundwater interactions. 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.

Table 4.5: 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]
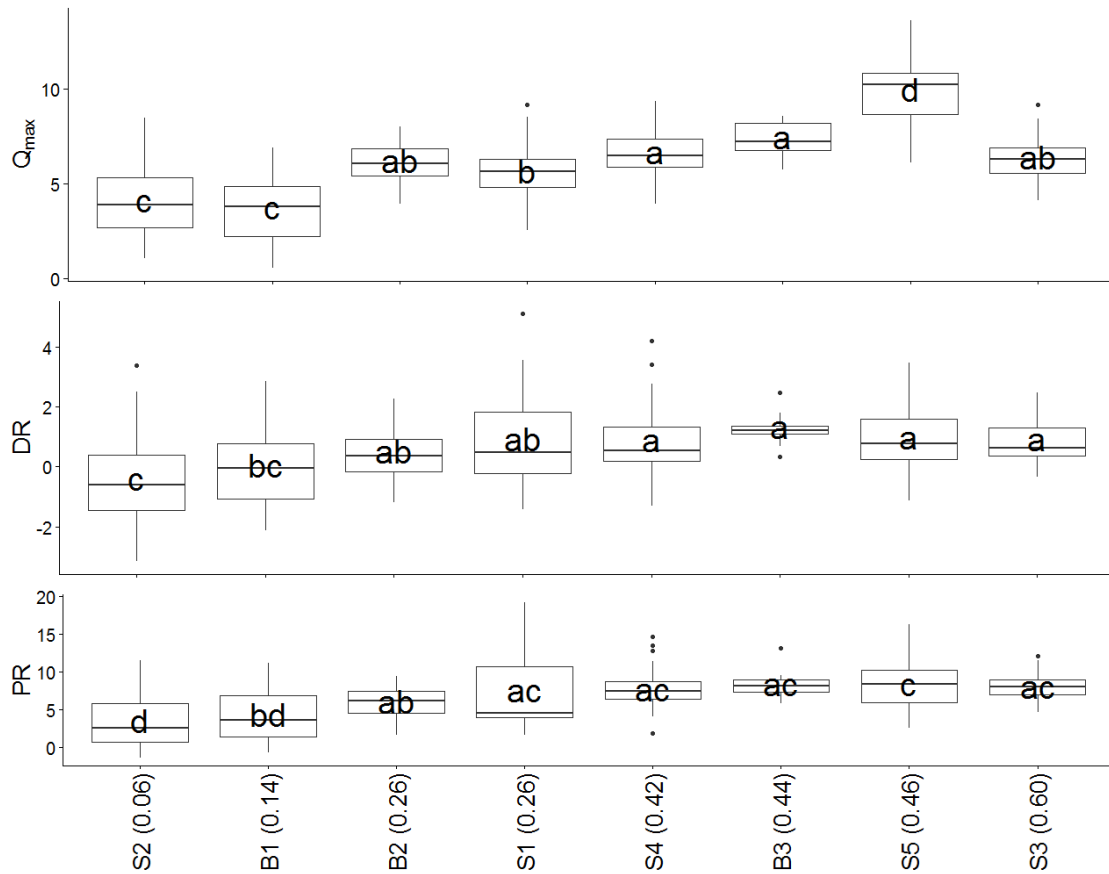
Figure 4.7: Boxplots of scaled and normalised peak flow (Q$_{max}$), storm runoff (DR), and percentage runoff (PR) across the study catchments – *URBEXT* in brackets. Box-plots sharing the same letter have means that are not significantly different.
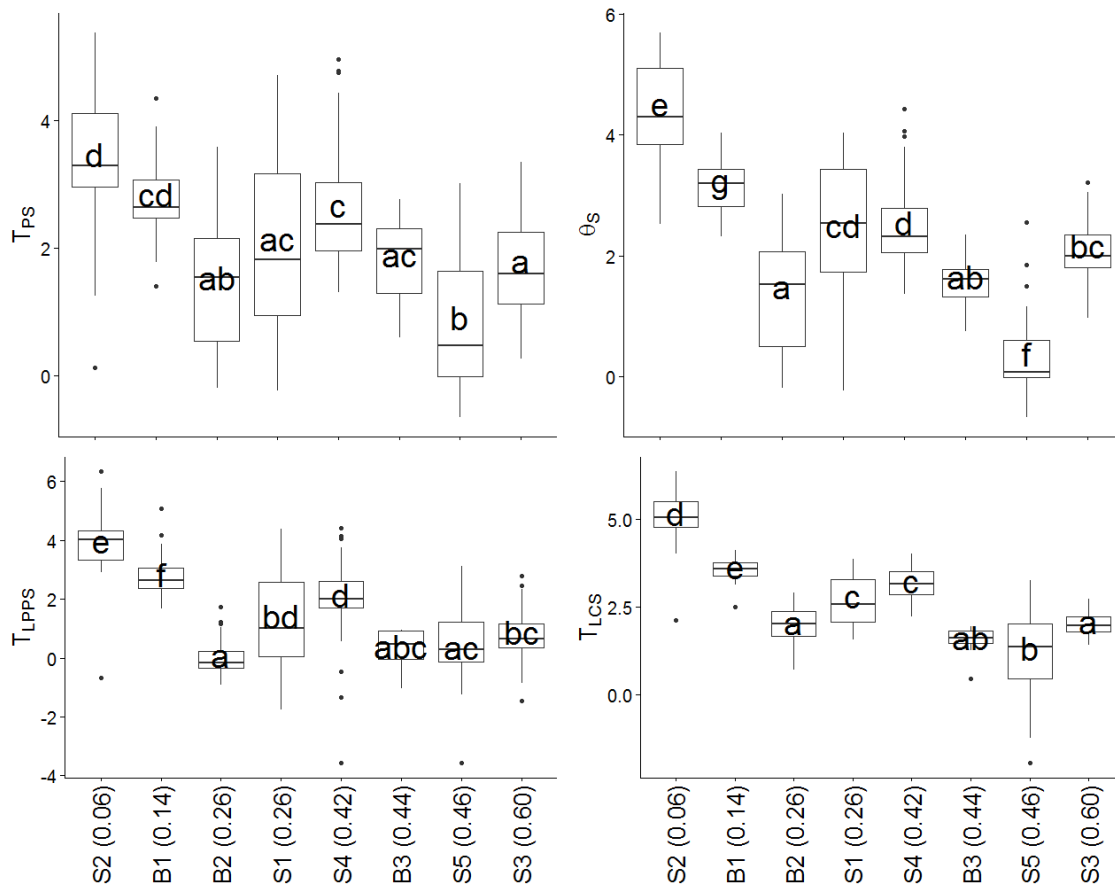
Figure 4.8: Box-plots of scaled and normalised time-to-peak (T_{PS}), flood duration (Θ_S), time lag-to-peak (T_{LPPS}), and time lag-to-centroid (T_{LCS}) across study catchments – *URBEXT* in brackets. Box-plots sharing the same letter have means that are not significantly different.

4.4.2 Objective 2: Role of antecedent soil moisture

A *SMD* value from the interpolated MORECS data 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 where flows were expected to be influenced by SMD (S2, B1: Figure 4.9). The value is close to the 6 mm *SMD* value used in the UK flood estimation methods to distinguish between a wet and dry catchment (Bayliss, 1999).
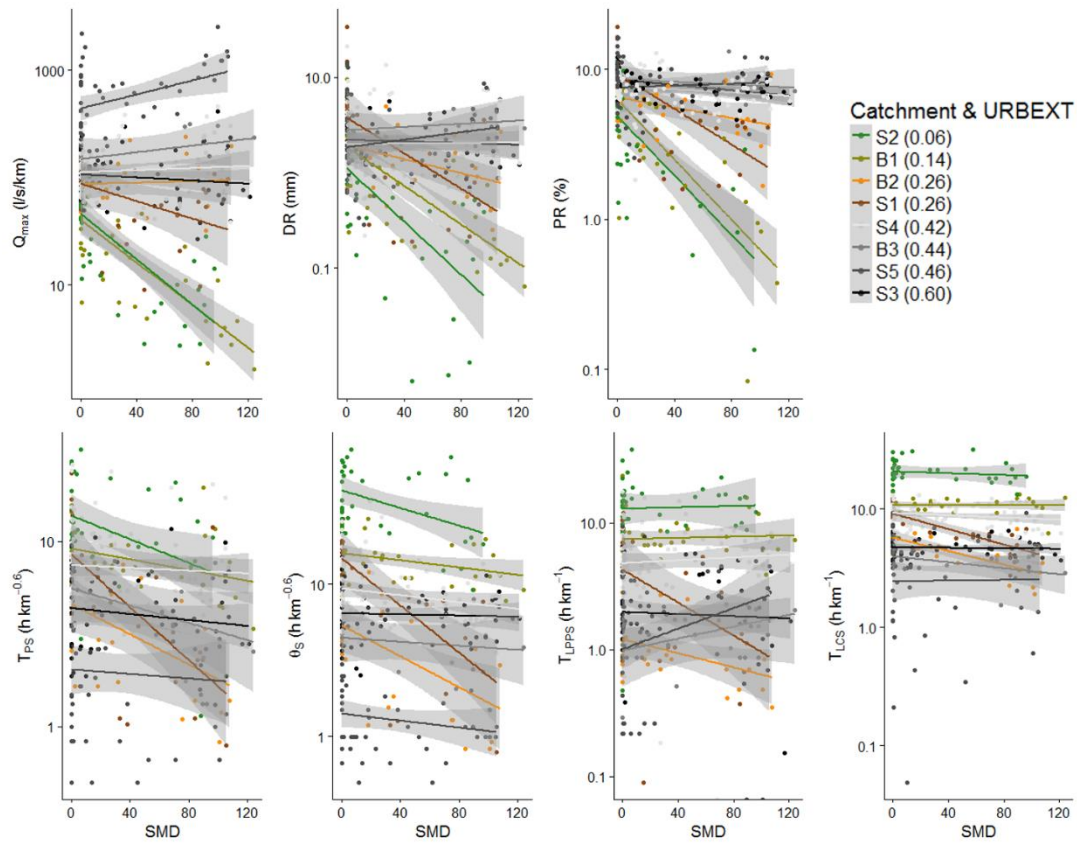
Figure 4.9: Change in metrics (Table 4) with *SMD* by catchment with linear fit and 95% confidence intervals shown in grey. (Y axis is log scale)

Plots of antecedent soil moisture deficit from MORECS data versus each of the metrics (Figure 4.9) 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.

The time-based metrics reveal less significant and less consistent changes along the urban gradient, compared to the volume-based metrics (Figure 4.9) reflecting

the increased variability observed in Figure 4.8. 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.

Table 4.6 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 4.8. 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 4.8. 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 (Figure 4.8) and clear effects upon volume-based metrics (Table 4.5) no significant difference has been shown in the response time of the least urban S2 and B1 under drier conditions for any metric (Table 4.6). 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.

Table 4.6: Mean metric values for each study site under wet and dry conditions. Values sharing the same superscript letter are not significantly different, while values with an asterisk 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	0.6	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^{abc}	152^{ab}	149^{a}	154^{ab}	667^{d}	118^{ab}	$10^{c}*$	$14^{c}*$	107^{ab}	46^{b}	136^{a}	224^{a}	764^{d}	116^{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} ($h\ km^{-0.6}$)	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}
$Θ_{S}$ ($h\ km^{-0.6}$)	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} ($h\ km^{-1}$)	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} ($h\ km^{-1}$)	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}

4.5 Discussion

4.5.1 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 & Shuster, 2009; Zhang & 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 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 & 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 & 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 due in part to the significant alterations in drainage that take place during the initial stages of urban development and general pattern of urban development starting in lower catchment areas surrounding the flat floodplain.

There is however little similar evidence to support the lack of variability in more heavily modified catchments.

The data is perhaps also suggestive of a threshold of urbanisation level, as quantified by URBEXT, 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 as both have been shown to affect the timing and quantity of runoff generated in urbanised catchments (Shuster et al., 2005; Graf, 1977). Other contributory factors include observations that impacts of urban land cover vary with rainfall magnitude (Gallo et al., 2013) 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. These include artificial drainage and related stormwater infrastructure (Braud et al., 2013), water treatment facilities (Schwartz & Smith, 2018), and water transfer (McGrane et al., 2016).

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).

4.5.2 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 or 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 4.1). 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 & Gnecco, 2015) and their value in terms of ecosystem services (Duku et al. 2015).

4.5.3 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 & 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, Wilson and Gulliver, 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 & 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 Table 4.2; Urban = 16%: Table 4.1) 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 4.1). 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 & 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 4.1). More likely, given its size and location, is that flows are attenuated by a large area of natural green space (Figure 4.1) 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.

4.5.4 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 (Figure 4.1).

Further research could focus on spatial variability of rainfall and storm type relationships with observed response.

- For the more urban study catchments ($URBEXT \geq 0.42$) there was a bias towards more summer events (Figure 4.2), 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 & Bledsoe, 2011) or cold climates (Sillanpää & Koivusalo, 2015).

4.6 Conclusion

This study used high-resolution rainfall-runoff data from eight small catchments at varying levels of urbanisation along a rural-urban gradient, in order to determine if the measure of urbanisation *URBEXT* can explain variability in catchment response to storm events. Further, it assessed whether antecedent soil moisture modifies the relationship between urbanisation and storm runoff. The results suggest that postulated 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 ($URBEXT \geq 0.42$), 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 that storm runoff in small urbanised catchments is not controlled solely by the level or extent of urbanisation or by

antecedent soil moisture and that other contributing factors are causing the observed variability in timing of runoff along the rural-urban gradient. This suggests 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 hydraulic and spatial controls are affecting storm runoff.

4.7 References

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5 – LANDSCAPE METRICS AND FLOOD ESTIMATION

This chapter addresses Objective 2 of the thesis, namely: to evaluate the potential for using hydrologically relevant urban catchment descriptors and landscape metrics for estimating the index flood in small urbanised catchments

A version of the material presented here has been published in 2018 in the journal *Landscape and Urban Planning*. Appendices from the published paper are contained in Appendix C of this thesis.

Miller JD and Brewer T (2018) Refining flood estimation in urbanized catchments using landscape metrics. *Landscape and Urban Planning* 175(September 2017): 34–49. Available from: https://doi.org/10.1016/j.landurbplan.2018.02.003

5.1 Introduction

The process of urbanisation entails a progressive loss of agriculture and natural habitat, converting pervious soil surfaces and natural drainage into impervious surfaces serviced by artificial drainage. These changes have a particular effect upon the storm runoff response of catchments, whereby impervious surfaces act to reduce soil infiltration and increase surface runoff (Jacobson, 2011), and artificial drainage speeds up the conveyance of runoff and the connectivity of urban surfaces to drainage channels (Shuster et al., 2005). This can increase the risk of flooding through higher peak flows (Hawley & Bledsoe, 2011) greater volumes (Packman, 1980) and more frequent flooding (Braud et al., 2013).

In order to quantify the impacts of urbanisation on the environment some form of classification or quantification of the urban fabric is required, for example, both the UK Countryside Survey (http://www.countrysidesurvey.org.uk/) and UK Flood Estimation Handbook (FEH) methods (Institute of Hydrology, 1999) rely upon a temporal range of UK wide Land Cover Mapping (LCM) products (Morton et al., 2011). Hydrological quantification of the urban environment can be derived from land use classes with variations based on density, for example, low-high density residential (Gallo et al., 2013) or using classes to derive an index of urbanization,

for example, the catchment index of urban extent (*URBEXT*: Bayliss et al., 2006). These both provide an index of catchment imperviousness, or total impervious area (TIA), which is increasingly being directly measured using remotely sensed data to faciliate an enhanced representation of the urban environment (Weng, 2012), often for use in high-resolution hydrological modelling (Salvadore et al., 2015). Combining remote sensing imagery with other spatial data has proven particularly effective at determining how connected urban surfaces are to storm drainage, producing indicators such as directly connected impervious area (DCIA) (Roy & Shuster, 2009) or effective impervious area (EIA) (Janke, Gulliver and Wilson, 2011). However such detail is not always required at catchment scales (>0.25 ha) where TIA is sufficiently accurate for estimating DCIA across multiple developed parcels in certain applications (Roy & Shuster, 2009) and *URBEXT* can be a direct index of imperviousness (Miller & Grebby, 2014). At national scales class based mapping remains more readily available and routinely used, particularly as it can offer historical picture of change. Progress is however being made across the globe in national mapping of imperviousness and temporal change, from Europe (EEA, 2016) to India (Wang et al., 2017) and USA (US Geological Survey, 2013).

For national methods of flood estimation at ungauged sites, there remains in many countries a reliance on the simplicity of empirical formulae relating the index flood to catchment characteristics (Bocchiloa et al., 2003) that include land class data to inform upon levels of imperviousness for more urbanized locations (Formetta et al., 2017). National agencies across Europe continue to employ such methods (Castellarin et al., 2012), based on regressions of index flood data to catchment characteristics in gauged basins. When considering more urbanized catchments, research has additionally highlighted the need to consider connectivity and location relative to the catchment outlet and scale considered (Kjeldsen et al., 2013; Miller et al., 2014; Sillanpää & Koivusalo, 2015). For example, in the UK, where such descriptors are routinely used to estimate the median annual flood (*QMED*), both Vesuviano et al (2016) and Faulkner et al. (2012) find that existing descriptors and equations perform with less certainty in

small urbanized catchments compared to rural catchments. Further, Miller and Hess (2017) find a non-distributed measure such as imperviousness does not mirror the variation in peak flows between urban catchments potentially driven by spatial layout. Thus, while imperviousness is important, class data remain employed for its estimation, and as Mejía & Moglen (2009) show, it is equally important to consider the spatial distribution of impervious land cover, as this can have consequences for the resulting flood peaks.

Spatial or landscape metrics are a tool for quantifying structure and pattern in thematic data, and have been highlighted by Herold et al. (2005) and Ogden et al. (2011) as valuable for improving representations of urban hydrological dynamics. The use of landscape metrics in hydrology has however been limited, despite showing promise in predicting urban land-use change impacts through representation of form and function (Lin et al., 2007; Van de Voorde et al., 2016). Comparatively, urban ecological research, which has long been using ecological typologies to study ecosystem dynamics (Brady et al., 1979), has evolved into many detailed landscape metrics of landscape structure in dedicated spatial statistical software (Kupfer, 2012) with diverse applications (e.g. Alberti, 2005; Jiao, 2015; Muhs et al., 2016). Within ecological landscape metrics, distance is often considered as Euclidean and thus is not calculated according to a hydrological network. The importance of hydrological distance to catchment outlet is demonstrated by Van Nieuwenhuyse et al. (2011), yet while aggregation based landscapes metrics have been tested for hydrological applications, and shown to be effective at providing an estimate for connectivity (Yang et al., 2011), there have been few efforts to consider hydrological distance. Wan Jaafar and Han (2012) have shown the potential for improving *QMED* using more hydrologically relevant descriptors to be derived from catchment form and information on land cover.

Local scale hydraulic features are increasingly being installed within the urban environment to control runoff, such as sustainable urban drainage systems (SuDS) (Woods Ballard et al., 2015). Studies suggest features such as green roofs (Vesuviano et al., 2014), offline storage (Wilkinson et al., 2010) and plot-

scale bio-retention features (Hood et al., 2007) reduce and attenuate runoff, but such features are not routinely mapped. Additionally, attenuation of runoff as baseflow (Rivett et al., 2011) can be altered by soil management (Holman et al., 2011) and evidence suggests that soils in urban areas can be so degraded through compaction and decreased hydraulic conductivity (Chen et al., 2014) that infiltration potential approaches that of impervious surfaces (Gregory et al., 2006) and increases runoff (Yang & Zhang, 2011). There are, however, currently no distinctions made in Land Cover Map (LCM) grassland classes between such surfaces (Morton et al., 2011). Conversely there is evidence that improving soil condition will improve infiltration (Chen et al., 2014) and better management of the urban landscape can provide green infrastructure (GI) and ecosystem services (Tratalos et al., 2007) that reduce runoff volumes (Shuster et al., 2014). Infiltration and local storage is also much improved in areas of preserved or managed nature and woodland (Nisbet & Thomas, 2006). Again, given the potential role of SuDS and GI for flood attenuation, there is surprisingly little attention paid to mapping such land-use and testing its effect on urban runoff. There is however a growing body of research mapping GI, based on using remote sensing data (Liquete et al., 2015; Vatseva et al., 2016) and developing a comprehensive classification of GI (Koc et al., 2017). Given these recent advances, and recent GI interest in both the UK (Kelly, 2016; POST, 2016) and internationally (Jarden et al., 2015), the lack of consideration regarding the functionality of SuDS and green space as GI, is clearly an area that should be expanded upon (Gill et al., 2007).

This study aims to use high-resolution spatial data alongside refined urban land cover classes from a UK case study to derive spatial landscape metrics and assess the potential application of landscape metrics for estimating the index flood in urbanized catchments. For this, three objectives are set: i) develop a set of hydrologically relevant urban land-use classes that can be mapped using readily available geo-spatial information, ii) derive enhanced urbanized catchment descriptors and identify suitable landscape metrics for use in flood estimation within the United Kingdom, and iii) test the performance of updated

catchment descriptors and landscape metrics for estimating *QMED* for selected study catchments compared with existing flood estimation methods. This will inform the potential for developing a wider method using spatial metrics and remote sensing data in attribution and modelling of floods.

5.2 Method

5.2.1 Study area

The selected catchments are located within and surrounding the urbanized towns of Swindon and Bracknell and include two national river flow gauging stations used by the UK Environment Agency (EA) (National River Flow Archive stations 39052 and 39087) (Figure 5.1). All catchments are tributaries within the Thames basin and have a similar climate, with the Standard Annual Average Rainfall (SAAR) of between 676 mm and 712 mm. Thames basin soils and geology are highly variable, but the selected catchments are generally similar, with shallow clay or loam soils, with neither dominated by groundwater inputs from Jurassic limestones. The similarity in soil hydrology, low slope, and overall topography was a basis for catchment selection (Miller & Hess, 2017). Alongside the two EA gauged catchments (herein labelled EA_39052 and EA_39087), data from a hydro-meteorological monitoring network spanning 16 variable urban catchments, of record length between 2 and 5 years between 2011 and 2016 (Miller et al., 2014; McGrane et al., 2016; Putro et al., 2016) were additionally used (Figure 5.1). These employed ultrasonic streamflow gauging technologies to monitor streamflow at high resolution and capture stormflow events and peak flows. These delineate a range of catchment types from rural to highly urbanized and contain a diversity of land cover and hydraulic infrastructure that influence the hydrological response (Miller & Hess, 2017).
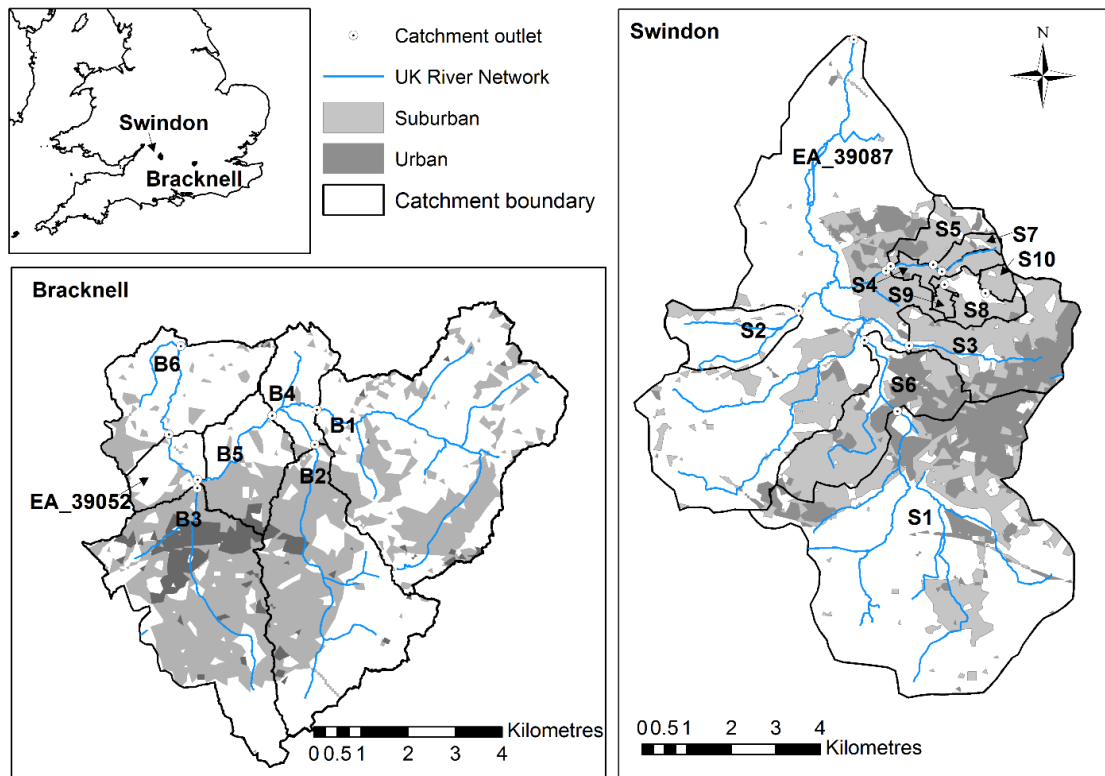
Figure 5.1: Study locations identifying Environment Agency (EA) gauging stations and selected sub-catchments for Bracknell (B) and Swindon (S), and showing Urban and Suburban extent: labels denote study catchments names (note some catchments are nested)

Swindon has grown from a small 19th century industrial town into an area of mixed urbanized and peri-urban development and commerce with a population now exceeding 215,000 (2015). Bracknell was previously a small village but after being designated a new town in 1949 has grown rapidly to a population of 120,000 (2015). Bracknell was designed with consideration of water management, utilizing a number of flood storage tanks and ponds within urbanized areas to attenuate floods and store sediment (Packman & Hewitt, 1998). Swindon has less flood storage infrastructure, but with increased development in recent years has had to adapt to increased flooding in certain dense areas of housing through flood protection measures.

5.2.2 Reclassification of land cover classes

The standard LCM groups of 50m gridded land cover classes used for flood estimation applications (EA, 2017) in urbanized areas of the UK (Table_APX C-1) were refined into more hydrologically relevant classes using a number of nationally available ancillary datasets (Table 5.1) illustrated in Figure 5.2. In order to identify key areas of 'natural' surfaces that might exist within the urban area and its fringes, relevant Natural England datasets were merged to provide a single dataset on natural areas.

Table 5.1: Source geo-spatial data and derived geo-spatial data

Dataset	Data type	Description
OS Master Map Topography Layer	Polygon	OS MasterMap Topography Layer is a large-scale digital database of detailed surface features in the landscape of Great Britain. (www.ordnancesurvey.co.uk)
Land Cover Map (LCM) (2015)	Raster (50m)	LCM is a national mapping product derived from satellite images and digital cartography and gives land cover information for the entire UK. LCM used in this study is an updated version of the most recent national dataset LCM 2007 (Morton et al., 2011)
Natural Areas	Polygon	Mapping of Local Nature Reserves, Country Parks, and Woodpasture and Parkland sites – from Natural England. (http://magic.defra.gov.uk/)
SuDS Infiltration Map	Polygon	Mapping of SuDS potential – based on derived substrate infiltration properties. (Dearden, 2016)
Urban/Suburban Land Use Change (1960 – 2010)	Raster (50m) aggregated from 1m raster	Mapping of Urban and Suburban LCM classes using historical topographical mapping (1960 – 2010) published by Ordnance Survey. (Miller & Grebby, 2014)
NEXTMap Digital Elevation Model (DEM)	10m DEM	Used to determine surface-water catchment boundaries and flow pathways/accumulation.

Figure 5.2: Refined urban land cover classes (scale 1:800): LD = Low Density, MD = Medium density, HD = High Density, URB = Urban, NAT = Natural.

Reclassification of LCM classes, outlined in Table 5.2 and illustrated in Figure 5.2, was based on a hydrological perspective and consideration of features across the study areas that could significantly alter the rainfall-runoff response of catchments. The justification for the reclassifications and the additional SuDS sub-class, along with method used to map each typology, are outlined here and the methods detailed in Tables APX C-2 to APX C-6:

Urban: Urban was not reclassified – agreeing with other studies assessing varying land use responses which have similarly used only one 'Urban' class, such as the 'commercial' class used by Gallo et al. (2013), and Van de Voorde et al. (2011) who reported classes of commercial and industrial areas had broadly similar levels of impervious cover (82% and 73%, respectively).

Suburban: Suburban has been noted as a highly generalized class for hydrological applications (Kjeldsen et al., 2013; Miller et al., 2014) and the refined classification used in this study followed a classification according to density: low, medium and high, which has been shown to be effective in other studies (Sjöman

& Gill, 2014; Gallo et al., 2013). Reclassification of *Suburban* grids was undertaken using Ordnance Survey MasterMap (OSMM) (Table_APX C-2).

Table 5.2: Refined Land Cover Mapping urban hydro-typologies. Suburban sub-classes were based on typical development density ranges (Table_APX C-2) for 9 selected training areas selected from visual analysis of aerial photography.

LCM classes	Refined typology	Sub-class (SuDS)	Description
Urban	Urban	Urban$_{SUDS}$	Town centre/ industry/commercial/office/ large infrastructure
Suburban	Suburban$_{HD}$ (High-Density)	Suburban$_{SUDS}$	High-density building (> 19% per 50 x 50m^2 grid) e.g. urban fringe and terraced
	Suburban$_{MD}$ (Medium-Density)	Suburban$_{SUDS}$	Medium density building (13% - 19% per 50 x 50m^2 grid) e.g. peri-urban housing developments
	Suburban$_{LD}$ (Low-Density)	Suburban$_{SUDS}$	Low density building (<13% per 50 x 50m^2 grid) e.g. rural and isolated developments
Woodland	Woodland		Areas of continuous woodland and shrub
Agricultural/ managed	Greenspace (Green)		Land with agricultural or managed land use not in an urban area
	Greenspace – urban (Green$_{URB}$)		Highly managed green space within urban areas (e.g. parks, recreation areas)
	Greenspace – natural (Green$_{NAT}$)		Natural/ low-management greenspaces such as nature reserves and conservation woodland
Water	Lake/Pond/Wetland		Natural water body identified on LCM and with additional water bodies from OSMM

Water: LCM areas of water were not found to cover many of the smaller and more fragmented water bodies evident in OSMM mapping in urban areas. Such features, despite their size, could play an active role in flood attenuation if receiving runoff from urban surfaces (Smith et al., 2013). The high level of water feature detail in OSMM mapping was used to develop a refined water raster and to identify any grids with a certain coverage of water features (Table_APX C-3).

Urban greenspace*:* Greenspaces in urbanized areas have been shown to be hydrologically impacted compared to grassland and agriculture (Chen et al., 2014) with explict effects evident as increases in runoff (Yang & Zhang, 2011). Existing approaches for semi-automated mapping of urban greenspace (e.g. Troy and Wilson, 2006; Gill et al., 2007; Vatseva et al., 2016) were not found to be suitable so patch size and location were utilized, whereby the size and location of the greenspace relative to urban areas were concurrently assessed (Table_APX C-4), to isolate urban greenspaces (*Green$_{URB}$*) such as recreation areas, roadside verges, and large gardens, from those larger, less altered, and more continuous areas of grassland and agriculture within or surrounding areas of development (*Green*) (Figure 5.2).

Natural Greenspace: Natural areas of vegetation, either managed or conserved, can potentially reduce runoff (Gill et al., 2007), thus reducing the index flood. Natural areas of greenspace within or surrounding urban areas were classified as areas managed to preserve natural vegetation and soils, improving soil condition and permeability, leading to an enhanced capacity for abstraction and mitigation of runoff formation processes. These were identified from Natural England ancillary datasets (Table 5.1) and subsequently merged and gridded to a 50m scale to subsequently reclassify such areas (except water) as *Natural Greenspace* (*Green$_{NAT}$*) (Table_APX C-5).

SuDS: An additional sub-class *SuDS* was applied to the *Urban* and *Suburban* classes to account for the presence of localized areas with potential sustainable urban drainage systems designed to reduce runoff and frequent flooding (Defra, 2014). The locations of SuDS were identified using a combination of geo-spatial

information on age and suitability for SuDS (Table_APX C-6). Age indicates developments designed and built after regulations required SuDS measures to be put in place (Flood and Water Management Act 2010). Sites built post 2000 were identified as having SuDS potential, here comparing all *Suburban* and *Urban* surfaces in 2010 with 2000 (Table 5.1). However, as not all sites are suitable for SuDS, due to lack of soil infiltration or issues with groundwater, the SuDS Infiltration Map (SIM: Dearden, 2016) was used to locate sites that could have SuDS in place. This map uses geological and soil data to identify areas where SuDS could be applied based on properties such as potential infiltration and groundwater risk. Sites built post 2000 where SIM indicated SuDS suitability, were subsequently re-classed as *SuDS*.

5.2.3 Identifying suitable catchment descriptors and landscape metrics

The second stage refined existing catchment descriptors using the refined land cover data, and calculated and identified a number of potentially relevant landscape metrics. In the UK, the index flood *QMED* is the flood exceeded in half of all years and forms the basis of subsequent derivation of flood estimates for rarer events, such as the 1 in 100 year flood. *QMED* can be accurately derived from hydrological observations of peak flows using the methods outlined in volume 3 of the FEH (H, 1999: Chapter 12) – herein termed *QMED$_{obs}$*. For ungauged sites, *QMED* is estimated from a number of FEH catchment descriptors (5-1) that are derived from a regression between catchment descriptors and *QMED$_{obs}$* (Kjeldsen et al., 2008) – herein termed *QMED$_{FEH}$*:

$$QMED_{FEH} = 8.3062\ AREA^{0.851}\ 0.1536^{\frac{1000}{SAAR}}\ FARL^{3.4451} 0.0460^{BFIHOST^2} \qquad \textbf{(5-1)}$$

In urban catchments, this is subsequently adjusted to account for the level of urbanization using an Urban Adjustment Factor (UAF) based on the catchment urbanisation index *URBEXT* (Table 5.3).

Table 5.3: FEH catchment descriptors used for estimating *QMED* and selected hydrologically suitable landscape metrics

	Formula	Explanation	Parameters
FEH catchment descriptors			
Area		Catchment drainage area (km^2)	A = Area of catchment
SAAR	$\dfrac{\sum_{i=1961}^{1990} P_i}{30}$	Standard-period Average Annual Rainfall (mm) rainfall for the period 1961-1990 in Great Britain and Northern Ireland	P = Precipitation (annual total)
FARL	$FARL = \prod_{i\in} \alpha_i$ where: $\alpha = \left(1 - \sqrt{r}\right)^w$ $r = \dfrac{water\ surface\ area}{subcatchment\ area}$ $w = \dfrac{subcatchment\ area}{catchment\ area}$	Index of flood attenuation from rivers and lakes. The overall *FARL* index has a value close to one when a catchment has low attenuation from water bodies, and as attenuation effects become more important the index decreases.	A = effect of individual water body r = relative size of water body to upstream catchment w = weighting reflecting importance of water body
BFIHOST	Area weighted base flow index (BFI) assigned from catchment 1km gridded dominant HOST class	Base flow index from Hydrology of Soil Types (HOST) Boorman et al. (1995)	
URBEXT	$URBEXT$ $= Urban + 0.5\ Suburban$	FEH index of fractional urban extent	*Urban* and *Suburban* are Land Cover Mapping (LCM) classes for urbanized surfaces
Class based landscape metrics			

Percentage of Landscape	$PLAND = A_C/A_T$	Equals the percentage of the landscape comprised of the corresponding patch type.	A_C = Class area A_T = Total catchment area
Perimeter-Area Ratio	$PARA = \dfrac{P_{ij}}{a_{ij}}$	*Perimeter-area ratio* is a simple measure of shape complexity, but without standardization to a simple Euclidean shape	p_{ij} = perimeter (m) of patch ij. A_{ij} = area (m²) of patch ij.
Total Edge	$TE = \displaystyle\sum_{k=1}^{m} e_{ik}$	*Total edge* at the class level is an absolute measure of total edge length of a particular patch type.	e_{ik} = total length (m) of edge in landscape involving patch type (class) i; includes landscape boundary and background segments involving patch type i.
Edge Density	$ED = \dfrac{E}{A}(10{,}000)$	*Edge density* reports edge length on a per unit area basis that facilitates comparison among landscapes of varying size	E = total length (m) of edge in the landscape. A = total landscape area (m²).
Contiguity Index	$CONTIG = \dfrac{\left[\dfrac{\sum_{r=1}^{z} c_{ijr}}{a_{ij}}\right]}{v-1}$	Assesses the spatial connectedness, or contiguity, of cells within a grid-cell patch to provide an index of patch boundary configuration and thus patch shape	c_{ijr} = contiguity value for pixel r in patch ij. V = sum of the values in a 3-by-3 cell template (13 in this case). A_{ij} = area of patch ij in terms of number of cells.
Largest Patch Index	$LPI = \dfrac{\overset{a}{\underset{j=1}{max(a_{ij})}}}{A}(100)$	*Largest patch index* at the class level quantifies the percentage of total landscape area comprised by the largest patch. As such, it is a simple measure of dominance.	A_{ij} = area (m²) of patch ij. A = total landscape area (m²).

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Clumpiness **index**	Given: $$G_i = \left(\frac{g_{ii}}{\left(\sum_{i=1}^{m} g_{ii}\right) - mine_i} \right)$$ $$CLUMPY$$ $$= \left[\frac{G_i - P_i}{P_i} \; for \; G_i < P_i \& P_i\right.$$ $$\left.< 5, e; else \; \frac{G_i - P_i}{1 - P_i}\right]$$	The proportional deviation of the proportion of like adjacencies involving the corresponding class from that expected under a spatially random distribution.	G_{ii} = number of like adjacencies (joins) between pixels of patch type (class) I based on the *double-count* method. G_{ik} = number of adjacencies (joins) between pixels of patch types (classes) I and k based on the *double-count* method. Min-e_i = minimum perimeter (in number of cell surfaces) of patch type (class) I for a maximally clumped class. P_i = proportion of the landscape occupied by patch type (class) i.
Cohesion	$$COHESION = \left[1 - \frac{\sum_{j=1}^{n} p_{ij}}{\sum_{j=1}^{n} p\,ij\sqrt{a_{ij}}}\right]\left[1 - \frac{1}{\sqrt{A}}\right]^{1} (100)$$	*Patch cohesion index* measures the physical connectedness of the corresponding patch type.	P_{ij} = perimeter of patch ij in terms of number of cell surfaces a_{ij} = area of patch ij in terms of number of cells. A = total number of cells in the landscape.

Landscape metrics

Contagion **Index**	$$CONTAG$$ $$= 1$$ $$+ \sum\sum [q_{ij}ln(q_{ij})]/2ln(2)$$	Assesses the extent to which patch types are aggregated or clumped as a percentage of the maximum possible; characterized by high dispersion and interspersion.	P_i = proportion of the landscape occupied by patch type (class) i. g_{ik} = number of adjacencies (joins) between pixels of patch types (classes) i and k based on the *double-count* method. M = number of patch types (classes) present in the landscape, including the

			landscape border if present.
Landscape **Shape** **Index**	$LSI = \dfrac{e_i}{\min e_i}$	*Landscape shape index* provides a simple measure of class aggregation or 111lumpiness and, as such, is very similar to the aggregation index.	E_i = total length of edge (or perimeter) of class i in terms of number of cell surfaces; includes all landscape boundary and background edge segments class i.
			$\min e_i$ = minimum total length of edge (or perimeter) of class i in terms of number of cell surfaces
Effective **Mesh Size**	$MESH \dfrac{\sum_{j=1}^{n} a_{ij}{}^2}{A}\left(\dfrac{1}{10000}\right)$	MESH provides a relative measure of patch structure	a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).

5.2.3.1 **Catchment descriptors**

The catchment descriptors used in the FEH statistical procedures for flood frequency estimation were refined for use in this study, being calculated using the methods (Table 5.3) outlined by Bayliss (1999) but with a higher resolution 10m DEM (Table 5.1) and the refined LCM classes (Table 5.2). Here we outline the method and improvements gained over existing FEH descriptors used in Eq. (5-1).

Catchment area – AREA: Catchment areas were calculated using 10m resolution DEM data in combination with storm drainage maps following the method of Rodriguez et al. (2013) (Table_APX C-7). The combination of DEM and drainage data is often necessary in urban environments as artificial drainage can alter catchment area from natural conditions (Braud et al., 2013). Finer scale resolution DEM data (5m) was not suitable as it captured manmade interventions in the urban landscape that significantly altered the natural elevation surface and thus drainage area, while lower resolution (50m) data did not capture small catchment areas and was not suitable for the urban scale.

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Urban extent – URBEXT: The index of urban extent provides a weighted index value for Suburban and Urban land cover (Table 5.3) to provide a proxy measurement for imperviousness within a catchment (Bayliss, 1999). This has been shown to be a robust method for estimating imperviousness from land class data at catchment scales (Miller and Grebby, 2014). With the refined *Suburban* classes (Table 5.2) the *URBEXT* calculation has been reclassified here (*URBEXT$_{rc}$*) using weightings (Eq. (5-2) that account for the variation in impervious/pervious surfaces between the new classes. Additionally, *Urban* or *Suburban* class areas re-classified as *SuDS* were not included in this revised calculation, as SuDS are designed to effectively remove the hydrological impact of impervious surfaces for all but extreme events (POST, 2007; Ballard et al., 2015; Environment Agency, 2013).

$$URBEXT_{rc} = URBAN + 0.75\,SUBURBAN_{HD} +\ 0.5\,SUBURBAN_{MD} \qquad \textbf{(5-2)}$$
$$+\ 0.25\,SUBURBAN_{LD}$$

Flood attenuation – FARL: The method used to calculate an index of attenuation from rivers and lakes – *FARL* – follows the FEH method outlined by Bayliss (1999) (Table 5.3) The basis of this method is that the storage of high flows in lakes and reservoirs will attenuate the flood hydrograph, and that large lakes with large drainage areas have a high storage potential, and can modify flood response to a greater extent than small lakes with small drainage areas. Bayliss (1999) utilized a 50 m gridded reservoir/lakes dataset developed as part of the Institute of Hydrology Digital Terrain Model (IHDTM) which was found to be broadly similar to the lakes and reservoirs mapped in the LCM data and OS 1:50,000 Landranger map series (Morris and Flavin, 1990). Here, we recalculate a refined flood attenuation index *FARL$_{rc}$* using the refined Water class detailed in 2.2 that captures much smaller local water bodies in urbanized areas. This is important due to the high number of small waterbodies and in particular the presence of many small ponds specifically installed to regulate and attenuate river flows in storm events.

Catchment slope and drainage path length – DPSBAR and DPLBAR: Mean catchment slope and mean drainage path length were calculated using the methods outlined by Bayliss (1999) (Table 5.3) but using the 10m DEM and associated flow accumulation network utilized in this study. This is more accurate in urban areas, capturing artificial drainage and associated alterations to natural pathways.

Hydrological soil type – BFIHOST: Soil hydrology type is defined by the base flow index (*BFI*) for the dominant hydrology of soil type (*HOST*) class (Boorman et al., 1995) within each catchment (*BFIHOST*).

5.2.3.2 **Landscape metrics for connectivity and location**

Landscape metrics suitable for connectivity representation were selected and calculated using the FRAGSTATS software (McGarigal and Marks, 1994). Both the class-based and landscape metrics selected are detailed in Table 5.3 along with details on the calculation method, parameters, and source.

While landscape metrics used in ecological applications have shown some effectiveness for attributing hydrological response through measuring general shape (Lin et al., 2007), other metrics using hydrological distance (flow pathway), rather than Euclidian (straight line) distance, have been shown to be more effective at representing hydrological connectivity. Van Nieuwenhuyse et al. (2011) found that landscape metrics can be particularly useful for expressing connectivity of hydrological systems, and that hydrological connectivity is determined by the spatial organisation of heterogeneity. They took the Proximity Index (PX) metric developed by Gustafson and Parker (1992) to account for Euclidean distance and connectivity and adapted this to capture the effects of both hydrological distance and connectivity of urbanized patches to the catchment outlet (Eq. (5-3)):

$$PX = \sum A_k / mdo_k \qquad \textbf{(5-3)}$$

where, A_k is the area of patch k, and mdo_k is the mean distance to the outlet of patch k, and PX is the sum of these ratios for all *Urban* and *Suburban* land use patches.

While the *PX* metric used by Van Nieuwenhuyse et al. (2011) did incorporate hydrological distance, the application was for a stochastic drainage network within a triangular conceptual catchment. Thus we have additionally normalized both patch area A_k and patch flow path length d_k by catchment area (*AREA*) and mean catchment drainage path length (*DPLBAR*), respectively, to additionally derive a normalized unit-less PX_N index (Eq. (5-4);

$$PX_N = \sum \frac{A_k/AREA}{mdo_k/DPLBAR}$$

(5-4)

In total, 30 separate landscape and class-based metrics were computed (Table_APX C-8) by using the selected metrics (Table 5.3) across the variable classes considered. This included 10 *Urban* and 10 *Suburban* class metrics, three landscape metrics, five hydrological metrics, and two *Green$_{NAT}$* class metrics. To determine which catchment descriptors and potentially suitable landscape metrics should be used in the development of a revised index flood equation (*QMED$_{rev}$*), we assessed correlations between descriptors/metrics against the observed index flood *QMED$_{obs}$* using Spearman's rank correlation coefficient (Spearman, 1904) which is a suitable nonparametric test for measuring the statistical dependence between the ranking of two variables. *QMED*$_{obs}$ was calculated for each catchment from the monitored data using the methods outlined in FEH (IH, 1999). Catchment descriptors are routinely used for deriving flood estimates for ungauged catchments based on derived relationships between peak flows and various catchment descriptors in both the UK (EA, 2012) and internationally (Feaster et al., 2014). The third stage introduced the refined descriptors and metrics into a regression model for estimating the index flood (*QMED*) for the selected catchments to assess the potential for using landscape metrics in flood estimation. Here this was done using three steps: i) identifying the best performing variables in a step-wise regression against *QMED$_{obs}$*; ii)

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deriving $QMED_{rev}$ for all sites using the regression variables, and; iii) comparing the performance of $QMED_{rev}$ and $QMED_{FEH}$ against $QMED_{obs}$ for all sites.

$QMED$ was derived for the 18 sites across both study sites using both the observation-based ($QMED_{obs}$) and catchment descriptor-based ($QMED_{FEH}$) methods for estimating $QMED$. The observation based value derives from statistical analysis of observed peak flows, while the descriptor-based estimate is taken only from catchment descriptor values. These provided the baseline estimates with which to compare the performance of the refined catchment descriptor equation ($QMED_{rev}$) that utilizes the refined descriptors and landscape metrics (Section 5.2.3). In order to identify the best performing descriptors/metrics as variables for $QMED_{rev}$ we employed the weighted least squares (WLS) approach to linear regression modelling (Ruppert & Wand, 1994). The WLS approach was the most suitable regression given that the limited number of catchments and limited quantity of annual maxima at 16 of the 18 sites precluded accounting for covariance in estimating $QMED$. The WLS approach involved iterative testing of potential variables for estimating $QMED$ and applying a weighting factor based on record length. For each iteration all metrics were compared using the following transformations: none, logarithmic, inverse (1000/x), and power (c^x) and the best performing combination of metrics was retained based on the adjusted r^2. This followed the methods used in the FEH to provide the best fitting model for $QMED$ (IH, 1999).

5.3 Results and discussion

5.3.1 Refining urban land cover classes

Mapping of the refined urban land use classes (Table 5.2) formed the first step in deriving enhanced catchment descriptors and landscape metrics. The results of refining the existing basic LCM classes for Swindon and Bracknell are illustrated in Figure 5.3 and summarized in Table 5.4.

The most evident and expected change observed in Figure 5.3 between the standard and refined classification is the significant change in the *Suburban*

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class. Table 5.4 reveals the majority becomes reclassified as either low-density $Suburban_{LD}$ (peripheral, isolated, satellite or rural) developments or medium-density $Suburban_{MD}$ (cores of large suburban) developments. A much lower portion becomes reclassified as high-density $Suburban_{HD}$ areas close to central urban development. This suggests that impervious cover, relative to development density, may be overestimated when using a less detailed index of urban extent such as *URBEXT* or taking an assumed impervious cover and applying it to a single urban land use class that is in reality highly variable, as identified by Redfern et al. (2016). Additionally, the form this takes differs between the two catchments, mainly due to historical development patterns. The higher relative coverage of low-density development in Bracknell (Table 5.4) further indicating variability in impervious cover not well represented by a single suburban class applied over a range of different catchment development types. Further, while Miller & Grebby (2014) found that *URBEXT* was indicative of impervious cover in small urban catchments, that study only considered a limited area with very similar development types. This points to the potential for significantly improving estimates of urbanisation impacts in catchment descriptor-based flood estimation methods for urbanized catchments by directly using impervious estimates derived from remote sensing imagery (Weng, 2012).

The high proportion of low-density suburban housing identified in this study poses significant potential for contributing large areas of domestic garden as green infrastructure (Cameron et al., 2012), which have been shown to have a role in runoff regulation (Warhurst et al., 2014). Such variability could be important for explaining the fact that generalized estimates of impervious cover based on *URBEXT* do not explain hydrological response in urbanized catchments (Miller & Hess, 2017). Further, while impervious estimates may be ultimately refined, the refined classes based on density may in fact offer additional information on the variability of water management and transfer, and therefore GI potential, not quantified by imperviousness alone.
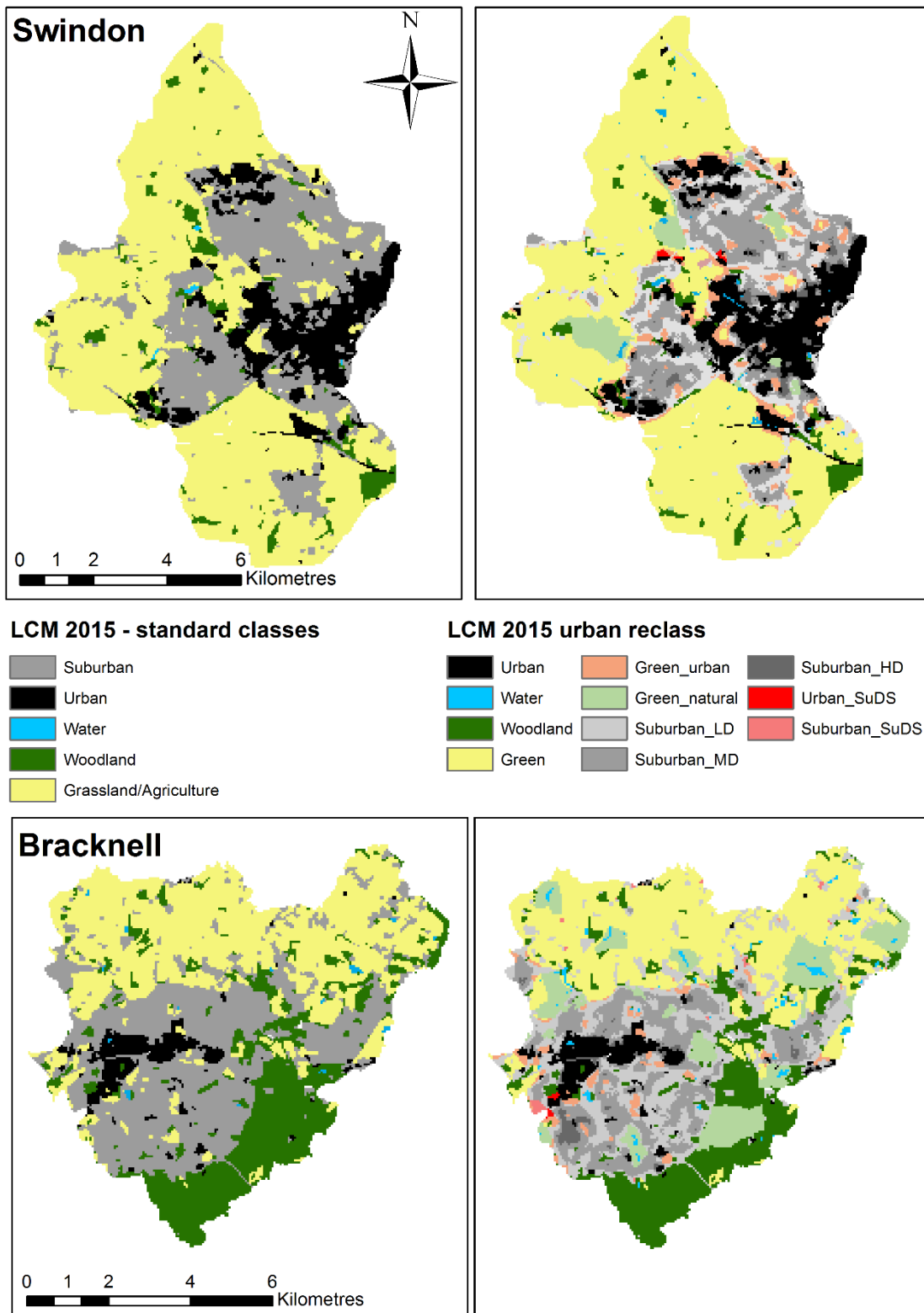
Figure 5.3: Comparison of land cover classes using standard and refined urban reclassification for both Swindon and Bracknell town (2015)

Table 5.4: Percentage coverage of standard and reclassified (rc) Land Cover mapping (LCM) classes, with distribution by catchment, and overall areas of Suburban and Urban areas serviced by Sustainable Urban Drainage Systems (SuDS).

LCM classes	LCM$_{rc}$ classes	Swindon			Bracknell		
		LCM	LCM$_{rc}$	SuDS	LCM	LCM$_{rc}$	SuDS
Urban	Urban	12.9%	12.8%	0.1%	4.7%	4.7%	0.1%
	Suburban$_{LD}$		11.9%			19.3%	
Suburban	Suburban$_{MD}$	26.8%	12.6%	0.2%	35.7%	13.8%	0.3%
	Suburban$_{HD}$		1.9%			1.3%	
Water	Water	0.1%	0.5%		0.3%	1.1%	
	Green		49.3%			31.1%	
Grassland/ Agriculture	Green$_{URB}$	56.2%	4.4%		38.8%	2.3%	
	Green$_{NAT}$		3.2%			10.7%	
Woodland	Woodland	4.1%	3.4%		20.5%	15.8%	

In both catchments the Water class in standard LCM mapping is not high (0.1-0.3%: Table 5.4), however the inclusion of OSMM water has significantly increased water cover in both catchments, by 400% in Swindon, and nearly 300% in Bracknell. Although the relative areas are not high compared to total catchment area (0.5% and 1.1% for Swindon and Bracknell, respectively), it must be considered that it is the area serviced by these water bodies that's important (Table 5.3) and thus these changes should affect *FARL*. Additionally much of this increased cover is within urban areas, so could be providing localized flood attenuation, with the higher value in Bracknell reflecting the deliberate design of flood attenuation features (Packman and Hewitt, 1998). The availability of high resolution OSMM data provides the user with up to date and accurate data from which to delineate such features. Given that new small waterbodies are increasingly being used in mitigating runoff in urban catchments (Jarden et al., 2015; Wilkinson et al., 2010) these results highlight the importance of using

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contemporary high-resolution imagery to map such features. One shortcoming however is that such methods do not facilitate identification of temporary storage features, such as swales or offline temporary storage. Subsurface retention areas are also not identified. Both have been identified as having flood storage capacity (CIRIA, 2014) but would be difficult to map from remote imagery.

The overall coverage of completely pervious classes (Grassland/Agriculture, Woodland) between the two towns and surrounding catchment is a combined 60.3% in Swindon, and 59.3% in Bracknell (Table 5.4), reflecting the urbanized nature of both catchments. The distribution within classes is different however, reflective of geographical location and planning controls: Bracknell being located near to London but having a large area of protected woodland to the south, and Swindon being more remote and surrounded by farmland. Urban reclassification of greenspaces indicates that urban greenspace ($Green_{URB}$) can make up significant areas within the urban fringes (2.3 – 4.4%). While less than 10% of overall pervious cover (31.1-49.3%), if such areas are fundamentally so altered or compacted as to behave like impervious surfaces (Chen et al., 2014) then the effect on runoff within the urban areas is likely to be significant at local scales. These effects could however be balanced by the areas of natural greenspace ($Green_{NAT}$) that have been shown to reduce runoff through enhanced infiltration (Zhang et al., 2015). Certainly such areas could play a role in localized runoff reduction, and given their location in these towns, this reveals the importance of considering types of urban greenspace and of using high accuracy datasets for estimating local runoff in urban areas (Verbeiren et al., 2013).

Further refinement by identification of likely areas of SuDS did not reveal any significant areas, with total areas of 0.3% and 0.4% in Swindon and Bracknell, respectively (Table 5.4). These are likely to be conservative values, reflecting that while much of Swindon is not hydro-geologically suitable for infiltration based SuDS, being composed of clay soils, retention based SuDS could be prevalent. Similarly, in Bracknell retention SuDS design is in fact integrated into the overall hydraulic design of the town, rather than having localized implementation or infiltration-based measures. Even so, the low values do not indicate these sub-

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classes will have a significant impact on refining *URBEXT* or explaining *QMED* in this study. However, with new developments required to implement such features where possible (Defra, 2011), such areas will increasingly become important. Going forward, accurately delineating areas serviced by SuDS is a clear priority for urban land cover mapping. This will enable better modelling of SuDs impacts and more accurate representation in a suitable catchment scale index for index flood methods.

5.3.2 Identifying suitable catchment descriptors and landscape metrics

A comparison between FEH catchment descriptors and those derived from refined classes across the 18 sites revealed there to be a high degree of correlation (>0.95), with associated minor improvements (<0.05) to the correlations with $QMED_{obs}$ for all except $FARL_{rc}$ (-0.22 → -0.38) which improved significantly. Regression model analysis of each descriptor against $QMED_{obs}$ for the 18 sites further indicated the significant relationships between both standard and reclassified descriptors across the 18 sites, with the lowest fit observed for $FARL_{rc}$ (r^2 = 0.894) while both $AREA_{rc}$ and $URBEXT_{rc}$ exceed an r^2 of 0.99. Taken together these results suggest the use of the reclassified $FARL_{rc}$ catchment descriptor will improve estimates of catchment flood attenuation from water bodies in small urbanized catchments, and subsequently replaces *FARL* in this study.

For $URBEXT_{rc}$ the correlation with $QMED_{obs}$ actually decreased (-0.05), indicating that the refined suburban classes and inclusion of SuDS areas provides no evident improvement in providing a descriptor of urban extent for use in *QMED* estimation across the 18 sites. Combined with the high r^2 for *URBEXT* in the fitted model for $QMED_{obs}$ this further suggests that detailed efforts to map variation in suburban land cover classes under current conditions has no real benefit for estimating *QMED,* suggesting that less dense areas balance out more dense areas, and that peak flows are well estimated from the existing URBEXT weighting of suburban and urban land cover. As such the standard *URBEXT* and

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Urban/Suburban land cover classes were retained for subsequent steps. Other studies have shown that such variation only becomes important at local scales (Shuster et al., 2005) or between distinct development types (Valtanen et al., 2013). Going forward however, as SuDS are increasingly adopted and more attention is paid to urban design to reduce runoff generation, such a refined approach could well become much more important.

AREA$_{rc}$ showed minor improvements in predicting *QMED$_{obs}$* over standard *AREA* descriptor values but importantly did not consider those four small urban catchments (S4, S7, S9, S10) in which it was not possible to automatically determine catchment area, as no natural catchment existed at these artificial drainage points. This is a limiting factor in using FEH catchment descriptors for small highly altered urban catchments (Miller et al., 2014). This highlights the need for a high resolution DEM to be used in conjunction with ancillary datasets on stormwater infrastructure and impervious areas to delineate artificial urban catchment boundaries (Braud et al., 2013). *AREA$_{rc}$* values were used henceforth in place of *AREA*.

From the 30 catchment descriptors and landscape metrics computed (Table_APX C-8), this was reduced down in four iterations to 17 descriptors/metrics (Table 5.5) through correlation analysis (5.2.3.2). This includes 12 landscape metrics that were not significantly (>0.8) correlated with at least three other metrics, alongside four catchment descriptors used in estimating *QMED* (5-1) and one (*URBEXT*) used to adjust for urbanization (Kjeldsen, Jones and Bayliss, 2008). Table 5.5 reveals that *AREA$_{rc}$*, as expected, was the most highly correlated descriptor to *QMED$_{obs}$* (0.95). For the landscape metrics, *PX* correlates surprisingly well with *QMED$_{obs}$* (0.82), as does *COHESION$_{URB}$* (0.61) – being significantly higher than correlations from URBEXT (-0.36) and perhaps indicating the importance of considering connectivity within urban patches alongside the overall coverage. Additionally, the normalised *PX$_N$* does not correlate as well with *QMED$_{obs}$* (-0.52), but performs better than *URBEXT* (-0.36) with which it is highly correlated (0.83). This suggests that efforts to normalize the *PX* metric reduces its descriptive ability and renders it more like *URBEXT,* further

illustrating the relatively weak performance of this catchment descriptor at such local urban scales compared to more spatially orientated landscape metrics. The results detailed in Table 5.5 suggest that some metrics could be important variables in the final *QMED* regression, thus reinforcing what Van Nieuwenhuyse et al. (2011) and others have found (e.g. Lin et al. 2007; Yuan et al. 2015) in that landscape metrics are a useful tool for comparing hydrological basins with significant potential for application in lumped hydrological studies and modelling.

Table 5.5: Refined list of potential *QMED* catchment descriptors and metrics. *QMED* and each descriptor across all sites are transformed using natural logarithm. Correlations greater than 0.8 are highlighted in bold. Correlations between 0.6 and 0.8 are shown in italics and underlined.

	QMED	AREA	BFIHOST	SAAR	FARL	URBEXT	PX	PXN	CONTAG	LPI$_{URB}$	CONTIG$_{URB}$	CLUMPY$_{URB}$	COHESION$_{URB}$	LPI$_{SUB}$	CONTIG$_{SUB}$	CLUMPY$_{SUB}$	COHESION$_{SUB}$	COHESION$_{NAT}$
QMED	1	**0.95**	-0.38	0.08	-0.38	-0.36	**0.82**	-0.52	-0.46	0.14	0.28	0.46	_0.61_	-0.51	-0.5	0.47	0.18	0.42
AREA	**0.95**	1	-0.41	-0.05	-0.5	-0.53	0.59	_-0.7_	-0.38	-0.13	-0.35	0.02	0.48	_-0.7_	-0.56	0.48	0	0.27
BFIHOST	-0.38	-0.41	1	0.48	0.04	-0.08	-0.31	0.11	_0.6_	-0.27	-0.44	-0.51	-0.54	-0.11	0.04	-0.18	_-0.6_	-0.47
SAAR	0.08	-0.05	0.48	1	0.19	-0.12	0.12	-0.02	0.36	0.08	-0.28	-0.22	-0.21	-0.32	0.02	-0.06	_-0.6_	-0.34
FARL	-0.38	-0.5	0.04	0.19	1	**0.82**	0	**0.88**	0.3	0.3	0.08	0.05	-0.07	0.53	_0.6_	-0.42	0.38	-0.3
URBEXT	-0.36	-0.53	-0.08	-0.12	**0.82**	1	-0.04	**0.83**	0.5	_0.75_	0.22	0.51	0.27	0.59	0.43	-0.41	0.22	_-0.6_
PX	**0.82**	0.59	-0.31	0.12	0	-0.04	1	-0.18	-0.17	0.29	-0.33	0.29	_0.77_	-0.57	-0.43	0.34	-0.14	-0.1
PXN$_{URBEXT}$	-0.52	_-0.7_	0.11	-0.02	**0.88**	**0.83**	-0.18	1	0.53	0.33	0.49	0.42	-0.12	_0.73_	**0.8**	-0.59	0.14	-0.41
CONTAG	-0.46	-0.38	_0.6_	0.36	0.3	0.5	-0.17	0.53	1	0.35	0.25	0.31	0.01	0.48	0.52	-0.06	0.3	-0.04
LPI$_{URB}$	0.14	-0.13	-0.27	0.08	0.3	_0.75_	0.29	0.33	0.35	1	-0.3	0.4	_0.65_	0.04	-0.18	0.08	0.08	_-0.6_
CONTIG$_{URB}$	0.28	-0.35	-0.44	-0.28	0.08	0.22	-0.33	0.49	0.25	-0.3	1	0.5	-0.29	_0.75_	_0.68_	-0.22	0.48	0.49
CLUMPY$_{URB}$	0.46	0.02	-0.51	-0.22	0.05	0.51	0.29	0.42	0.31	0.4	0.5	1	_0.61_	0.43	0.2	0.16	_0.64_	0.16
COHESION$_{URB}$	_0.61_	0.48	-0.54	-0.21	-0.07	0.27	_0.77_	-0.12	0.01	_0.65_	-0.29	_0.61_	1	-0.28	-0.5	0.49	0.31	-0.11
LPI$_{SUB}$	-0.51	_-0.7_	-0.11	-0.32	0.53	0.59	-0.57	_0.73_	0.48	0.04	_0.75_	0.43	-0.28	1	_0.76_	-0.36	_0.6_	0.08
CONTIG$_{SUB}$	-0.5	-0.56	0.04	0.02	_0.6_	0.43	-0.43	**0.8**	0.52	-0.18	_0.68_	0.2	-0.5	_0.76_	1	_-0.6_	0.15	-0.02
CLUMPY$_{SUB}$	0.47	0.48	-0.18	-0.06	-0.42	-0.41	0.34	-0.59	-0.06	0.08	-0.22	0.16	0.49	-0.36	_-0.6_	1	0.37	0.53
COHESION$_{SUB}$	0.18	0	_-0.6_	_-0.6_	0.38	0.22	-0.14	0.14	0.3	0.08	0.48	0.16	0.31	_0.6_	0.15	0.37	1	0.47
COHESION$_{NAT}$	0.42	0.27	-0.47	-0.34	-0.3	_-0.6_	-0.1	-0.41	-0.04	_-0.6_	0.49	0.16	-0.11	0.08	-0.02	0.53	0.47	1

5.3.3 Catchment descriptors and landscape metrics for flood estimation

The optimal configuration for refining the *QMED* equation was to follow the FEH *QMED$_{FEH}$* equation (5-1) and iteratively select four catchment descriptors and/or landscape metrics as variables based on forward step-wise maximisation of the adjusted r^2 using the weighted least squares (WLS) function (Ruppert and Wand,

1994) against *QMED$_{obs}$* for the 18 sites. The four variables identified were catchment areas (*AREA$_{rc}$*), and three landscape metrics: *PX, COHESION$_{SUB}$,* and *CONTAG*. The values for the selected variables are detailed for each catchment in Table 5.6, alongside, for reference, two key FEH descriptors (*FARL, URBEXT*) used in the FEH index flood equation.

The final derived equation of the maximised WLS regression for *QMED$_{rev}$* across the 18 sites using the variables selected is shown in equation (5-5). Table 5.6 details the catchment values for the selected variables and differences in estimated index flood values for both *QMED$_{rev}$* and *QMED$_{FEH}$* compared with *QMED$_{obs}$* (catchment *FARL* and *URBEXT* values are also included for reference). Importantly, the addition of *PX* proved highly effective at explaining the variability in *QMED$_{obs}$* not covered by *AREA$_{rc}$* alone, from an adjR^2 of 0.848 to 0.972, and the inclusion of the final two metrics only improved the overall fit to adjR^2=0.984. The range of values for both these additional metrics is generally low across the sites but a very high *CONTAG* value at S10 (93.8) and low *COHESION$_{SUB}$* value for S2 (81.4) could explain their inclusion in the final equation, given both sites have the same *QMED$_{obs}$* (0.64 m^{3}s^{-1}) but are significantly different in area (S2 – 3.24 km^2; S10 – 0.49 km^2). The high *CONTAG* value at S10 is indicative of the fact that the area is almost entirely *Suburban* and has high storm drainage connectivity, while the low *COHESION$_{SUB}$* value at S2 is clearly indicative of a rural catchment with patchy areas of housing and low drainage connectivity.

$$QMED_{rev} \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\text{(5-5)}$$
$$= 357.0943 \, AREA_{rc}{}^{0.4007} \, PX^{0.8195} \, 1.0595^{COHESION_{SUB}} \, 1.0115^{CONTAG}$$

To ensure independence in determining the performance of the selected variables for estimating the revised index flood, *QMED$_{rev}$*, for each catchment, a leave-one-out cross-validation (LOOCV) was undertaken to calculating model parameters. This form of validation uses a single catchment from the 18 sites as validation data and the remaining catchments as training data. Table 5.6 details the resulting estimates for both *QMED$_{rev}$* and *QMED$_{FEH}$* compared with *QMED$_{obs}$*

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(catchment *FARL* and *URBEXT* values are also included for reference) along with the respective errors compared to $QMED_{obs.}$

Assessing the performance across the 18 sites and between each method for estimating *QMED* it is clear from Table 5.6that $QMED_{rev}$ performs well against the observed values. The overall mean of $QMED_{rev}$ values is close to that of $QMED_{obs}$ with a mean absolute error value of only 0.2, and a mean percentage error of only -0.1% and a mean square error (MSE) of only 0.6. Only five cases exceeded 25% of the observed value in only where it significantly over (S3, S10, B1) or underestimates (S2, S9) *QMED*.

The FEH equation, as expected, performed less well than the fits achieved using the revised descriptors and landscape metrics. However, considering these are small highly-urban catchments and the $QMED_{FEH}$ is derived from national data across a wide range of catchment types and scales, a mean absolute error of 1.0, and a mean percentage error of -27.5%, and a MSE of 2.5 are not indicate of poor performance relative to the overall low mean value of $QMED_{obs}$ (4.5 m^{3}s^{-1}). However, a majority of sites (12) exceeded 25% of observed QMED, is indicative of the problems associated with applying a nationally fitted equation to small urban catchments for the estimation of the index flood.

Overall, there are no discernible patterns to explain why certain catchments performed better or worse, either relative to size or potential flood attenuation (*AREA$_{rc}$* and *FARL$_{rc}$*: Table 5.6), level of urbanization (*URBEXT*), location (Swindon or Bracknell), monitoring source (EA gauging or local monitoring) or between methods. This would indicate that the selected catchment descriptors and landscape metrics perform well across a range of catchments from predominantly rural, e.g. B1 and S2, to highly urbanized e.g. S9 and B3. While *FARL$_{rc}$* was not included in the step-wise variable selection it should be noted that it may well pose a greater significance across a broader selection of study catchments as in certain Bracknell catchments (B1, B5, B6, EA_39052: Table 5.6) *FARL$_{rc}$* falls below the threshold value 0.9 below which the EA do not recommend using the catchment descriptor method for estimating *QMED* (EA,

2012). This demonstrates the value of using high-resolution imagery for identifying such small but potentially hydrologically important features.

Considering urbanization, the lack of a significant relationship between *URBEXT* and *QMED_{obs}* (adjR^2=0.09) compared to the stronger relationship with *PX* (adjR^2=0.634), would indicate that urbanization is not a good indicator of high flow variability in urbanized catchments without explicit consideration of spatial layout. This unexpected pattern was similarly observed by Miller & Hess (2017) and highlights the value of considering both the relative coverage and hydrological distance to outlet of each urban patch. This study demonstrates that such a landscape metric could improve flood estimation in urban catchments and should be considered at a more national scale in flood estimation, particularly in the light of growing urbanization, and poor performance of existing methods in small urban catchments (Faulkner et al., 2012). Further, both TIA and distribution of impervious area, will certainly be improved by using detailed mapping of imperviousness from remote sensing imagery, as shown in numerous detailed hydrological studies (Dams et al., 2013; Verbeiren et al., 2013). Further, the inclusion of both the class-based *COHESION* metric applied to suburban areas and the landscape-based *CONTAG* metric, demonstrates that such metrics could be useful at capturing variability in between catchments not covered by explicit representation of area or urbanisation.

Table 5.6: Selected variable and index flood values from observed data (QMED$_{obs}$), fitting of variables to QMED$_{obs}$ using a leave-one-out cross-validation (QMED$_{rev}$), and the FEH QMED catchment descriptor equation (QMED$_{FEH}$) – with associated errors compared to QMED$_{obs}$: light and dark grey denotes relative percentage errors equal to or exceeding 25% and 50% respectively.

	AREA$_{rc}$	PX	CONTAG	COHESION$_{SUB}$	QMED$_{obs}$	QMED$_{rev}$	Relative percentage error	Absolute value of error	Square of error	QMED$_{FEH}$	Relative percentage error	Absolute value of error	Square of error	FARL$_{rc}$	URBEXT
Site_ID	(km²)				(m³s⁻¹)	(m³s⁻¹)	[F$_t$-A$_t$/A$_t$]	[A$_t$-F$_t$]	[A$_t$-F$_t$]²	(m³s⁻¹)	[F$_t$-A$_t$/A$_t$]	[A$_t$-F$_t$]	[A$_t$-F$_t$]²		
S1	28.97	3.88	57.5	95.1	8.84	8.89	0.5%	-0.05	0.00	6.28	-28.9%	2.56	6.54	0.97	0.23
S2	3.24	0.2	76.4	81.4	0.64	0.26	-58.9%	0.38	0.14	0.24	-62.0%	0.40	0.16	0.85	0.03
S3	5.98	1.68	61.7	98.4	1.38	1.94	40.8%	-0.56	0.32	2.01	46.1%	-0.64	0.40	1	0.57
S4	3.09	1.38	68.0	99.6	1.17	1.02	-12.5%	0.15	0.02	0.91	-21.9%	0.25	0.06	1	0.33
S5	2.18	3.53	52.5	96.0	2.94	2.90	-1.5%	0.04	0.00	0.69	-76.6%	2.25	5.08	1	0.39
S6	35.2	4.28	55.5	96.0	9.37	10.22	9.0%	-0.85	0.72	7.56	-19.4%	1.82	3.30	0.96	0.29
S7	0.54	1.54	52.7	94.7	0.97	0.86	-11.9%	0.12	0.01	0.16	-83.9%	0.81	0.66	1	0.4
S8	2.16	1.07	52.7	98.9	0.80	0.96	20.7%	-0.16	0.03	0.78	-2.3%	0.02	0.00	1	0.31
S9	0.27	0.66	62.3	100.0	0.25	0.01	-96.0%	0.24	0.06	0.13	-47.5%	0.12	0.01	1	0.51
S10	0.49	2	93.8	95.1	0.64	0.80	25.0%	-0.16	0.03	0.15	-77.1%	0.49	0.24	1	0.37
EA_39087	82.5	3.95	55.5	97.4	13.41	11.73	-12.5%	1.68	2.81	13.72	2.3%	-0.31	0.10	0.95	0.23
B1	18.37	1.15	51.0	93.6	2.31	3.36	45.6%	-1.05	1.11	3.19	38.2%	-0.88	0.78	0.88	0.09
B2	12.49	1.69	58.1	98.9	2.97	2.53	-14.8%	0.44	0.19	1.84	-38.1%	1.13	1.28	0.94	0.19
B3	12.55	2.76	52.8	99.2	3.90	4.00	2.6%	-0.10	0.01	2.11	-45.9%	1.79	3.20	0.92	0.37
B4	33.66	2.07	50.0	96.7	5.35	5.61	4.9%	-0.26	0.07	5.11	-4.4%	0.24	0.06	0.9	0.12
B5	37.5	1.85	50.4	97.2	5.61	5.11	-8.8%	0.50	0.25	5.12	-8.6%	0.48	0.23	0.87	0.13
B6	58.24	2.84	48.3	98.2	10.63	8.21	-22.8%	2.42	5.87	7.35	-30.8%	3.28	10.76	0.87	0.17
EA_39052	51.96	3.55	47.9	98.4	9.70	9.60	-1.0%	0.10	0.01	6.35	-34.6%	3.35	11.25	0.86	0.19
Mean	21.6	2.2	58.2	96.4	4.5	4.3	-0.1	0.2	**0.6**	3.5	-27.5%	1.0	**2.5**	0.9	0.3

The omission of both variables *FARL* and *URBEXT* from the revised index flood equation *QMED$_{rev}$*, and the performance of landscape metrics compared to such routinely used descriptors, was surprising and indicates such metrics, could have significant potential in improving flood estimates in ungauged small urban catchments. Similarly, other studies have shown that alternative catchment descriptors can be derived from readily available geo-spatial data, and prove both more heterogeneous and perform better at estimating *QMED* (Wan Jaafar & Han, 2012). Overall, this study has demonstrated the potential of ecological landscape metrics (Yang et al., 2011) and hydrologically relevant metrics (Van Nieuwenhuyse et al., 2011) for estimating *QMED* in urbanized catchments.

5.4 Conclusions

This study has sought to assess the potential for refined land cover information and landscape metrics in flood estimation. The results of refining catchment descriptors using higher-resolution data suggest that using such data alongside emerging datasets can alter the representation of the urban environment, having particular impacts on how urban water features are accounted for and where the catchment boundaries exist. Additionally, they suggest that class based approaches can be limited by nationally available data, indicating the need to test the application of more detailed global remotely sensed data. The results of employing landscape metrics alongside catchment descriptors has shown that index flood estimation in urbanized catchments could be improved by employing landscape metrics that represent hydrological distance relative to patch size and connectivity of urbanized areas. These provide a means of representing the hydrological complexity of an urban catchment in a single but spatially-explicit distributed numeric form, suitable for design flood methods and lumped hydrological modelling. We conclude the evidence indicates that a 'one-size-fits-all' national approach to flood estimation in urbanized areas could be improved by having more spatially explicit catchment descriptors and urban focused *QMED* equations, specifically by refitting the QMED equation to selected urban catchments using landscape metrics. This should be the focus of further research

to upscale and validate the application of such metrics and refined index flood equations.

The ability of landscape metrics to express hydrological connectivity and relative size and location of urban development to the location of interest has been clearly shown and promises significant urban planning improvements for flood management. This suggests metrics that provide description of the connectivity and location of urbanised surfaces such as PX, COHESION and overall landscape fragmentation (CONTAGION) could further be useful in the design and testing of green infrastructure for natural flood management, given their respective role in mitigation of floods and clear links between runoff and catchment properties.

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6 – LANDSCAPE METRICS AND STORM RUNOFF

This chapter addresses Objective 3 of the thesis, namely: to evaluate the performance of urban catchment descriptors and landscape metrics for explaining inter-catchment variation in storm runoff.

6.1 Introduction

The process of urbanisation involves hydrological and hydraulic changes to catchment rainfall-runoff relationships through the progressive loss of pervious surfaces and natural drainage pathways and their replacement with impervious surfaces and artificial drainage. Such changes decrease infiltration and localised soil storage (Yang and Zhang, 2011), thereby increasing runoff volume (Arnell, 1982) and pluvial flooding where local drainage capacity is not sufficient (Falconer et al., 2009). Combined with more rapid conveyance of runoff as a result of artificial drainage (Burns et al., 2012) this results in a more flashy response with earlier flood peaks (Graf, 1977), reduced baseflow (Braud et al., 2013) overall increased peak flow (Lee & Heaney, 2004; Konrad & Booth, 2005; Ogden et al., 2011; Prosdocimi et al., 2015) and increased downstream fluvial flooding (Praskievicz & Chang, 2009; Jacobson, 2011; Fletcher et al., 2013).

Catchment impervious area is widely recognised and used as an indicator for characterising the impacts of urbanisation on hydrology (Arnold & Gibbons, 1996; Lee & Heaney, 2004; Dams et al., 2013; Kelly, 2016). It is conceptually easy to understand (Lim, 2016) but simplifies the complex urban processes of hydrological response (Shuster et al., 2005; Redfern et al., 2016). . This leads toa reliance in attribution methods and lumped element hydrological models for simplifying the properties of a spatially distributed system into a catchment wide approximation of that system. Thus while differences in rainfall-runoff response between rural and urban catchments are robustly attributed to impervious cover in empirical studies (Rose & Peters, 2001; Schoonover & Lockaby, 2006) this leads to hydrological theories concerning increases in runoff and peak flows, and reductions in lag time and flood duration (Leopold 1968; Jacobson, 2011) that have not been robustly assessed for more urabised catchments being routinely

employed in urban catchments. More recently, high-resolution monitoring technologies and distributed hydrological models have facilitated research beyond the effects of imperviousness alone, including: connectivity of impervious surfaces (Ebrahimian, Wilson and Gulliver, 2016), urban layout (Mejía & Moglen, 2010; Gallo et al., 2013), interactions with storm water infrastructure (Meierdiercks et al., 2010) and green infrastructure (Golden & Hoghooghi, 2017), soil condition (Ferreira et al., 2013) and soil moisture (Nied et al., 2016) along with climate (Järvi et al., 2017) and local meteorological factors such as storm distribution (Ten Veldhuis et al., 2018) scale (Cristiano et al., 2018) and storm type (Yao et al., 2016). Such research has revealed the importance of considering both the connectivity of impervious areas (Alley and Veenhuis, 1983; Roy and Shuster, 2009; Ebrahimian et al., 2016) and the spatial distribution of these surfaces (Zhou et al., 2014; Zhang & Shuster, 2014; Du et al., 2015).

Empirical testing of spatial effects is hampered by the limitations acknowledged in using lumped representations of the environment where spatial variability is disregarded (Herold et al., 2005; Oudin et al., 2018). The majority of empirical studies seeking to investigate the relationship between urbanisation and runoff are therefore generally constrained to characterising urbanisation with lumped catchment values such as total impervious area (TIA) (e.g. Sillanpää and Koivusalo, 2015) or urban extent (*URBEXT*) (Putro et al., 2016). A more realistic rendering of the hydrological impacts of impervious surfaces is available by using directly connected (or effective) impervious area (Lee and Heaney, 2004) - a measure of connectivity of such surfaces to drainage. Its application however has been limited in empirical studies due to difficulties in its estimation (Roy & Shuster, 2009; Ebrahimian et al., 2016).

Hydrological models are increasingly used to predict the impacts of urbanisation on storm runoff and test emerging hypotheses urbanisation impacts and mitigation as they facilitate analysis of complex scenarios in controlled situations. Distributed hydrological models provide the most suitable tool for determining spatial impacts. However, lumped models are useful when data is limited or the discharge at one point is required, and can be more accurate than distributed

models which are prone to over parameterisation (Salvadore, Bronders & Batelaan, 2015). Despite relying on lumped catchment properties they are remain widely used to model urbanisation impacts. The SCS model (Chow et al, 1988) for example is still routinely used to determine urbanisation impacts and (Huang et al., 2008; Sjöman & Gill, 2014; Cheng & Wang, 2002) while the Revitalised Flood Hydrograph (ReFH) model (Kjeldsen, 2007) is the UK industry standard for design flood estimation in ungauged catchments (EA, 2012).

The growing availability of geospatial data was noted by Shuster et al. (2005) in the 2000's as an opportunity for deriving more spatially explicit landscape metrics that offer hydrological significance beyond catchment impervious area. Yet nearly ten years later studies were only just beginning to explicitly address the role of spatial patterns of impervious areas on runoff response (Zhang & Shuster, 2014). Ecologists have long applied spatially explicit landscape metrics (LMs) to study ecosystem dynamics (Brady et al., 1979; Gustafson & Parker, 1992; Grafius et al., 2016). Landscape metrics provide a means to characterise the composition and spatial configuration of patches of land cover typologies to link to ecological processes (Turner et al., 2001) and thus offer potential improvements over lumped catchment descriptors. *PX,* for example, was developed by Gustafson & Parker (1992) for ecological purposes to determine the relative isolation of homogeneous patches and was adapted by Van Nieuwenhuyse et al. (2011) to represent functional hydrological connectivity in a conceptual basin and was shown to capture effects of both clumping and distance. Landscape metrics are increasingly being used in hydrological studies (Schröder, 2006; Yuan et al., 2015) and combining established landscape metrics alongside hydrologically relevant metrics is an emerging area of investigation for characterisation of catchment properties affecting hydrological response (Van Nieuwenhuyse et al., 2011; Miller & Brewer, 2018; Oudin et al., 2018).

In this study we aim to evaluate the performance of urban catchment descriptors and landscape metrics for explaining inter-catchment variation in storm runoff in small urbanised catchments. To achieve this aim we have a number of related objectives: i) to quantify differences in inter-catchment rainfall-runoff behaviour

across a range of urbanised catchments, ii) to characterise catchment properties using a range of catchment descriptors and landscape metrics, and iii) to identify the relative performance of catchment descriptors and landscape metrics for explaining rainfall-runoff response . The findings will be used to assess what landscape metrics can tell us regarding the role that spatial layout of urban surfaces has on storm runoff response.

6.2 Method

6.2.1 Study area and hydrological monitoring

The study area used in this research focuses on two towns in the south of the UK (Figure 6.1). Both Swindon (population 210,000) and Bracknell (population 77,000) are rapidly urbanising urban centres typical of post-war development and of progressive peri-urbanisation. Both are tributaries of the river Thames (Figure 6.1, inset) and have a similar climate and geology, with neither dominated by groundwater input. Swindon has a large STW outfall located in sub-catchment S6, while in Bracknell a STW outfall is located downstream of the gauging station in B6 along with a smaller STW in B2 that transfers wastewater from a nearby town.

Both catchments have local an Environment Agency (EA) gauging station located downstream of the main urban centre and have a local EA rain gauge – both recording data at a 15min resolution. Flow data from the two gauging stations were combined with high resolution rainfall-runoff monitoring that combined rain gauges distributed across the study areas with in-situ ultrasonic flow instruments to provide rainfall and runoff data with a record length of two to five years between 2011 and 2016 for 16 further catchments and sub-catchments of varying size and degree of urbanisation (Figure 6.1, Table 6.1). Miller and Hess (2017) provide a detailed description of equipment and data processing. 11 'calibration' catchments, found to be generally independent of inflows from an upstream sub-catchment (Figure 6.1), were selected for fitting linear models. The remaining seven 'validation' catchments were used for testing the performance of fitted models.
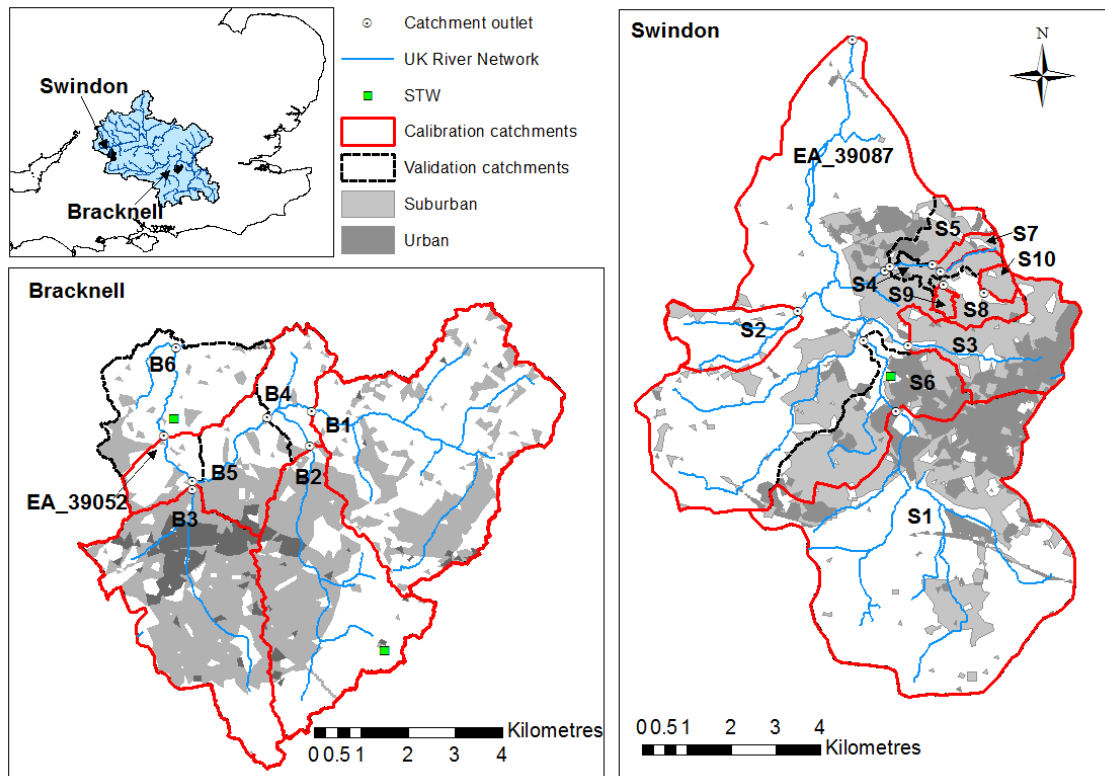
Figure 6.1: Study area and location of monitored catchments

6.2.2 Storm event data

The variable pattern of rainfall-runoff response across the catchments was quantified using event data from storm events captured in the rainfall-runoff monitoring. The events were characterised by a range of hydrological metrics suitable for quantifying the rainfall-runoff response during storm events (Table 6.2) using the methods outlined by Miller & Hess (2017). This involved first isolating storm events, then using automated baseflow separation methods to isolate the surface runoff hydrograph, and finally filtering out erroneous events and ensuring only single-peak events are selected. To improve independence in the dataset a flow time series was used that did not employ infilling of missing flow time series using data from other sites.

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Table 6.1: Summary of catchment land cover and period of data monitoring – ending October 2015. (d/s = downstream, stw = sewage treatment works)

Site ID	Area (km²)	Monitoring years	Urban (%)	Suburban (%)	Catchment description
EA_39052	51.96	5	5	37	Mixed land-use combining three main tributaries- gauged at d/s exit of large pond
B1	18.37	2	1	26	Mainly rural with low-density suburban developments
B2	12.49	2	3	43	Suburban with forested u/s area. Heavily modified.
B3	12.55	0.9	15	53	Highly urban and heavily modified with significant storm drainage.
B4	33.66	2	2	31	Flow junction between suburban (B2) and rural (B1) tributaries.
B5	37.5	2	2	32	Mixed use combining two main tributaries and suburban storm drainage.
B6	58.24	2	5	34	Flow site d/s of gauging station and combining diurnal stw outflows
EA_39087	82.5	5	13	26	Mixed land-use with high density suburban/urban land use in central area. Includes STW outfall.
S1	28.97	2	16	18	Mainly rural with high density development near gauged outlet.
S2	3.24	2	0	10	Rural catchment with organic agriculture and pasture.
S3	5.98	4.4	32	56	Highly urban catchment, heavily modified.
S4	3.09	4.6	2	79	High-density peri urban housing with large nature reserve. Highly modified - natural area reduced (S5)
S5	2.18	4.6	15	62	High-density peri urban housing and commerce. Highly modified storm drainage.
S6	35.2	1.9	19	24	Mixed use draining u/s rural area and heavily urban town centre - d/s of STW outfall.
S7	0.54	4.6	6	82	High density peri urban housing, Highly modified storm drainage.
S8	2.16	4.3	2	72	Mixed housing and large natural area, including recreation areas.
S9	0.27	4.6	0	100	Medium density suburban housing. Highly modified storm drainage.
S10	0.49	4.6	0.0	93.6	Medium density suburban housing. Highly modified storm drainage.

6.2.3 Catchment descriptors and landscape metrics

A number of catchment descriptors (and landscape metrics were selected to provide characterisation of catchment properties (Table 6.3). Both catchment descriptors and landscape metrics were based on 50 m resolution mapping provided by the UK Land Cover Map updated for 2015 (LCM2015), using methods outlined by Morton et al. (2011). This includes the classes *Suburban* and *Urban* for areas of development, *Rural* for the combined woodland/grassland/arable areas, alongside *Water* to cover areas of freshwater

in the selected catchments. Using data and methods outlined by Miller and Brewer (2018), the *Rural* and *Water* classes were further refined using higher-resolution spatial data for elevation and water bodies, and detailed data on the location of nature reserves. This provided five land-cover classes that were used to determine catchment descriptors and landscape metrics: *Urban, Suburban, Water, Grassland/agriculature/woodland, Natural Greenspace*.

Table 6.2: Storm hydrological metrics used in the study to quantify variability in catchment responses to storm events

	Metric	Description and units	Reference application
Hydrograph shape	DR	Direct Runoff – storm runoff volume expressed as depth over catchment area (mm)	Shaw et al. (2010)
	PR	Percentage runoff – proportion of rainfall converted to direct runoff (%)	Burn and Borman (1993)
	Q_{max}	Peak flow – maximum recorded flow during storm event (cumecs)	Hollis and Ovenden (1998)
	θ	Flood duration - measure of hydrograph shape defined by duration where Q/Q_{max}= 0.5 (h)	Braud et al. (2013)
Rainfall runoff timing	TP	Time-to-peak – time between onset of storm runoff and peak flow (h)	Gallo et al. (2013)
	T_{LPP}	Lag-time peak-to-peak – time between peak rainfall and peak flow from storm event (h)	Scheeder et al. (2003)
	T_{LC}	Lag-time centroid-to-centroid – time between centroid of rainfall and centroid of storm flow (h)	Hall (1984)

The eight catchment descriptors selected are those used for estimating floods in ungauged catchments in the UK (IH, 1999; Kjeldsen, 2007) and provide characterisation of catchment geometry, climate, geology, soil hydrology, and urban extent (Table 6.3). The 11 selected landscape metrics were identified by Miller and Brewer (2018) as uncorrelated and highly descriptive of urban spatial form and function such as connectivity and location with regard to catchment

hydrological function (Table 6.3). The majority of landscape metrics were derived using the Fragstats software package (McGarigal and Marks, 1994) while *PX* was derived using the method outlined by Miller and Brewer (2018).

Table 6.3: Catchment Descriptors and Landscape Metrics used for characterising catchment properties (full details on derivation provided in Appendix A)

Catchment Descriptors

AREA	Catchment drainage area (km^2)
SAAR	Standard-period Average Annual Rainfall (mm) rainfall for the period 1961-1990
FARL	Index of flood attenuation from rivers and lakes.
BFIHOST	Base flow index from Hydrology of Soil Types (HOST) Boorman et al. (1995)
URBEXT	FEH index of fractional urban extent
PROPWET	Index of proportion of time that soils are wet (%)
DPLBAR	Mean drainage path length
DPSBAR	Mean drainage path slope

Landscape Metrics

CONTIG	Contiguity Index assesses spatial connectedness, or contiguity, of cells within a grid-cell patch to provide an index of patch boundary configuration and thus patch shape.
LPI	Largest patch index quantifies the percentage of total landscape area comprised by the largest patch. As such, it is a simple measure of dominance.
CLUMPY	Clumpiness index quantifies the deviation of the proportion of like adjacencies involving the corresponding class from that expected under a spatially random distribution.
COHESION	Patch cohesion index measures the physical connectedness of the corresponding patch type.
CONTAG	Contagion Index assesses the extent to which patch types are aggregated or clumped as a percentage of the maximum possible; characterised by high dispersion and interspersion.
PX	Proximity Index (PX) accounts for hydrological distance and connectivity of all suburban and urban patches relative to catchment outlet

6.2.4 Calibration and validation of linear models

Using data from the 11 calibration catchments (Figure 6.1) the best performing model variables were identified using 'leaps' regression subset selection (Lumley, 2017). Leaps identifies the best combination of variables for performing a linear

regression of the observed response metric, using an efficient 'branch-and-bound' algorithm that systematically searches for the optimal solution. This algorithm uses a systematic enumeration of solutions that explore branches of a tree that represent possible subsets of the solution, each branch being checked against bounds of the optimal solution. Given the relatively small subset of calibration catchments and variables, the adjusted r-squared (R^2adj) performance criterion, with an associated weighting based on data frequency (events captured), was used to account for the number of predictor variables in the model relative to the number of data points. A further check for consistency, and to ensure no over-fitting, was undertaken by extracting the Akaike information criterion (AIC) scores (Akaike, 1987) for model variants. The AIC compares the quality of a set of statistical models, with the AIC criterion seeking a model with a good fit to observed values but with minimal parameters.

Leaps was bounded to selecting the best three subsets of variables at each level of complexity, from one to four variables, in order to identify patterns in model complexity and between catchment descriptors and landscape metrics selected. This first stage involved using only catchment descriptors as a baseline for comparing model performance. The second stage added landscape metrics to see if there was improved performance when landscape metrics are additionally considered. This approach also facilitated identification of which catchment descriptors were supplemented. The AIC scores of selected model variants were also calculated in R using the function 'extractAIC' which computes the (generalised) AIC for a fitted parametric model. The model with the highest R^2adj and lowest AIC was then taken forward to fit model parameters.

The second stage of model development involved fitting parameters for the optimal combination of catchment descriptor or landscape metric variables identified for each response metric across the 11 calibration catchments. We employed the weighted least squares regression method (Ruppert and Wand, 1994), applying a weighting factor based on number of events captured for each site, as this was most suitable given the limited number of calibration catchments (11) and variation in monitoring duration between sites (Figure 6.1). Hydrological

metric data normality across the 11 sites was tested using the Shapiro-Wilk statistic test and where non-normal ($p < 0.05$), data were transformed using the natural logarithm. For these transformed metrics, and to maximise performance, parameter values were compared using the following transformations: none, logarithmic, inverse ($1000/x$), and power (c^x).

The independence of data among study sites was ensured by selecting only catchments with little or no physical relationship in the event hydrographs (2.2) while multicollinearity of model variables was reduced by selecting only landscape metrics shown by Miller & Brewer (2018) to have little or no significant correlation. Linear model assumptions were further tested using model residuals to ensure that linear regressions conformed to the assumptions of linear regression, primarily: linearity of y with respect to x, no variable collinearity, homoscedacity of residuals, and normal distribution of residuals (Faraway, 2005). The fitted models were subsequently tested on the seven validation catchments (Figure 6.1) to determine the performance on catchments not included in the fitted model and to identify any outliers that could indicate potential weaknesses or areas of further development.

6.3 Results

6.3.1 Storm events

Table 6.4 details the mean values for all storm event hydrological metrics across the 18 selected catchments. The large variability in size of catchments selected (0.27 km^2 – 82.5km^2) means there is a wide range of all non-normalized metric values. Importantly, for the analysis that follows, the data indicate a wide range of hydrological responses have been captured across the sites, with a balanced number of events between the calibration (438) and validation (326) catchments.

Table 6.4: Catchment average storm event hydrological metric values – subset by Calibration (11) and Validation (7) catchments

Site ID	AREA (km^2)	Freq	Q_{max} (m^{3}s^{-1})	DR (mm)	PR (%)	Θ (h)	TP (h)	L_{TPP} (h)	T_{LCC} (h)
Calibration									
EA_39052	51.96	52	3.45	2.3	18.2	12.4	7.5	3.1	8.4
B1	18.37	50	0.61	1.7	12.4	18.0	14.9	10.5	13.5
B2	12.49	30	1.30	1.8	16.5	4.7	5.2	1.2	5.3
B3	12.55	12	2.50	3.9	34.0	3.5	5.7	1.6	4.1
EA_39087	82.5	72	6.14	3.5	25.6	15.8	15.3	10.7	14.2
S1	28.97	27	2.67	4.4	29.4	11.4	8.4	4.5	8.2
S2	3.24	30	0.14	1.5	10.5	21.8	12.6	8.8	11.0
S3	5.98	53	0.74	3.2	31.4	5.7	6.0	2.2	4.9
S7	0.54	39	0.43	2.4	22.5	0.5	3.6	0.3	1.0
S9	0.27	34	0.15	2.5	21.0	0.8	3.7	0.3	2.5
S10	0.49	39	0.27	1.7	16.1	0.8	3.5	0.3	0.9
Validation									
B4	33.66	34	0.93	1.1	9.8	13.3	10.2	6.4	9.2
B5	37.5	37	1.74	2.2	15.4	14.4	10.6	6.6	10.0
B6	58.24	51	4.26	3.0	21.6	13.3	9.6	5.1	9.5
S4	3.09	74	0.45	3.0	24.9	5.5	6.9	3.4	5.5
S5	2.18	56	1.50	2.9	26.4	0.8	3.8	0.7	1.2
S6	35.2	18	4.49	6.0	43.9	17.7	9.3	5.6	10.5
S8	2.16	56	0.37	2.3	21.3	2.9	4.9	1.4	3.5

6.3.2 Catchment characterisation

Land cover mapping of the five main classes is illustrated in Figure 6.2. Table 6.5 details the derived catchment descriptor and landscape metric values for each catchment. Urbanisation clearly varies across the selected catchments and reveals Swindon to have much higher *Urban* coverage across the town centre and satellite industry/business parks than Bracknell, reflected in generally higher *URBEXT* values (Table 6.5). Bracknell has a much higher number of urban water bodies (*Water*: Figure 6.2) compared to Swindon, resulting in lower catchment *FARL* values (Table 6.5). Likewise, mapping of *Natural Greenspace* (Figure 6.2) shows these areas are clearly present in varying degrees of area and distribution across the 18 catchments/sub-catchments. In general, individual patches of *Natural Greenspace* are not relatively large but notable exceptions include the

urban B2 and S8, the rural B1, and EA_39052 which has a large patch located near to the catchment outlet.
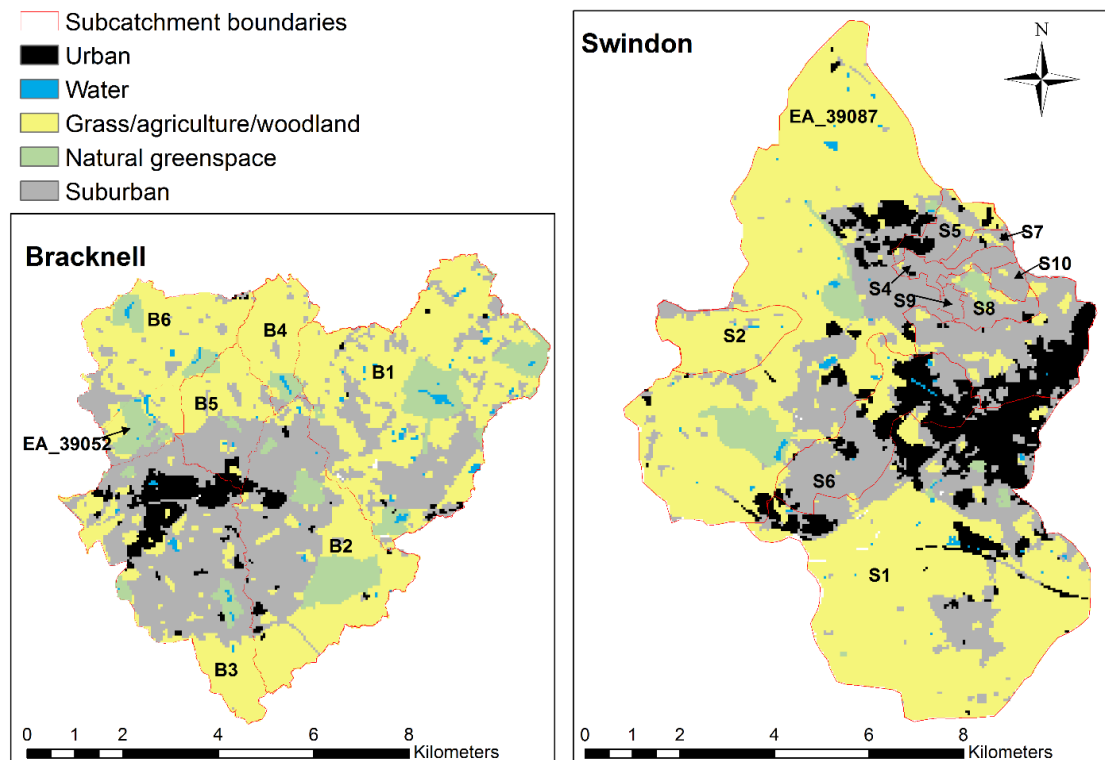
Figure 6.2: Land cover mapping used in derivation of catchment descriptors and landscape metrics

The majority of catchment descriptors and landscape metrics (Table 6.5) have high variability between the selected calibration/validation catchments (e.g. *AREA, URBEXT, PX*) while only two have little variation across catchments (*SAAR, PROPWET*) and three have general low variability but with outlier values (*BFIHOST, CONTAG, CLUMPY$_{SUB}$*). Certain catchments do not contain particular classes and thus have zero values for derived landscape metrics. Landscape metrics based on *Suburban* and *Urban* land-cover patches vary considerably compared to the catchment descriptor *URBEXT*.

Table 6.5: Catchment descriptor and landscape metric values

	FEH catchment descriptors								Landscape metrics										
Site ID	AREA (km²)	DPLBAR (km)	*BFIHOST*	SAAR (mm)	FARL	*URBEXT*	DPSBAR	PROPWET	PX	CONTAG	LPI$_{URB}$	CONTIG$_{URB}$	CLUMPY$_{URB}$	COHESION$_{URB}$	LPI$_{SUB}$	CONTIG$_{SUB}$	CLUMPY$_{SUB}$	COHESION$_{SUB}$	CONTIG$_{NAT}$
EA_39052	51.96	7.46	0.36	676	0.86	0.19	24.7	0.29	3.55	47.89	3.66	0.40	0.81	93.77	26.88	0.36	0.81	98.42	0.60
B1	18.37	4.77	0.29	679	0.88	0.09	25.3	0.29	1.15	50.96	0.15	0.37	0.54	59.62	11.89	0.39	0.74	93.65	0.53
B2	12.49	3.9	0.51	686	0.94	0.19	21.5	0.29	1.69	58.08	1.44	0.38	0.74	78.94	41.75	0.37	0.85	98.89	0.63
B3	12.55	3.75	0.43	672	0.92	0.37	17.9	0.29	2.76	52.81	13.30	0.48	0.83	95.90	51.63	0.36	0.78	99.24	0.64
B4	33.66	6.22	0.36	680	0.9	0.12	25.8	0.29	2.07	49.96	0.53	0.38	0.68	74.27	17.11	0.39	0.80	96.74	0.64
B5	37.5	6.52	0.34	678	0.87	0.13	22.5	0.29	1.85	50.35	0.63	0.38	0.71	80.54	19.15	0.38	0.80	97.19	0.64
B6	58.24	7.84	0.34	674	0.87	0.17	30.2	0.29	2.84	48.34	3.26	0.37	0.81	93.58	23.95	0.37	0.81	98.20	0.65
EA_39087	82.5	9.31	0.39	698	0.95	0.23	27.4	0.34	3.95	55.55	8.10	0.42	0.83	96.77	11.73	0.40	0.83	97.41	0.55
S1	28.97	5.82	0.38	707	0.97	0.23	35.8	0.34	3.88	57.48	10.96	0.36	0.82	96.23	6.66	0.36	0.76	95.09	0.47
S2	3.24	2.12	0.67	712	0.85	0.03	33.8	0.34	0.2	76.41	0.00	0.00	0.00	0.00	6.26	0.39	0.69	81.36	0.00
S3	5.98	2.84	0.32	683	1	0.57	33.4	0.34	1.68	61.72	31.27	0.34	0.85	97.68	50.79	0.44	0.74	98.38	0.00
S4	3.09	2.11	0.43	688	1	0.33	14	0.34	1.38	68.04	1.05	0.55	0.82	70.68	79.31	0.89	0.66	99.64	0.84
S5	2.18	1.79	0.43	688	1	0.39	33.7	0.34	3.53	52.52	9.91	0.40	0.77	85.53	38.82	0.57	0.70	96.05	0.17
S6	35.2	6.29	0.36	705	0.96	0.29	40.6	0.34	4.28	55.45	13.56	0.40	0.83	97.06	10.43	0.40	0.81	95.98	0.47
S7	0.54	0.95	0.56	692	1	0.4	45.2	0.34	1.54	52.68	3.65	0.44	0.70	66.01	48.86	0.69	0.19	94.72	0.00
S8	2.16	1.79	0.34	684	1	0.31	27.3	0.34	1.07	52.68	1.50	0.60	0.94	74.81	70.47	0.63	0.72	98.88	0.84
S9	0.27	0.69	0.37	685	1	0.51	28.9	0.34	0.66	62.34	0.00	0.00	0.00	0.00	99.08	0.83	0.00	99.95	0.00
S10	0.49	0.6	0.54	686	1	0.37	35	0.34	2	93.82	0.00	0.00	0.00	0.00	6.66	0.36	0.76	95.09	0.00

6.3.3 Identifying model parameters and testing models

The best performing combination of catchment descriptors and landscape metrics for each metric were identified using the 'regsubsets' plot (Figure 6.3) in leaps (Lumley, 2017) and by comparing results with the associated AIC. The use of AIC scores provided a further means of differentiating between model selections and isolating the optimal model variables for both Q_{max}, PR and T_{LC}, where more than one combination had resulted in the same recorded R^2adj.

For each hydrological metric the plot lists the catchment descriptors and landscape metrics along the x-axis and the y-axis indicates the model performance using R^2adj to 2 decimal places. Four levels of model complexity are included (each separated by a horizontal dashed line), from 1 variable (M1) to 4 variables (M4), and the plot showing the 3 best performing models for each level of complexity (and associated R^2adj). The shaded rectangles indicate which variables are included in the given model and increasing shading indicates a higher R^2adj. Those of similar value are ranked by subsequent decimal places. Figure 6.3a plots the results of only using the eight catchment descriptors, while Figure 6.3b plots the eight catchment descriptors alongside the 11 landscape metrics (separated by a vertical line).

A number of observations can be discerned by comparing the selection and performance of catchment descriptors (Figure 6.3a) to the selection and performance of considering both catchment descriptors and landscape metrics (Figure 6.3b):

- The additional consideration of landscape metrics (Figure 6.3b) increases model performance at the four variable level (M4) over simply using catchment descriptors (Figure 6.3a) for all but one hydrological metric, Q_{max}, which, in both cases has an optimal model with four variables and a R^2adj of 0.98.
- The optimal variables for Q_{max} were found to be the highest ranked set from combining catchment descriptors with landscape metrics, which had

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a similar R^2adj but lower AIC (*AREA, URBEXT, BFIHOST, CONTIG_NAT*: AIC = -18.7) than the four variables selected using only catchment descriptors (*AREA, BFIHOST, URBBEXT, DPLBAR*: AIC = -14.4). The difference, however, is marginal, and suggests landscape metrics are not adding to enhanced characterisation of peak flow.
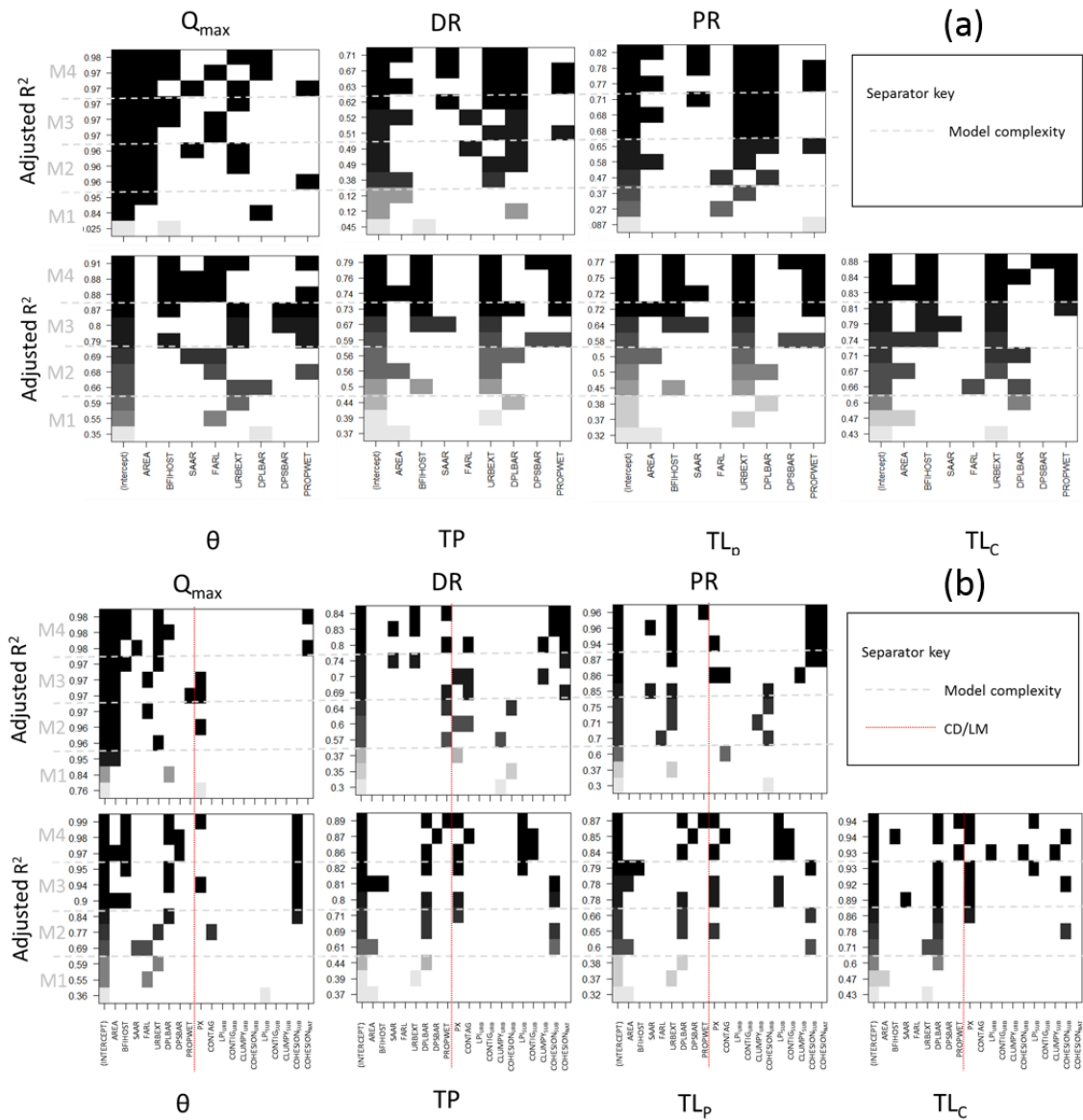
Figure 6.3: Subset plots of variables for each hydrological metric: a) Catchment Descriptors, b) Catchment Descriptors and Landscape Metrics.

- For the other two quantity-based hydrological metrics, *DR* and *PR*, the addition of landscape metrics considerably improves performance. For both, the same optimal set of catchment descriptors and landscape metrics are selected using the landscape metrics $COHESION_{SUB}$ and $CONTIG_{NAT}$. For *DR* the highest ranked subset had the lowest AIC (AIC=-18.1). In the case of *PR* two M4 model subsets had the same R^2adj but the highest ranked subset had a lower AIC (12.4) than the second (*SAAR, URBEXT, COHESION$_{SUB}$, COHESION$_{NAT}$*: AIC=14.3), further validating retaining the highest ranked set. For both, *URBEXT* is retained as an optimal means of characterising the overall urban area within the catchments considered, particularly for *PR* across all model complexities (M1 – M4).

- The optimal model variables for prediction of flood duration - θ – was a mix of expected catchment descriptors (*BFIHOST, DPLBAR*) and urban focused landscape metrics (*PX, COHESION$_{SUB}$*). This selection also had by far the lowest AIC score of any model variant (AIC=-1.7). Likewise the inclusion of landscape metrics ($R^2adj=0.99$) improves prediction significantly over just using catchment descriptors ($R^2adj=0.91$). The pattern of variable selection across model complexity differs between θ and the remaining time-based metrics. In particular, there is a consistent inclusion of $COHESION_{SUB}$ for θ across the more complex models (M3, M4) that suggests this is an important landscape metric for predicting flood duration.

- The optimal variable selection is identical for *TP, T_{LPP}* and *T_{LC}*. AIC scores were the lowest for the highest ranked models for *TP* and *T_{LPP}* (AIC=17.5, 16.8), but for *T_{LC}*, where two models had the same R^2adj, the highest ranked model actually had a higher AIC (10.6) than the one ranked second in 6.3b (*BFIHOST, DPLBAR, PX, COHESION$_{SUB}$*: AIC= 5.7). However, given the associated R^2adj was no better ($R^2adj=0.94$), and that the highest ranked variable selection mirrored that of both *TP* and *T_{LPP},* where

BFIHOST is not selected in the optimal model, the first ranking set is retained.

- Time-based hydrological metrics all indicate that *URBEXT* in Figure 6.3a is replaced by a combination of *Urban* and *Suburban* class based Landscape metrics in Figure 6.3b, and that *PX* in particular has a strong role in characterising urban runoff timing. *FARL* is a strong determinant of θ in simpler models (M1, M2) but is dropped in more complex models.

- *DPLBAR* is retained in all four time-based hydrological metrics and is consistent across most model complexities. *PROPWET* was not included as a significant descriptor in the models with less variables (M1-M4) but was selected in the most complex (M4) models.

6.3.4 Model development and validation

The equations and optimal variable transformations (where required) for estimating each response metric from selected variables are detailed in Table 6.6, alongside their respective performance (R^2adj) to the observed calibration data. The linear models on which all equations were based were all found to meet linear model assumptions (6.2.4). Table 6.7 details the observed metric values for each validation site against values derived using the equations in Table 6.6, alongside comparative predictive performance – using the mean square error (MSE) - for equations using either calibration or validation data. The derived equations and relative performance across the selected catchments under calibration and validation reveal a number of insights concerning the relative performance of catchment descriptors and spatially explicit landscape metrics for characterising urban storm runoff:

Q_{max} – model fit is good (Table 6.6: R^2adj = 0.98) and parameter performance highlights that the three catchment descriptors selected are all significant, while the additional landscape metric $CONTIG_{NAT}$ is not (p > 0.05). The fitted model performs well across the validation sites (Table 6.7: MSE = 0.71) compared to

calibration (MSE = 0.12), with no tendency to over- or under-predict Q_{max}, but some sites are poorly predicted (B4, B6, S6).

DR and PR – Both models shows that all selected variables are significant and that in combination the overall model fit is good (Table 6.6: DR R^2adj = 0.84, PR R^2adj = 0.96). The high significance of $CONTIG_{NAT}$ in both the DR and PR models (0.01 < p <0.001) highlights the potentially important role of urban greenspace for explaining the amount of runoff generated in the urbanised catchments. The good predictive ability observed in calibration (Table 6.7: MSE = 0.88, 1.93) is not however replicated in its performance when applied to validation catchments where this drops considerably for DR_{calc} (MSE = 4.58) and results in very poor performance for PR_{calc} (MSE = 143.5) as a result of significant over prediction of runoff volume in S4 and S8 and to a lesser degree in S6. There is also an overall tendency to over predict.

θ – All selected variables are shown to be highly significant (Table 6.6) but the equation applied to validation data results in a large drop in predictive performance (Table 6.7: MSE = 10.7) compared to calibration data (MSE = 0.35), mainly due to under prediction of flood duration in S6. There is also one result (S5) indicating a negative value (-1.7 h).

TP, T_{LPP} and T_{LC} – Fitted models for all three hydrological metrics show a similar pattern in the significance of variables and overall high model predictive performance (Table 6.6: R^2adj>0.82) but with variable significance in the role of urban landscape metrics. Of the catchment descriptors only $DPLBAR$ is significant in all three calibrated models, while the landscape metric PX is significant in two. For both TP and T_{LPP} the fitted model applied to the validation catchments resulted in increases in predictive performance (Table 6.7: MSE = 0.64, 2.25) over calibration data (MSE = 3.56, 5.68), whereas for T_{LC} the performance dropped considerably (MSE = 1.19 > 11.18). For both lag-time metrics there is a tendency to under predict for Swindon sites, while across the larger Bracknell catchments (B4, B5, B6) both metrics are over predicted.

Table 6.6: Derived model equations for response metrics based on multivariate regression between selected variables and observed hydrological response metrics for the 11 calibration catchments, with associated model fit to observed data using the adjusted R-squared (R^2adj) criterion: * p value: 0.01 < p < 0.05, **p value: 0.01 < p < 0.001, *** p value: p < 0.001.

Metric	Var 1	Var 2	Var 3	Var 4	Linear model	R^2adj
Q_{max}	AREA***	$URBEXT$***	$BFIHOST$*	$CONTIG_{NAT}$	$Q_{max} = 2.196\,AREA^{0.705}0.924^{\left(\frac{1}{URBEXT}\right)}0.520^{\left(\frac{1}{BFIHOST}\right)}0.613^{CONTIG_{NAT}^2}$	0.972
DR	$URBEXT$*	PROPWET**	$COHESION_{SUB}$*	$CONTIG_{NAT}$**	$DR = 12.442 + 10.901\,URBEXT + 25.031\,PROPWET - 0.243\,COHESION_{SUB}$ $+ 7.039\,CONTIG_{NAT}$	0.84
PR	$URBEXT$***	SAAR**	$COHESION_{SUB}$**	$CONTIG_{NAT}$***	$PR = 19.351 + 110.392\,URBEXT + 0.210\,SAAR - 1.974\,COHESION_{SUB} + 48.459\,CONTIG_{NAT}$	0.96
θ	DPLBAR***	$BFIHOST$*	$COHESION_{SUB}$***	PX**	$\theta = 128.878 - 19.42\,BFIHOST + 2.287\,DPLBAR - 2.068\,PX - 1.215\,COHESION_{SUB}$	0.99
TP	DPLBAR**	PROPWET	PX*	LPI_{SUB}	$TP = 24.606\,DPLBAR^{0.592}PROPWET^{1.482}1.204^{\left(\frac{1}{PX}\right)}LPI_{SUB}^{-0.193}$	0.83
T_{LPP}	DPLBAR**	PROPWET	PX	LPI_{SUB}	$T_{LP} = 150.506\,0.11^{\left(\frac{1}{DPLBAR}\right)}PROPWET^{1.482}1.204^{\left(\frac{1}{PX}\right)}LPI_{SUB}^{-0.492}$	0.82
T_{LC}	DPLBAR***	PROPWET	PX***	LPI_{SUB}*	$T_{LC} = -2.905 + 2.369\,DPLBAR + 30.562\,PROPWET - 3.712\,PX - 0.051\,LPI_{SUB}$	0.94

Table 6.7: Observed ($_{obs}$) and predicted ($_{calc}$) hydrological response metric values for seven independent validation catchments – with model predictive performance (MSE – Mean Square Error) using either calibration or validation data shown (calibration performance – in italics – based on 11 calibration catchments data).

	Site ID							Predictive performance	
	B4	B5	B6	S4	S5	S6	S8	Validation (MSE)	*Calibration (MSE)*
freq	34	37	51	74	56	18	56		
$Q_{max,obs}$ (m^{2}s^{-1})	0.9	1.7	4.3	0.4	1.5	4.5	0.4		
$Q_{max,calc}$ (m^{2}s^{-1})	1.8	1.8	2.9	0.6	0.9	3.0	0.3	0.71	*0.12*
$DR_{,obs}$ (mm)	1.1	2.2	3.0	3.0	2.9	6.0	2.3		
$DR_{,calc}$ (mm)	2.1	2.1	2.3	6.3	3.1	4.2	6.3	4.58	*0.88*
$PR_{,obs}$ (%)	9.8	15.4	21.6	24.9	26.4	43.9	21.3		
$PR_{,calc}$ (%)	15.5	15.3	17.2	44.2	25.4	32.8	42.6	143.47	*1.93*
$\theta_{,obs}$ (h)	13.3	14.4	13.3	5.5	0.8	17.7	2.9		
$\theta_{,calc}$ (h)	14.4	15.3	15.0	1.5	-1.7	10.8	4.0	3.94	*0.35*
$TP_{,obs}$ (h)	10.2	10.6	9.6	6.9	3.8	9.3	4.9		
$TP_{,calc}$ (h)	10.0	10.4	9.8	5.2	4.1	10.4	5.2	0.64	*3.56*
$T_{LPP,obs}$ (h)	6.4	6.6	5.1	3.4	0.7	5.6	1.4		
$T_{LPP,calc}$ (h)	4.6	4.4	4.1	1.4	1.5	7.1	1.3	2.25	*5.68*
$T_{LC,obs}$ (h)	9.2	10.0	9.5	5.5	1.2	10.5	3.5		
$T_{LC,calc}$ (h)	12.1	13.6	12.8	3.3	-3.4	6.0	4.2	11.18	*1.19*

6.4 Discussion

6.4.1 Landscape metrics for explaining storm runoff

6.4.1.1 Peak flow and runoff volume

Landscape metrics were found to provide little added value for attribution of peak flows in urbanised catchments, though as expected this response if primarily a function of catchment area, and to a lesser degree, urban area. This suggests spatial layout is not an important factor compared to the overall urban extent. This contrasts with observations from Miller and Brewer (2018) and modelling results from Mejía and Moglen (2009) that both suggest that spatial pattern affects flood peaks. This warrants further investigation as there is considerable interest in

using spatial planning of impervious surfaces and green infrastructure within a catchment to specifically reduce flood peaks (Jiang et al., 2018).

Parameter selection and fitting for hydrograph metrics of runoff volume - *PR* and *DR* - showed the optimal combination included landscape metrics representing the connectedness and shape of *Suburban* and *Natural Greenspace* patches, alongside lumped catchment descriptors indicative of urban extent and climate or soils. This suggests that connectivity and extent of urbanised and pervious surfaces within an urbanised catchment are important variables driving the volume of runoff, and are mediated by location specific catchment hydrological functions. This validates findings from other studies that have found that connectivity is an important determinant of runoff volume (Boyd et al., 1994; Lee and Heaney, 2004; Krebs et al., 2013) and that pervious surfaces have notable effects on runoff volume (Ellis, 2010; Jarden et al., 2015; Golden and Hoghooghi, 2017).

6.4.2 Runoff timing

Combining landscape metrics representing the connectivity and location of urbanised surfaces within a catchment alongside catchment descriptors greatly improved the attribution of runoff timing compared to combinations that relied on catchment descriptors and *URBEXT* to characterise the urban effects.

Flood duration (θ) was particularly well characterised by a combination of information on catchment length and landscape metrics capable of representing connectivity and the location of the dominant urbanised surface classes within catchments relative to the catchment outlet. In particular, the consistent inclusion of $COHESION_{SUB}$ – indicative of physical connectedness of patch type (Table 6.3) - alongside *DPLABR* for θ across the more complex models (M3, M4) and high significance in the derived regression (Table 6.6) shows that the physical connectedness of the predominant suburban class is a driving factor, alongside flow path length, for explaining the flashiness of storm runoff for the selected catchments. A similar finding was reported by Mejía and Moglen (2010b) when using a dedicated modelling framework.

Time-to-peak (*TP*) was also well characterised using a combination of information on catchment length alongside layout and connectivity of urban patches (*PX*) and percentage of landscape comprised by the largest patch (*LPI*) (Table 6.6). The optimal combination provided good predictive ability across the range of catchment shapes, sizes and levels of urbanisation. Conversely, the lack of any catchment descriptor or landscape metric that might characterise attenuation of runoff (e.g. *BFIHOST, FARL, CONTIG$_{NAT}$*) was surprising. Features such as retention ponds and greenspace are generally thought to slow down the speed of runoff and delay runoff peaks, especially in small urban areas where they are specifically installed for such purposes (Woods Ballard et al., 2015). Given the prominence of such features in Bracknell this is even more surprising as such features have ben expressly installed for this purpose, *PROPWET* was selected only once but this was in the best performing M4 combination, despite having only minor variation by urban location. Its inclusion suggests it's important to consider general patterns of catchment wetness irrespective of urbanised surfaces that are generally considered to reduce this influence (Jacobson, 2011; Shuster et al., 2005).

For both lag-time metrics (*T$_{LC}$, T$_{LPP}$*) runoff timing was primarily a function of flow path length (*DPLBAR*) and the location and connectivity of urban patches (*PX*), while the other catchment descriptors and landscape metrics (*PROPWET, LPI*) were less significant indicators (Table 6.6). The higher model fit and significance of selected variables for *T$_{LC}$* was expected as we would expect less inter-event variability in centroid-to-centroid values than peaks, which would be highly influenced by the spatial and temporal distribution of rainfall between events (IH, 1999). For both lag-time metrics there is a tendency to under predict for Swindon sites, while across the larger Bracknell catchments (B4, B5, B6) both metrics are over predicted. This suggests that either, despite *PROPWET* being used in the fitted model this does not enable the fitted model to account for the pattern observed in Table 6.7, or, that the overall greater role of attenuation ponds in Bracknell is not being well characterised, with *FARL* not being a selected variable.

6.4.3 Performance limitations in validation catchments

Poor performance in estimating peak flow, runoff volume, and runoff timing in certain validation catchments is put down to localised factors that have not been accounted for in the catchment descriptors and landscape metrics selected: Over prediction of peak flow and runoff volume for catchment B4 is likely due to not considering the attenuating effect of a large pond just upstream of the site. *FARL* was not included in the fitted models (Table 6.6) which was unexpected, as *FARL* is an important indicator of attenuation from rivers and lakes (IH, 1999; Kjeldsen et al., 2008), and the Bracknell catchments are characterised by sites with low *FARL* values (Table 6.5) indicative of attenuation. Other studies have pointed to the important role that urban waterbodies play in reducing flood peaks (Meierdiercks et al., 2010) but there is evidence to suggest that the level of control measures in many urban catchments could be insufficient to influence hydrological response (Bell et al., 2016). The two sites with the highest observed Q_{max} (B6 and S6) are both under-predicted. This is likely due to a sewage treatment works (STW) outflow located just upstream, which could be diverting significant storm water flows from other contributing areas, in effect increasing the natural drainage catchment. Likewise, the low fitted *PR, DR* and *θ* values at S6 could also reflect this STW outfall influence. The importance of representing the influence of STW outfalls on peaks flows is evinced in other empirical studies (e.g. Braud et al., 2013; McGrane et al., 2016).

High fitted *PR* and *DR* values for S8 and S4 suggests the parameter applied to this variable in the fitted model underestimates the attenuating effect of such urban greenspace. This is likely due to a lack of calibration sites with such a large relative area of *Natural Greenspace* (Figure 6.2). The role of such spaces is well covered in literature on green infrastructure (Gill et al., 2007) given their perceived role in acting like a sponge for runoff from urban areas (Jiang et al., 2018). However, given they may not be as effective when soils are wet (Nied et al., 2016) the use of mean metric values across the monitoring period may be masking their potential contribution in drier periods.

6.4.4 Landscape metrics for hydrological applications

6.4.4.1 Imperviousness and urban landscape metrics

The retention and significance of *URBEXT* in all quantity-based models indicates that total coverage of impervious surfaces is a more important factor in runoff generation and peak flows than the distribution and layout of such surfaces, reflecting the general literature (Jacobson, 2011; Krebs et al., 2013; Shuster et al., 2005). Conversely, while the high significance of mean drainage path length (*DPLBAR*) for all time-based metrics was expected, the replacement of *URBEXT* with *PX*, even in simpler models, clearly indicates that layout, connectivity and location of urban surfaces can be more important than impervious area alone for characterising the timing of runoff. This is an important observation as impervious area or urban extent are often used in modelling/attribution studies involving the timing of runoff to design hydraulic infrastructure based on event-based hydrograph analysis (e.g. ReFH: Kjeldsen 2007) or for water resource planning (Mejía & Moglen, 2009).

The findings presented here suggest that proximity index (*PX*) could be an improved measure of urbanisation for lumped hydrological applications. We have validated this finding and shown that when applied to a real-world urbanised basin the *PX* metric performs well at characterising the widely reported (Roy & Shuster, 2009; Mejía and Moglen, 2009; Krebs et al., 2016) effects that connectivity and spatial distribution of urban surfaces have on the timing of runoff. The lack, or unexpected pattern, of variability in runoff timing across a range of urban developments found in some studies when only considering imperviousness or *URBEXT* (e.g. Gallo., 2013; Miller & Hess, 2017) could be in part due to such effects. Further, the method, that considers hydrological distance of urban patches to outlet could be expanded to other land classes, such as *Natural Greenspace.*

A further limitation of only using impervious area or *URBEXT* as a lumped catchment index of urbanisation is that both underestimate the effect of permeable surfaces, and the hydrological effects of such surfaces are spatially

significant (Shuster et al., 2005). The potential role of Landscape metrics based on natural greenspace for characterising storm runoff volume has been demonstrated, with results indicating the importance of capturing suitable catchments with large connected areas of natural greenspace in model calibration. While empirical research is limited and primarily set at local or plot scales (e.g. Jarden et al., 2015) the science at catchments scales is emerging and based primarily on modelling, showing that spatial distribution of green infrastructure affects relative effectiveness in urban areas (Bell et al., 2016). Certainly modelling of storm water green infrastructure indicates spatial pattern in combination with land cover impacts upon storm response (Loperfido et al., 2014) and a recent study by Fry and Maxwell (2017) suggests location could be more important than overall coverage. Golden and Hoghooghi (2017) find this is an area of fertile research and suggest that novel measurements and big data are required. This is refelected by the difficulties first in mapping such features (Bhaskaran et al., 2010) and secondly how to represent their effect at a catchment scale without distributed hydrological modelling (e.g. Palla & Gnecco, 2015). Landscape metrics could provide a less data-intensive and more repeatable means of investigating how the spatial configuration of green infrastructure interacts with hydrological response.

6.4.4.2 Additional landscape metrics

The poor performance of fitted models to certain catchments is linked to catchment features including storm drainage and artificial transfer of water that have not been captured in the Catchment descriptors or Landscape metrics used in this study. Results from the wider literature suggest form and function of storm drainage networks can accelerate runoff and increase peak flows (Meierdiercks et al., 2010; Ogden et al., 2011), while STW outfalls have arrange of impacts on both the quality and quantity of storm runoff (Braud et al., 2013; Hale et al., 2014; McGrane et al., 2016). The difficulties and limitations in representing storm drainage in any catchment descriptor for lumped hydrological models is well acknowledged (Kjeldsen et al., 2013; Salvadore et al., 2015) due to the sub-surface nature of the features and lack of systematic method for linking with other

urban descriptors such as imperviousness (Ebrahimian et al., 2016) and this is a key area for further investigation. No systematic method was found for mapping storm drainage systems, with industry data incomplete, and empirical methods shown by other studies to be limited and geographically focused (Roy & Shuster, 2009). Attention should be paid to developing a landscape metric that acknowledges the STW artificial drainage area and also its in-built attenuating capacity. This concern also relates to questions concerning how to represent and test the efficacy of green infrastructure at the catchment scale (Golden & Hoghooghi, 2017).

6.4.5 Study limitations and further work

The limited number of sites, and their size and relative levels of urbanisation, means the statistical analyses are not representative of, and cannot be immediately applied to, larger catchments with more dense urban centres or types of development. Further, the lack of any extreme storm events limits any investigation into whether the patterns observed would change with more intense storm events. Wider testing of the landscape metrics used here across a range of catchment sizes and levels of urbanisation, alongside additional metrics to represent storm drainage and green infrastructure, is required to determine if landscape metrics could improve the operational methods and is a key area for further research. A more representative study would include a number of urban centres in different geographical locations and of different age or urban type and would include data over a longer time period in order to capture a greater range of storm events.

6.5 Conclusions

This study assessed the potential of spatially explicit landscape metrics compared to lumped catchment descriptors for explaining storm runoff from urbanised catchments. This had not been explored before and provided an opportunity to test whether findings from the limited modelling studies considering spatial configuration and hydrology are reflected in monitoring data at catchment

scales and whether landscape metrics could lead to improvements in lumped hydrological modelling and flood estimation.

The study showed that attribution of the volume and timing of storm runoff using lumped urban catchment descriptors, such imperviousness or urban extent, could be significantly improved in combination with more spatially explicit landscape metrics capable of representing the connectivity, layout and location of urban surfaces. It was also demonstrated that landscape metrics applied to areas of natural greenspace within urban areas can be useful for explaining the volume of runoff generated in storm events. These observations suggest potential improvements in modelling design flood events or water resources in ungauged catchments where models rely on lumped catchment parameters. Landscape metrics pose significant potential for bridging the gap between the spatial limitations of more simple lumped modelling approaches and the more complex but data intensive limitations of distributed modelling approaches.

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7 SYNTHESIS AND DISCUSSION

7.1 Introduction

This chapter provides a synthesis of the work contained within this thesis and discusses the key findings of thesis in the wider context of scientific understanding regarding attribution of storm runoff in urban catchments and potential improvements to UK flood estimation methods. Section 7.2 provides a synthesis of the three objectives and uses key findings from Chapters 4 to 6 to address the three related thesis hypotheses. 7.3 provides a discussion of the thesis aim. 7.4 outlines potential limitations of the data and methods used. Further work is outlined in 7.5.

7.2 Synthesis of objectives - key findings and hypotheses testing

The aim of this thesis was to evaluate the potential of lumped and spatially explicit characterisations of urban land cover to explain storm runoff in urban catchments and their application in UK flood estimation methods. To achieve the aim the thesis had three research objectives and related hypotheses. The basis for developing the objectives were four knowledge gaps and three related *a priori* hypotheses that considered together facilitate an informed consideration of the aim. These objectives and hypotheses are evaluated here with discussion on the overall aim the thesis following in 7.3.

7.2.1 Urbanisation impacts on storm runoff along a rural-urban gradient

The first thesis hypothesis was that urbanisation causes changes in the hydrological response (storm hydrograph) of a catchment to storm events and these changes are directly proportional to the level of urban extent and affected by antecedent conditions. To test this, the first objective assessed urbanisation impacts on storm runoff along a rural-urban gradient defined by the lumped catchment descriptor urban extent – *URBEXT* - to determine its suitability for

characterising urbanisation effects on storm runoff and the contributing role of soil moisture.

Hydrological response was compared along a rural-urban gradient of urbanisation between catchments using scaled and normalised quantity- and time-based hydrograph metrics and considering the effect of antecedent soil moisture. Clear differences were found between more rural and urbanised catchments but above a certain threshold of urban extent runoff quantity was relatively unaffected by further urbanisation and runoff response times were highly variable and did not reduce linearly with increased urbanisation. The findings demonstrated that while a lumped catchment measure of urbanisation like urban extent can explain broad differences in the hydrological response between rural and urban catchments, it is insufficient to explain differences between more urbanised catchments with variable spatial patterns of land cover relative to the catchment outlet. Furthermore, antecedent soil moisture was shown to alter the volume and timing of runoff generated in catchments dominated by rural land use, but was not found to affect the runoff response where urban development dominates.

The hypothesis (H1) can therefore be rejected as the findings suggest that while urbanisation does causes changes in the hydrological response of a catchment at low levels of urbanisation – evincing broad differences between rural and urbanised catchments – the relationship does not continue to be proportional at higher levels of urbanisation. Likewise, while antecedent soil moisture is important for rural catchments, storm runoff in more urban catchments is relatively unaffected.

7.2.2 Landscape metrics and flood estimation

The second hypothesis was that spatially explicit landscape metrics can improve characterisation of urban land cover over lumped catchment descriptors and improve estimates of the index flood. To evaluate this the second objective assessed the potential for using hydrologically relevant urban catchment

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descriptors and landscape metrics for estimating the index flood *QMED* in small urbanised catchments.

Hydrologically relevant urban catchment descriptors and landscape metrics were derived to characterise urban catchments using high-resolution geospatial data and tested for application in UK statistical flood estimation methods compared to existing methods and data. Using high resolution geospatial data improved the hydrological representation of the urban land cover, including: delineation of small urban water features that were previously unmarked in LCM2007, locating specific areas of natural greenspace that could have higher infiltration, areas with potential sustainable urban drainage that would attenuate runoff, and provided more hydrologically suitable flow boundaries for highly altered catchments that traditional flow pathways analysis missed. Catchment descriptors for indexing flood attenuation and catchment area from these spatial data showed significant changes in value, while for urban extent the change was not significant. A range of uncorrelated landscape metrics suitable for providing spatially explicit and more hydrologically relevant characterisation urban land cover were also derived. When applied to observed values of *QMED* using a weighted least squares regression it was shown that landscape metrics can better represent the hydrological complexity of an urban catchment in a spatially explicit form suitable for statistical attribution. Combining the spatially explicit landscape metrics with catchment descriptors led to minor improvement in estimates of *QMED* using a leave-one-out cross-validation *(MSE = 0.6)* over simply using only the existing FEH catchment descriptors (*MSE* = 2.5).

The hypothesis (H2) that spatially explicit characterisation of urban land cover will improve estimates of the index flood over lumped catchment descriptors has been accepted. However, the improvements were only minor and the method suffers bias from its limited and localised application. Thus while a more hydrologically relevant set of urban catchment descriptors, based on landscape metrics, has been shown to improve estimates the index flood (*QMED*) compared to existing data and methods, the positive result may have been due to this being a more localised and urban specific regression, with limited data. Despite this,

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this represents the first known investigation of landscape metrics for use in flood estimation methods and more importantly it demonstrated that landscape metrics provide diverse means for characterising land cover with potential for explaining hydrological response in urban catchments.

7.2.3 Landscape metrics and storm runoff

The third and final hypothesis posited that urban runoff is controlled by the extent and layout of urban land cover and that attribution of both the quantity and timing of storm runoff can be improved by characterising urban land-cover using spatially explicit landscape metrics, compared to lumped catchment descriptors. To asses this, the third objective evaluated the relative performance of urban catchment descriptors and landscape metrics for explaining inter-catchment variation in storm runoff.

The relative performance of landscape metrics and catchment descriptors for attribution of storm runoff response in small urban catchments was tested. The first stage used 11 independent calibration catchments and tested regressions of catchment descriptors against observed storm runoff data, while the second stage combined these in a regression with a number of uncorrelated landscape metrics. Performance was further tested, and potential limitations identified, by applying the fitted regressions to seven independent validation catchments and testing their relative performance. Results showed attribution of hydrological response in urban catchments was improved by at least an *adjR^2* of 0.06 by combining both catchment descriptors and landscape metrics, except in the case of peak flow (no improvement). Landscape metrics representing the connectedness and shape of suburban and natural greenspace patches improved attribution of percentage runoff and direct runoff and over all quantity metrics the lumped urban catchment descriptor urban extent retained its greater importance than more spatially explicit means of urban land cover characterisation. Landscape metrics characterising layout, connectivity and location of urban surfaces relative to the catchment outlet within a catchment

improved attribution of all time-based metrics, including time-to-peak, flood duration and lag-time between rainfall and runoff.

The hypothesis (H3) that urban runoff is controlled by the extent and layout of urban land cover has been accepted, as have elements of the associated hypothesis, namely that attribution of both the quantity and timing of storm runoff can be improved by characterising urban land-cover using spatially explicit landscape metrics, compared to lumped catchment descriptors. For runoff quantity the hypothesis that storm runoff is controlled (to some degree) by the extent of urban land cover was accepted, however peak flow was not controlled (to any degree) by the layout of these surfaces within an urbanised catchment. Further, peak flow estimates were not improved by considering landscape metrics. Instead they remained best predicted by catchment area, soil hydrology and by the overall urban extent. For the remaining volume- and time-based metrics it was shown that runoff was controlled by the extent and layout of urban land cover and that and attribution of both the volume and timing of storm runoff can be improved by characterising urban land-cover using landscape metrics, compared to using lumped catchment descriptors.

7.3 Discussion

This thesis had the overall aim to evaluate the potential of lumped and spatially explicit characterisations of urban land cover to explain storm runoff in urban catchments and their application in UK flood estimation methods. This will be addressed in two stages. First, through a discussion that evaluates what the thesis findings indicate for potential attribution and hydrological modelling of storm runoff in urban catchments using lumped and spatially explicit measures of urban land use. Second, a discussion of the relevance of the thesis findings for potential application in UK design flood estimation methods.

7.3.1 Using lumped and spatially explicit characterisation of urban land cover to explain and model storm runoff in urban catchments

7.3.1.1 **FEH urban catchment descriptors - lumped characterisation of urban land cover**

This thesis used the widely used measure of urban extent – *URBEXT* – used in FEH methods (IH, 1999), that has been shown to be a robust measure of catchment impervious area (Miller &Grebby, 2014). Such a lumped measure was shown to be suitable for characterising the fundamental shifts in hydrological function that differentiate rural pervious catchments from disturbed urban catchments with large areas of impervious surfaces and artificial drainage. However, across more urban sites (*URBEXT* ≥ 0.26) there was little separating the observed quantity of runoff between sites and inter-catchment variability in the timing of runoff was not directly related to increased urban extent. These findings were suggestive of two causal factors that are explored in the wider literature: i) the presence of a threshold of urbanisation, ii) non-linear relationships between urbanisation and runoff, and iii) spatial land cover and water management factors that disrupt runoff generation and conveyance.

The thesis had not set out to investigate thresholds but the observation of an occurrence above which the assumed relationships between urbanisation and storm runoff was changed was suggestive that catchment imperviousness may not be sufficient to explain storm runoff in more urbanised catchments and that urbanised catchments could become so disturbed as to effect a profound shift in hydrological response. Thresholds in natural environment properties that alter the response of a related system are commonly understood to exist in ecology for explaining shifts in ecological structure (Smol and Douglas, 2007) and also in geomorphology for explaining landslides (Van Asch et al., 1999). Such thresholds are also considered to occur in hydrological systems, such as the onset of large floods (Zehe and Sivapalan, 2009) but they are rarely observed in empirical data (e.g. Zehe et al. 2007; Ali et al. 2015) and evidence in urban systems is limited. The observation of such a threshold across such a limited number of catchments provides evidence that such thresholds exist in urban systems and should be

considered but it is uncertain to what degree the changes are due to percentage urbanisation or change in type and use of land cover with urbanisation.

Using a small set of sub-catchments would always limit specific identification of a threshold and while this thesis has not uncovered evidence of a particular threshold, the findings suggest a change in rainfall-runoff behaviour in an urban extent of between 0.10 and 0.25. This is in agreement with the wider literature that reports values between 5% (Booth & Jackson, 1997) and 20% (Brun & Band, 2000). Oudin et al. (2018) came to a similar conclusion when using data from 142 catchments, identifying 10% impervious area as a threshold above which high flows are impacted. Interestingly, the authors also concluded that the presence of a threshold suggests that imperviousness alone is not sufficient for attributing the impacts of urbanisation on hydrological response and pointed to the need for considering a wider range of land cover classes and more spatially explicit measures for characterising urban land cover.

The lack of a clear relationship between urban extent and peak flow and runoff volume between the more urbanised catchments was not expected and does not fit generalised assumptions of the relationship between imperviousness and runoff (Jacobson, 2011; Lim, 2016).   There is limited evidence of such phenomena whereby urbanisation does not always result in elevated peak flows (Wibben, 1976; Dudly et al., 2001). The reasoning provided is that impervious increases were not accompanied by associated drainage (Shuster et al., 2005). This could explain why only one site in this thesis (S5) exhibited an increase, given it was the only one dominated by storm drainage at higher levels of urbanisation. The observation of a threshold of urbanisation that alters storm runoff processes implies   hydrological modelling studies should not simply assume a more linear relationship between urbanisation and runoff response (e.g. Dixon & Earls, 2012; Miller et al., 2014; Palla & Gnecco, 2015).

7.3.1.2 **Landscape metrics - spatially explicit characterisation of urban land cover**

The lack of a clear relationship between urban extent and catchment response time, coupled with the high degree of inter-catchment variability across all time-based metrics, provided evidence that additional factors require consideration for potentially explaining the lack of a clear relationship between urban extent and storm runoff. Additional and refined urban land cover classes were used to characterise catchment land cover to account for the effects of variable land cover beyond simply suburban and urban areas. Landscape metrics were employed to account for the role that spatial layout could have on storm runoff (e.g. Mejía & Moglen 2009; Zhang & Shuster 2014; Wang et al. 2015). This need to move away from impervious area as a lumped and spatially limited metric for hydrological response has been suggested in the wider contemporary literature (Mejía & Moglen, 2010a; Ferreira et al., 2016; Lim, 2016). The testing of a range of landscape metrics used in quantitative ecology thus posed a unique opportunity to investigate their suitability for overcoming the limitations identified in the lumped catchment descriptor *URBEXT* and to consider their potential application for flood estimation. Other opportunities included the development and testing of the hydrologically relevant landscape metric proximity index (*PX*), that was conceptually employed by Van Nieuwenhuyse et al. (2011) and here represents a first application to real-world data. Additionally, the mapping and characterisation of urban greenspace and areas employing SuDS using landscape metrics provided an untested means for characterising the attenuation effects that such spaces are considered to have.

It was shown that landscape metrics are well suited to derivation from national land cover data as provided by widely available datasets such as LCM and mapping of natural areas by Nature England. As such they are suited to being derived at a national scale. They offer a range of potentially uncorrelated (in this study) measures suitable for characterising urban land cover that expands upon simply using a single lumped measure of urban extent or impervious area. The proximity index (*PX*) in particular was shown to be a landscape metric capable of

expressing both the location of urban land-cover relative to the catchment outlet, and also the connectivity of urban surfaces in patches. This mirrors the finding from Van Nieuwenhuyse et al. (2011) that *PX* captures effects of both clumping and distance – being particularly effective at capturing the relative importance pf location close to the catchment outlet, while small remote patches have little impact. As such it was considered to be a suitable means for capturing the information used in the unused FEH catchment descriptors *URLOC* and *URBCONC* that were developed to characterise location and connectivity of urban areas within a catchment (Bayliss et al., 2006).

In order to account for the potential attenuating influence of certain contemporary urban land cover involved creative use of existing data to bypass difficulties of primary designation from remote imagery. The development of a refined urban land-cover class in the form of *Natural Greenspace* provided an additional area of investigation, that the wider literature suggested could provide a means for characterising the attenuating influence of such areas (e.g. Gill et al., 2007; Jiang et al., 2018). Mapping of these areas using existing geo-spatial data provided a means of overcoming the difficulties identified in the wider literature of using remote sensing imagery, especially in urbanised areas (Vatseva et al., 2016), but still requires ground truthing to ascertain the hydrological condition is as expected. The mapping revealed relatively large patches of natural greenspace in the urban catchments selected and could be used to overcome the limitations of current LCM mapping in urban areas. Efforts to map and characterise the influence of SuDS in urban areas also used axillary geospatial data for mapping SuDS suitability (Dearden, 2016). The rationale for using the mapping in recalculating urban extent was based on the assumption that such areas should not be treated as urbanised given areas with SuDS should mitigate to greenfield runoff rates (Defra, 2011). While mapping was successful the overall areas were so small as to have no discernible effect on calculations of urban extent, which was not surprising. However, given urban areas of the UK are expanding at record rates due to high rates of population growth (14% 2012-2037: ONS, 2012) and new developments require SuDS (DEFRA, 2015) their relative importance

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will grow in the future. This therefore suggests FEH methods will need to specially consider such mitigation effects in producing flood estimates in the future.

Improvements in estimating the index flood *QMED* for the selected catchments using landscape metrics were demonstrated and offered a number of insights with regard to their potential use for explaining storm runoff. Primarily they clearly offer a means of representing the spatial properties of urban land cover in a single suitable catchment value. By using these landscape metrics alongside the existing catchment descriptors used they can provide a more heterogeneous means of characterising catchment properties which could reduce information redundancy for providing more reliable models. This quality means they can offer a more urban-orientated and spatially representative means of estimating *QMED* that does not rely on *URBEXT*. These are all positive results given the limitations noted in the literature on using the FEH statistical approach in small urban catchments (Kjeldsen et al., 2008; EA, 2012a).

A more detailed investigation into the potential use of urban landscape metrics for attribution of storm runoff was carried out in Objective 3. The selected landscape metrics provided a demonstration of the potential they offer for characterisation of urban catchment properties that were identified as limitations in Objective 1 and offered a number of insights regarding the relationship between storm runoff response and urban catchment properties. Results showed the spatial distribution of urban areas does not determine the peak flow, which contrasts with findings from Objective 2 (Miller & Brewer, 2018) and with the wider literature (e.g. Mejía and Moglen, 2009; Bell et al., 2016). However, it should be considered that the mean of observed peak flows (shown to vary considerably across urban sites: Objective 1) is a different to taking the median annual flood, particularly from such a short duration of data.

Connectedness and shape of suburban and natural greenspace patches were empirically shown in this study to influence runoff volume, validating modelling studies (Mejía and Moglen, 2009; Zhang and Shuster, 2014) and further highlighting the importance of location and connectivity of pervious surfaces for

storm runoff generation shown in other studies (Lim 2016). Connectivity and location of urban surfaces were the spatial factors shown in this study to replace urban extent for improving attribution of runoff timing. Results clearly demonstrated how greater connectivity and proximity to the catchment outlet were influential on reducing catchment response times, as found elsewhere (Shuster et al., 2005; Mejía and Moglen, 2010b) but rarely empirically demonstrated (Braud et al., 2013). These observations highlight the value of landscape metrics for attribution of urban runoff and the associated potential for improving the performance of lumped hydrological models to estimate both runoff volume and timing based. In particular, they provide a means for setting urban land cover based parameters responsible for the production and transfer of runoff, not simply based on relative coverage, but location and connectivity relative to an outlet of interest. This therefore reduces the need for in-model calibration of parameters to modify lumped runoff generation in order to account for runoff volume and timing processes affected by distributed processes.

Utilising landscape metrics in hydrological studies is still a fertile area of research and applications for studying hydrological processes have been limited (e.g. Yuan et al., 2015) or based on modelling (e.g. Yang et al., 2011) and has only recently been applied to empirically assess urban processes (Miller & Brewer, 2018; Oudin et al., 2018). There is a general perception that because lumped models take the entire basin as a single unit and that spatial variability is disregarded, there is an overall inability to consider spatial processes that renders them less performance than distributed models (Moradkhani and Sorooshian, 2008). In reviewing the future of hydrological models of urbanised catchments Salvadore et al (2015) highlights spatial variability as a key element that lumped approaches are not capable of describing, thus pointing to a future reliance solely on distributed approaches. While this is likely true of the (far) future where technology is bound to exponentially increase, this must of course be considered in the context of the current (and near future) reality whereby such lumped approaches are actually more suitable in many cases where only an outlet discharge is required, as they pose less over parametrisation problems (Vrebos

et al. 2014) and require significantly less data than distributed models (Beven, 2001). The potential demonstrated by selection and performance of landscape metrics in this thesis points towards a middle ground for hydrology to work on in the intervening period. They pose a potential means of bridging the gap between the parameter simple but spatially limited lumped modelling approaches and the spatially-explicit but parameter heavy distributed models. Their strength, as shown in this thesis, rests on their ability to be spatially explicit, yet in a form suitable for testing in a statistical attribution framework against observed data. Alongside the improving availability of high-resolution data for characterising urban land cover this could facilitate improvements in hydrologic understanding and theories that as Bahremand (2015) notes will only occur by focusing on the process model and on systematic learning from observed data. It is such improvements that are ultimately required to justify suitability and performance of models for urban applications, and the findings of this thesis suggest development and testing of hydrologically relevant landscape metrics will continue being a productive area of research. One particular area that is likely to benefit in the near term is flood estimation methods that rely on empirical data and means for characterising physical catchment characteristics that affect runoff generation. The next section discusses this in detail.

7.3.2 Potential application of landscape metrics in UK design flood estimation methods

This section focuses upon the second part of the thesis aim, namely, considering the implications of data and research findings contained in this thesis for UK flood estimation methods and data used in the UK. It discusses potential improvements with regard to particular limitations that have been identified in the literature review concerning the application of current methods applied in small urban catchments. The focus is on methods used in the Flood Estimation Handbook (FEH): the statistical method for estimating the index flood, and the revitalised flood hydrograph (ReFH) hydrological model.

7.3.2.1 **Develop and test improved catchment descriptors**

This thesis has shown the value of developing and testing refined urban land cover typologies and improved catchment descriptors to improve upon the limitations of those currently used in FEH methods. It has demonstrated workable methods that build on existing datasets for developing a more hydrologically relevant characterisation of urban land cover to include areas of potential SuDS and to classify suburban areas by density of development. Methods to delineate more accurate urban catchment boundaries and small urban waterbodies have been provided. It also provided a means for differentiating between what is currently considered as rural and what in urban areas is more likely urban greenspace (parks, recreation) or areas of natural greenspace (nature reserves, conservation areas). Impervious mapping was not considered as it is not currently available as a national map and *URBEXT* has been shown to be a robust proxy (Miller & Grebby, 2014). Given developments in mapping imperviousness in major urban areas across Europe (EEA, 2016) it will not be long before this is available. Such mapping will facilitate direct mapping of impervious cover across a catchment and replace the simplified Suburban and Urban LCM classes currently used. Combined with landscape metrics it should be possible to quantify the relative location and connectivity of variably impervious areas, greatly improving the ability to characterise urban land cover for flood estimation.

Improvements to existing catchment descriptors for urban applications by using the refined typologies have been demonstrated. Catchment areas account of detailed urban topography and storm drainage that enabled delineation of catchments with artificial drainage areas. Given the value of this approach being shown in other studies (Jankowfsky et al., 2014; Miller et al., 2014) and the importance of area for estimating *QMED* (IH, 1999; Kjeldsen et al., 2008) this is a particular area that offers urban improvements. *FARL* was significantly altered for certain catchments and demonstrated the pressing need to update the catchment descriptor to include more modern high-resolution mapping, given it remains derived from dated low-resolution mapping (Bayliss, 1996) that will not include many contemporary features. Results suggest that for the key urban

catchment descriptor the data and methods presented offer no discernible improvements, particularly accounting for areas of SuDS. Despite this, as SuDS become more prevalent they will need to be considered, either as a land cover class detracted from *URBEXT* or as point features that mitigate upstream land cover.

This thesis offers a range of landscape metrics that could be used as alternative catchment descriptors for characterising urban land cover beyond *URBEXT*. Many offered little value for explaining storm runoff but certain landscape metrics provided a means for characterising some common hydrological effects such as attenuation from areas of natural greenspace (Golden & Hoghooghi, 2017) or variations in the spatial distribution of impervious areas (Zhang and Shuster, 2014). In particular, the proximity index – *PX* – was shown to have the potential to replace *URBEXT* by facilitating a more spatially explicit and hydrologically relevant characterisation of urban land cover. This signals this as a potentially valuable means of improving the spatial representation of urban land-cover in the lumped framework of the existing methods. The benefits of providing a wider range of variables representative of catchment properties for use in flood estimation was also demonstrated by Wan Jaafar and Han (2012).

While the landscape metrics used in this study have not before been evaluated for use in flood estimation methods there is one catchment descriptor currently used that is spatially explicit (*FARL*). Despite refinement of *FARL* to characterise the effects for the attenuation effects of many small waterbodies it was not included in any of the best performing regressions for *QMED* or the suite of hydrological metrics considered. This was surprising given its prominence in the nationally derived regression used to estimate *QMED* (Kjeldsen et al., 2008) and being the only option for characterising the attenuating influence of the urban ponds and lakes. Its attenuating influence on the time-based metrics was expected given the wider literature pointing to the effects and design rationale for such features being to delay the timing of runoff and delay the flood peak (Walker, 1998; Wilkinson et al., 2010; Woods Ballard et al., 2015). Given such features are so prominent in Bracknell where they were installed for such a purpose

(Packman and Hewitt, 1998) one would expect it to have a role in differentiating between runoff timing observed between the two towns. This suggests the features may not in fact performing as designed.

URBLOC and *URBCONC*, which characterise urban location and concentration respectively (IH, 1999), were not included in the nationally derived FEH regressions. The results for this thesis however show the important role that both location and connectivity have for attribution of runoff timing. Easily derived landscape metrics have been shown to be effective for capturing such effects and could offer improved catchment descriptors for catchment properties that are generally considered to have spatial effects. These can be applied to any class and so it could be possible to re-evaluate the spatial effects of land use by using spatially explicit landscape metrics. *PX* in particular is one that poses good potential given its hydrological relevance and capturing information on location, connectivity and size.

The findings regarding thresholds of urbanisation above which changes in hydrological response were observed is interesting to consider in relation to the current definitions of what level of urban extent constitutes an 'urban' catchment. According to FEH methods all the catchments used in this study would by definition be considered at least 'slightly urbanised' and on average 'very heavily urbanised' (Table 3.2). These definitions were based on a national scale evaluation of catchments that could be very large. In such a case an *URBEXT* value of 0.06 could be indicative of a large catchment containing a town. In this study the same urban extent was indicative of a small highly rural catchment with only a small hamlet and some farm buildings (S2: Table 4.1). This suggests a re-evaluation of how catchments are classified that considers scale and spatial configuration should be considered. This could be facilitated, for a catchment of similar URBEXT but different configuration, by using landscape metrics such as the proximity index or contiguity to compare between catchments with a dense urban area located near the outlet, with that of a fragmented distribution weighted towards the upper reaches. This is important as the 'urban' classification affects the catchments considered for regression and the methods the threshold for

applying the UAF – currently set as *URBEXT* > 0.03. Such a re-evaluation will also be important in the future for urbanised catchments that employ large scale SuDS and GI to mitigate storm runoff, as despite having potentially large areas of urban development, these should by design be producing runoff at effective greenfield (rural) rates.

7.3.2.2 Improved methods for small urban catchments

For the FEH statistical method the findings of Chapter 5 show that current methods can result in significant under estimation of *QMED* for most small urbanised catchments and that the inclusion of spatially explicit landscape metrics for characterising urban land cover can lead to improvements in estimation of *QMED* (Table 5.6). As noted, however, this comes with important limitations that limits direct comparisons to current flood estimation methods for the index flood. Primarily the regression was only undertaken on small set of localised and generally heavily urbanised (*URBEXT* ≥ 0.15) catchments. This therefore limits the applicability of the findings for a national method based on regressions across a range of catchment types and sizes. A further problem to consider is that the FEH statistical method employs an urban adjustment factor (UAF) to the 'as rural' estimate of *QMED*, rather than directly considering the effect of urbanisation in a single formula, as done in this thesis.

Considerable work has been undertaken to improve the representation of urban effects on estimates of *QMED* (Packman, 1980; Kjeldsen, 2009; WHS, 2016). Considering the scale and time-line of work that went into these improvements and the limitations identified in the methods and data used in this thesis it is difficult to directly identify, in this study alone, how more high resolution urban data and landscape metrics could improve estimates of *QMED* for urbanised catchments. What has been shown however is that there are potential avenues to be explored that could benefit from having high resolution urban data and landscape metrics. These are listed below with potential limitations:

- A possible improvement could be to replace UAF with a different catchment descriptors equation for *QMED* for catchments at a certain level

of urbanisation. However this would present difficulties in that whatever threshold was used as it would introduce a discontinuity in estimates of *QMED*, particularly for catchments near the threshold.

▪ A reassessment of the UAF could be undertaken using landscape metrics to investigate if they could improve upon the use of *URBEXT* for characterising the effect of urbanisation on *QMED*. This could employ a similar approach as taken in the WINFAP 4 urban adjustment procedures update (WHS, 2016).

▪ Using landscape metrics could provide a more suitable index of the effect of catchment soils (*BFIHOST*) on runoff UAF equation. Given the effect of urbanisation on peak flows is considered to be more dramatic when development tales place on a permeable and less-responsive soil than on a more impervious soil such as clay then improving catchment representation of *BFIHOST* would be beneficial. At present *BFIHOST* is estimated using an area weighted catchment value (IH, 1999: Vol 3). This loses information on the variety of soils in a catchment and the related spatial nature of the soils relative to the catchment outlet. Landscape metrics could provide a more representative means for characterising the diversity and layout of catchment *BFIHOST*. This could be particularly well represented by using a landscape metric such as PX that considers the location and size of patches of similar class. Further, in combination with information on the location and size of urban patches, it would be possible to represent which areas of urbanisation generate more or less runoff.

▪ The identification of a threshold or urbanisation above which rainfall-runoff process were observed to alter (Chapter 4) and that percentage runoff (*PR*) was partially explained by the connectivity of *Urban Greenspace* and *Suburban* patches (Table 6.6) suggests improvements could be made to UAF estimates. Further, the relationship between *URBEXT* and *URBCONC* – which is a measure of connectivity between urban patches – has been shown to alter at a value of *URBEXT* around 0.1 (IH, 1999), above which subsequent increases in *URBEXT* result in a less dramatic

increase in *URBCONC*. Therefore, if this relationship is not stable, and percentage runoff is affected by connectivity as well as urban extent, then having variables for both extent and connectivity in the UAF equation could improve estimates of *QMED* at higher levels of urbanisation.

Despite not being specifically considered in this thesis the ReFH rainfall-runoff model has some key areas that could benefit from some of the findings of this thesis. The important areas relate to the catchment descriptors currently used for estimating parameters in the loss model and the routing model.

- This thesis demonstrated the value of refining urban catchment boundaries by using sub-surface information on storm drainage and higher resolution DEM (Chapter 5). Estimates of modelled peak flow for small urban catchments would be improved by using a more realistic catchment area. The value of more realistic catchment boundaries that reflect storm drainage effects was shown by Vesuviano & Miller (2018).

- Estimates of *Tp* using catchment properties were shown in Chapter 6 to be improved by using landscape metrics and in particular by using *PX*. Kjeldsen et al. (2013) explored the relationship between the Tp (IUH) ratio used in ReFH2 and the catchment descriptors *URBEXT*, *URBCONC* and *URBLOC* and found evidence of a relationship between *URBLOC* and the Tp ratio values used in their study. The findings from Chapter 6 suggest a revaluation of this ratio using *PX* and a wider number of catchments could lead to an improved means for estimating the ratio based on information concerning both the connectivity and location of urban development within a catchment.

- The inclusion of landscape metrics that can represent the connectivity of areas of *Suburban* development and *Natural Greenspace,* alongside both *URBEXT* and SAAR was shown in Chapter 6 to improve estimates of percentage runoff. Percentage runoff is an important parameter in ReFH methods as it has a direct scaling influence on the magnitude of the resulting direct runoff flood peak. ReFH2 uses an assumption that 30% of an urban area is impervious and a fixed estimate of percentage runoff from

urban areas (70%) and relies on relationships between dated mapping (Kjeldsen et al., 2013). It could therefore streamline the process and reduce reliance on previously derived relationships and outdated geospatial data if a new method for estimating the percentage runoff from urban areas within a catchment was developed, based on a regression between the direct runoff attributed to urban areas (achieved by removing the modelled direct runoff from rural areas) and landscape metrics.

While findings from this thesis regarding the potential use of landscape metrics for explaining flood duration and lag-time do not have a direct application in UK FEH methods the findings could have a wider application. For example, the flashiness of storm events, represented by θ, is a key consideration for measures to reduce flood risk (Sauer et al., 1983) with urban areas typically having a more flashy response (Braud et al., 2013) and is used in engineering to define storm hydrographs (Serinaldi & Kilsby, 2013). Lag-time is also required by many synthetic unit-hydrograph models for flood simulation (McEnroe and Zhao, 2001).

Landscape metrics have been shown to be suitable for characterising the attenuating effects of urban greenspace that could also be applied to other forms of GI such as SuDS. Given there is considerable interest in using spatial planning of impervious surfaces and GI within a catchment is to reduce flood peaks (Jiang et al., 2018) the use of landscape metrics offer a potential means for characterising such features and thus for attributing their effects in flood estimation methods.

The integration of spatial planning with flood-risk management has gained prominence for planning flood mitigation but has been impeded by a lack of suitable integrated information, technologies and tools (Ran and Nedovic-Budic, 2016). Likewise, despite an acknowledgement that enabling a more geometric catchment descriptor of urban land-cover could improve current UK flood estimation methods (Kjeldsen et al., 2013; Vesuviano & Miller, 2018) there has not been suitable data. Given this thesis has shown that landscape metrics are a workable method for improving characterisation of land cover effects on storm

runoff response a more detailed analysis across a wide number of urban catchments with long flow records would provide a more suitable approach for determining if landscape metrics offer potential improvements for applying the index flood or ReFH methods in ungauged urban catchments.

7.4 Limitations

This section assesses the limitations of the data and analysis undertaken in this thesis with regard to the thesis aim and the implications for taking the findings forward into further research to enable some of the potential areas of flood estimation method improvements identified.

7.4.1 Limited number of extreme events

The hydro-meteorological data collected from the observation network over the period 2010-2015 provide only a limited time-series of rainfall-runoff behaviour across the selected catchments. This limits the potential for capturing extreme events such as the 1 in 20 year flood or beyond as only one event exceeding a 2 year return period was captured. It is therefore uncertain to ascertain the impact of urbanisation on the runoff response for more extreme events. This is an important limitation the given relative effect of urbanisation on flooding decreases with storm magnitude and/or rarity. Furthermore, the observed relationships between landscape metrics and either *QMED* or the hydro-meteorological metrics selected could therefore change if more extreme events were considered.

7.4.2 Nested catchments

The majority of monitored sites are sub-catchments within the two EA gauging stations that drain two towns in the south of the UK. This was the monitoring design used to enable a high-density monitoring network across a range of urbanised catchments within a limited geographical area. While this facilitates comparisons between catchments with broadly similar geology, climate and soils, the main limitation is that the subsequent statistical analyses have required careful consideration of suitable study design to ensure independence of data when deriving regressions (Chapter 6) or comparing catchment responses

(Chapter 4). This limited the number of catchments that could be used in statistical tests.

7.4.3 Limited geographical relevance

A key limitation of the study design used is the limited geographical coverage provided by the selection of the two study towns. The study design required both towns to be of reasonably similar age and composition, and to be situated in catchments of similar climate and geology/soils. They cannot therefore be taken as representative of towns and cities across the UK, as many others are situated on different geology or have varying climate, and both study towns are typical examples of planned towns developed in the post-war period to the present day. This has implications for the landscape metrics derived and the relationship to storm runoff as the type and age of development in both towns differs greatly from older urban centres and from larger cities with a mix of development types and ages. As such the findings of this thesis can only be considered as relevant to the locations studied and indicative of relationships and processes in other urban areas of the UK.

7.5 Further work

In order to address the limitations of this theses findings for assessing the wider potential for landscape metrics in storm runoff attribution and UK flood estimation methods a number of key areas of further work are suggested:

- A more suitable study that would be able to make more robust conclusions concerning the attribution of flooding requires longer time series of rainfall and runoff. This would capture more of the extreme events that lead to flooding and which are the focus of efforts to mitigate storm runoff. Maintaining the ongoing presence of such networks in urban areas is however difficult due to degree of urban development that takes place and the costs involved. Current national river gauging by the EA includes only a limited number of small urban catchments with data suitable for high flows analysis.

- To be more representative of different types of urban development and the role of climate requires undertaking a similar study but over a much wider geographical area and using a greater number of catchments. This would be particularly important in the case of potential applications in UK flood estimation methods. It would also be advisable is these catchments were not nested as this would ensure greater independence in the data. An improved study design that includes a similar diversity of urbanised catchments but across a wider area and with suitable hydrological data would however be difficult to realise in terms of finding suitable catchments.
- Additional landscape metrics that could be used to characterise the effects of storm drainage, SuDS and STWs could improve the attribution of storm runoff in catchments where such factors have been suggested to alter the storm runoff response. Methods do not currently exist for characterising such features but as datasets such as the SuDS asset register become available this could be researched using the production of a national scale map locating such features and their properties.

7.6 References

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8 – CONCLUSIONS

8.1 Conclusions

Taken together the findings of this thesis have challenged some common assumptions in urban hydrology that have not been subject to specific empirical testing across a suitable range of small urbanised catchments. It has been shown that the relationship between urban extent and storm runoff is not stable along a rural-urban gradient in more urbanised catchments, that factors relating to the location, shape and connectivity of impervious and pervious surfaces alter this relationship, and that thresholds of urbanisation exist above which such factors become more dominant controls.

Landscape metrics that have only been conceptually tested for hydrological applications have been applied to real-world hydrological data and shown great potential. Landscape metrics have been shown to present a workable mechanism for lumped models and methods to differentiate between different spatial distributions of the same land cover type. This enabled testing and validation of findings from distributed modelling studies that indicated the importance of considering spatial distribution and connectivity of impervious areas. This thesis also demonstrated (for the first time) that it is possible to improve estimates of urbanisation impacts of storm runoff in urban catchments by using landscape metrics capable of representing the connectivity, location and layout of urban land-cover. This had not been possible to empirically validate without a suitable spatially-explicit means for catchment scale characterisation. This shows landscape metrics can act as a bridge between lumped and distributed modelling approaches and will be increasingly useful for attribution of storm runoff as hydrological catchment descriptors.

The methods and data used, and the findings they have led to, offer unique contributions to scientific understanding in the domains of theoretical knowledge, empirical evidence, method, and knowledge of practice. By demonstrating for the first time the possibility of improving attribution of storm runoff using landscape metrics this thesis opens a number of potential research avenues that could lead

to further scientific understanding of the processes occurring in urban hydrological systems and means for characterising and attributing the effects of urbanisation. Furthermore, these findings suggest a re-evaluation of FEH and ReFH methods using landscape metrics could improve the methods and support improved fluvial flood risk assessments in small urban catchments.

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APPENDICES

Appendix A – Table of symbols

	Formula	Explanation	Parameters
Hydrological symbols			
DR	Storm runoff volume expressed as depth over catchment area in the observed hydrograph	Direct Runoff (mm)	
PR	Proportion of rainfall converted to direct runoff in the observed hydrograph	Percentage runoff (%)	
Q_{max}	Maximum recorded flow during storm event	Peak flow (cumecs)	
θ	$Q/Q_{max}= 0.5$ (in median hydrograph scaled by Q_{max})	Flood duration - measure of hydrograph shape or flashiness (h)	
T_P	Time between onset of storm runoff and peak flow in the unit hydrograph	Time-to-peak (h)	
TP	Time between onset of storm runoff and peak flow in the observed hydrograph	Time-to-peak (h)	
T_{LPP}	Time between peak rainfall and peak flow from storm event in the observed hydrograph	Lag-time peak-to-peak (h)	
T_{LC}	time between centroid of rainfall and centroid of storm flow in the observed hydrograph	Lag-time centroid-to-centroid (h)	
SMD	The amount of water required for a soil to reach field capacity	Soil moisture deficit (mm)	UK Meteorological Office rainfall and evaporation system (MORECS)
FEH symbols			

Area		Catchment drainage area (km^2)	A = Area of catchment
SAAR	$$\frac{\sum_{i=1961}^{1990} P_i}{30}$$	Standard-period Average Annual Rainfall (mm) rainfall for the period 1961-1990 in Great Britain and Northern Ireland	P = Precipitation (annual total)
FARL	$$FARL = \prod_{i\in} \alpha_i$$ where: $$\alpha = (1 - \sqrt{r})^w$$ $$r = \frac{water\ surface\ area}{subcatchment\ area}$$ $$w = \frac{subcatchment\ area}{catchment\ area}$$	Index of flood attenuation from rivers and lakes. The overall *FARL* index has a value close to one when a catchment has low attenuation from water bodies, and as attenuation effects become more important the index decreases.	A = effect of individual water body r = relative size of water body to upstream catchment w = weighting reflecting importance of water body
BFIHOST	Area weighted base flow index (BFI) assigned from catchment 1km gridded dominant HOST class	Base flow index from Hydrology of Soil Types (HOST) Boorman et al. (1995)	
URBEXT	$URBEXT$ $= Urban + 0.5\ Suburban$	FEH index of fractional urban extent	Urban and Suburban are Land Cover Mapping (LCM) classes for urbanized surfaces
PROPWET	$$\frac{\sum_{i=1961}^{1990} No.\,days\,SMD\,>\,6mm}{\sum_{i=1961}^{1990} No.\,days}$$	Index of proportion of time that soils are wet (%)	SMD = soil moisture deficit (as calculated on last day of month and linearly interpolated)
DPLBAR	Mean distance of all 10m DEM grids to catchment outlet	Mean drainage path length	NEXTmap Digital Elevation Model (10m)
DPSBAR	Mean slope between all 10m DEM grids –based on steepest route – within catchment	Mean drainage path slope	NEXTmap Digital Elevation Model (10m)

URBLOC	$URBLOC = \dfrac{URB_{EXT}URB_{LOC} + {}^{1}/_{2}\,SUB_{EXT}SUB_{LOC}}{URB_{EXT} + {}^{1}/_{2}\,SUB_{EXT}}$	Index of location of urban and suburban land cover	See FEH Vol. 5 for full details (Institute of Hydrology, 1999)
URBCONC	$URBCONC = \dfrac{\sum_{1}^{n} INFLOW_{URB/SUB}}{\sum_{1}^{n} INFLOW_{TOTAL}}$	Index of concentration of urban and suburban land cover	See FEH Vol. 5 for full details (Institute of Hydrology, 1999)
UAF	$UAF = PRUAF(1 + URBEXT)^{0.83}$ $PRUAF = 1 + 0.615\,URBEXT\left(\dfrac{70}{SPRHOST} - 1\right)$	Urban adjustment factor	$URBEXT$ = urban extent SPRHOST – standard percentage runoff of HOST class
$QMED$	Flood exceeded on average every other year	Index flood	See FEH Vol. 3 for full details (Institute of Hydrology, 1999)
FPEXT	Fraction of the catchment that is estimated to be inundated by a 100-year flood	Flood plain extent	See Kjeldsen et al. (2008) for full details
FPLOC	Mean distance of floodplain nodes divided by mean distance from all nodes to catchment outlet	Flood plain location	See Kjeldsen et al. (2008) for full details

Landscape metric symbols

PLAND	$PLAND = A_C/A_T$	Equals the percentage of the landscape comprised of the corresponding patch type.	A_C = Class area A_T = Total catchment area
PARA	$PARA = \dfrac{P_{ij}}{a_{ij}}$	*Perimeter-area ratio* is a simple measure of shape complexity, but without standardization to a simple Euclidean shape	p_{ij} = perimeter (m) of patch ij. A_{ij} = area (m^2) of patch ij.

TE	$$TE = \sum_{k=1}^{m} e_{ik}$$	*Total edge* at the class level is an absolute measure of total edge length of a particular patch type.	e_{ik} = total length (m) of edge in landscape involving patch type (class) i; includes landscape boundary and background segments involving patch type i.
ED	$$ED = \frac{E}{A}(10{,}000)$$	*Edge density* reports edge length on a per unit area basis that facilitates comparison among landscapes of varying size	E = total length (m) of edge in the landscape. A = total landscape area (m²).
CONTIG	$$CONTIG = \frac{\left[\frac{\sum_{r=1}^{z} c_{ijr}}{a_{ij}}\right]}{v-1}$$	Assesses the spatial connectedness, or contiguity, of cells within a grid-cell patch to provide an index of patch boundary configuration and thus patch shape	c_{ijr} = contiguity value for pixel r in patch ij. V = sum of the values in a 3-by-3 cell template (13 in this case). A_{ij} = area of patch ij in terms of number of cells.
LPI	$$LPI = \frac{\overset{a}{\underset{j=1}{max(a_{ij})}}}{A}(100)$$	*Largest patch index* at the class level quantifies the percentage of total landscape area comprised by the largest patch. As such, it is a simple measure of dominance.	A_{ij} = area (m²) of patch ij. A = total landscape area (m²).
CLUMPY	Given: $$G_i = \left(\frac{g_{ii}}{(\sum_{i=1}^{m} g_{ii}) - mine_i}\right)$$	The proportional deviation of the proportion of like adjacencies involving the corresponding class from that expected under a spatially random distribution.	G_{ii} = number of like adjacencies (joins) between pixels of patch type (class) I based on the *double-count* method. G_{ik} = number of adjacencies (joins) between pixels of patch types (classes) I and k based on the *double-count* method. Min-e_i = minimum perimeter (in number

	$CLUMPY$ $= \left[\dfrac{G_i - P_i}{P_i}\; for\; G_i < P_i \& P_i \right.$ $\left. < 5, e; else\; \dfrac{G_i - P_i}{1 - P_i}\right]$		of cell surfaces) of patch type (class) I for a maximally clumped class. P_i = proportion of the landscape occupied by patch type (class) i.
COHESION	$COHESION = \left[1 - \dfrac{\sum_{j=1}^{n} p_{ij}}{\sum_{j=1}^{n} p\,ij\sqrt{a_{ij}}}\right]\left[1 - \dfrac{1}{\sqrt{A}}\right]^{1}(100)$	*Patch cohesion index* measures the physical connectedness of the corresponding patch type.	P_{ij} = perimeter of patch ij in terms of number of cell surfaces a_{ij} = area of patch ij in terms of number of cells. A = total number of cells in the landscape.
CONTAG	$CONTAG$ $= 1$ $+ \sum\sum [q_{ij} ln(q_{ij})] / 2ln(2)$	Assesses the extent to which patch types are aggregated or clumped as a percentage of the maximum possible; characterized by high dispersion and interspersion.	P_i =proportion of the landscape occupied by patch type (class) i. g_{ik} =number of adjacencies (joins) between pixels of patch types (classes) i and k based on the *double-count* method. M =number of patch types (classes) present in the landscape, including the landscape border if present.
LSI	$LSI = \dfrac{e_i}{\min e_i}$	*Landscape shape index* provides a simple measure of class aggregation or 224lumpiness and, as such, is very similar to the aggregation index.	E_i = total length of edge (or perimeter) of class i in terms of number of cell surfaces; includes all landscape boundary and background edge segments class i. min e_i = minimum total length of edge (or perimeter) of class i in terms of number of cell surfaces

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MESH	$$MESH\frac{\sum_{j=1}^{n} a_{ij}^{2}}{A}\left(\frac{1}{10000}\right)$$	MESH provides a relative measure of patch structure	a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).
PX	$$PX = \sum A_{k}/mdo_{k}$$	Proximity Index (PX) accounts for hydrological distance and connectivity of all suburban and urban patches relative to catchment outlet	A_k = area of patch k, mdo_k = mean distance to the outlet of patch k

Appendix B - Monitoring and data processing

B.1 Flow monitoring equipment

The UDFM instruments are sealed in a streamlined unit that is mounted to a channel bed of pipe invert and situated facing upstream into the incoming flow. The unit is connected to a control box situated well above the water level and with ease of access which contains the control/download ports and battery. A number of different instrument designs are available, each with its own particular design and suitable for differing applications. For this monitoring programme two types have been applied:

1) The stingray portable level-velocity meter from Greyline instruments inc (http://www.greyline.com/stingray20.htm). Suitable for smaller sites and where very shallow low flows are experienced.
2) The 6526H Starflow from Unidata (http://www.unidata.com.au/products/water-monitoring-modules/ultrasonic-doppler-instrument#Documents). An industry standard logger that has been employed in countless urban monitoring studies and is very rugged and more suitable for larger channels.

B.2 Flow data processing

Processing step	Details
Correction of data to GMT	All velocity-depth and rainfall data corrected to GMT
Derivation of Flow at first QC level (QC1)	Flow derived using R script FLOW_QC1_UPLOAD_V1. Zero values filtered out.
Data analysis and QC processing of velocity-depth data (QC2)	Depth-Velocity-Flow data analysed and re-formatted for QC 2 using TSP software package. New series generated using tools in software. Uploaded to Oracle.
Data analysis and QC processing of velocity-depth data (QC3)	Derivation of velocity-index ratings and depth offsets from comparison of spot gauging with QC2 data. Applied in SQL and uploaded to Oracle.

Table_APX B-1: Processing steps for derivation of quality controlled flow time series

The first step ensured all data was stored on an Oracle database and date corrected to GMT – as different equipment were storing dates in different formats. Next flow was derived using an R script for each site that related depth to area using measured cross section, and then using velocity, could calculate flow in units of square metres per second (m^3s^{-1}) – this data was marked in Oracle databases as QC1. The following step utilised the CEH Oracle data management software Time Series Plotter (Swain, 2011) to visually analyse both rainfall and runoff time-series and to infill and correct any periods of drift or equipment malfunction, sometimes using local data scales to the selected site for infill. The final stage utilised the velocity-index ratings acquired during spot gauging's to apply any offsets required for velocity or depth.

B.3 Rainfall data processing

Estimates of areal rainfall were obtained using methods outlined in BSI Standard 7843-4:2012 (Guide for the estimation of areal rainfall (BSI, 2012b)) through the application of different weighting methods. Both methods utilised data from the precipitation monitoring in combination with data from the most local EA gauge and were formatted to a 15min resolution as this was the finest scale at which verification data were available. The first method calculated areal rainfall using the Thiessen polygon approach, widely used in urban hydrological studies (e.g. Blume et al., 2007); Yue and Hashino, 2000). This required the mapping of Thiessen polygons for all possible arrangements of active raingauge and applying the associated weighting factors to the concurrent data. The second method calculated the arithmetic mean of rainfall for all active gauges at each time step. A disadvantage of the arithmetic mean is its sensitivity to raingauge distribution, whereby clusters ban cause a spatial bias. The Thiessen method is considered more appropriate as it provides an area weighting based upon the Thiessen method of using polygons to construct perpendicular bisectors of lines joining nearby raingauges (BSI, 2012b). It was found for Bracknell the arithmetic mean performed best, due in part to the uniform distribution of raingauges and also the low weight given to the EA gauges despite it providing the most robust data. For Swindon the areal rainfall across this larger and longer catchment was best estimated using the Thiessen polygon method as this could

account for the possible clustering and associated bias of certain gauges and also the lack of raingauges to the south.

Appendix C – Chapter 5 appendices

Class number	Class name	Reclass number	Reclass name
1	Broadleaved / mixed woodland	4	Natural
2	Coniferous woodland	4	Natural
3	Arable	5	Agricultural/managed
4	Improved grassland	5	Agricultural/managed
~~5~~	~~Neutral grassland~~	~~na~~	
6	Calcareous grassland	4	Natural
~~7~~	~~Acid grassland~~	~~na~~	
~~8~~	~~Fen, marsh, swamp~~	~~na~~	
9	Dense dwarf shrub heath (heather)	4	Natural
10	Open dwarf shrub heath (heather grassland)	4	Natural
~~11~~	~~Bog (deep peat)~~		
12	Inland rock	4	Natural
~~13~~	~~Sea / Estuary~~		
14	Water (inland)	3	Water
~~15~~	~~Coastal~~		
~~16~~	~~Saltmarsh~~		
17	Suburban	1	Suburban
18	Urban	2	Urban

Table_APX C-1: Class names and numbers for the vector data– the vector data set is the master data set from which the other products are derived. Note the table contains class numbers for some classes not found in the Thames Basin area – this is to allow the classifications to be extended to wider areas if required in the future

Step	Tool and data	Description
1	Select 'buildings' from OSMM attribute table and make new polygon layer	
2	**Polygon to raster** (Step1) (5m)	
3	**Reclassify** (no data 0, building 1)	
4	**Aggregate** to 50m (mean)	
5	Identify suitable breaks – test 10 selected areas of different development type and density using 3 classes.	0.13, 0.19 identified as breaks.
6	**Reclassify** using breaks (Step 5)	Set grids as 11, 12, 13
7	**Clip** LCM 2015 to catchment	1 = Suburban
8	**Clip** (5) to catchment	
9	**Raster Calculator**: Con(Step7==1,Step8,Step7)	Re-classes Suburban grids as 11 (LD), 12 (MD), or 13 (HD)
10	**Data export**	LCM_RC1

Table_APX C-2: ArcGIS method for deriving Suburban classes (LCM, R1) based on density information from OSMM. Input data LCM2015 (Suburban), OSMM (buildings)

Step	Tool and data	Description
1	Select 'water' from OSMM attribute table and save as new layer	
2	**Polygon to raster** (Step1) (1m)	
3	**Reclassify** (no data 0, water 3)	
4	**Aggregate** to 50m (mean)	
5	Identify suitable breaks – test 10 selected areas of water feature (river-lake) using 2 classes.	0.23 identified as suitable break – not encompassing very small features or rivers.
6	**Reclassify**	0 no water, 3 water.
7	**Clip** (Step 6) to catchment	
8	**Raster Calculator**: Con((Step6==3) & (LCM_RC1 != 3),3,LCM_RC1)	Converts non LCM_RC1 water grids to 3.
9	**Data export**	LCM_RC2

Table_APX C-3: ArcGIS method for deriving refined Water classes (LCM_RC2) based on water features indicated on OSMM. Input data: LCM_RC1 (3), OSMM (water)

Step	Tool and data	Description
1	**Reclassify** LCM_RC2	Urban and Suburban HD = 3, Suburban M D & LD = 2, Greenspace and Natural =1, Water = 0.
2	**Focal Statistics:** circle, mean, 5.	Mean value (0-3) in 250m circle around each grid
3	**Reclassify** (5 classes – values 0-3)	1 (1), 2 (1.5), 3 (2), 4 (2.5), 5 (3)
4	**Clip** (step 3 to catchment)	
8	**Raster Calculator**: Con((LCM_RC2==5) & (Step4>2),6, LCM_RC2)	Converts selected LCM_RC2 Greenspace to Green$_{URB}$ (6)
9	**Data export**	LCM_RC3

Table_APX C-4: ArcGIS method for deriving refined greenspace classes (LCM_RC3) based on spatial statistics of LCM_RC2 greenspace (5). Input data: LCM_RC1 (5). Method rationale is to identify small greenspaces in urban areas and separate from larger greenspaces in urban areas or outside urban areas. Key method refinement was altering step 2 Focal Statistics size until smaller greenspaces in urban areas could be separated from larger less-urban greenspaces at the fringes or in areas of ingress. This took some 10 iterations – from 100m to 1km. 250m was an ideal patch size below which urban greenspaces such as parks and playing fields could be separated from less managed surfaces such as parks and fields.

Step	Tool and data		Description
1	**Merge** Natural England datasets		
2	**Clip** merged dataset (Step2) to catchment		
3	**Add Field**: Nature (7)		
4	**Polygon to Raster** (5m), Step3 (7)		
8	**Aggregate** (50m) Mean		
9	**Reclassify: No data 0, Nature 7**		Set extent to catchment + Snap
10	**Raster Calculator:** Con((LCM_RC3=!3) (Step9==7),7,LCM_RC3)	&	Convert non-water features to Greenspace natural - Green$_{NAT}$
	Data export		LCM_RC4

Table_APX C-5: ArcGIS method for deriving 'Green$_{NAT}$' class (RC4) based on Natural England mapping of Local Nature Reserves, Country Parks, and Woodland and Pasture. Input data: LCM_RC3, Local Nature Reserves, Country Parks, and Woodland and Pasture.

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Step	Tool and data	Description
1	**Stage 1: Process SuDS maps** The following features were selected from each layer as being indicative of features that would negate the possibility of SuDS installation: Drainage summary – identified areas with 'Very significant constraints are indicated' Ground stability summary – identified areas with 'Significant potential for geohazard' and 'Very significant constraints are indicated' Groundwater protection summary – identified areas with 'Considerable susceptibility' and 'Very significant constraints are indicated'	Using the British Geological Survey (BGS) – SuDS infiltration map (SIM: Dearden, 2016) - that accounts for such factors has been used to locate sites, indicating SuDS suitability
2	Merge the SuDS layers in step 1 to one polygon dataset.	Single layer showing areas of SuDS not being suitable.
3	Clip SuDS layer to catchment – and add field SuDS with value 55.	
4	Polygon to Raster, 50m, snap LCM2015	Convert to raster (50m)
	Reclassify RC5 as SuDS raster with 1=Suds potential, 44=no potential, and clip to catchment > RC5	Reclassify and clip to final SuDS raster RC5
8	**Stage 2: Identify areas of new (post 2010) development** Raster calculator: Con((RC4==2) & (LCM2010>2),14,RC4) >RC4 Raster calculator: Con((RC4==11)|(RC4==12)|(RC4==13) & (LCM2010>2),15,RC4) > RC4 Data export : SuDS	Identify new areas of development – and reclass as either Urban post 2010 (14) or Suburban post 2010 (15) (SuDS)
9	**Stage 3: Identify areas likely to have SuDS** Convert Urban post-2010 to Urban$_{SUDS}$ (141): Con((RC5==14)&(SuDS<44),141,RC5) Convert Suburban post-2010 to Suburban$_{SUDS}$ (151): Con((RC5==15)&(SuDS<44),151,RC5) Convert back areas that were not suitable to their previous classes – removes class 14,15: Con((RC5==14)|(RC5==15),RC4,RC5) Export data>RC6	Identify areas that are post 2010 and have SuDS potential.

Table_APX C-6: Geoprocessing to determine areas of Urban$_{SUDS}$ or Suburban$_{SUDS}$– post 2010 developments only

Step	Tool and data	Description
1	**Hydrology** tools were used to delineate natural drainage areas to manually mark pour points that identify monitoring locations.	
2	For locations where there was no natural drainage, the contributing drainage area was manually delineated using a combination of drainage map and topographical mapping from OSMM	
3	For catchments where there was a visual discrepancy between the natural drainage area and artificial drainage (B3, S1, S3 - S10), the natural drainage polygon was manually altered to encompass areas where artificial drainage crosses natural boundaries derived from the DEM.	

Table_APX C-7: Method for reclassifying catchment area – *AREA$_{rc}$* - manipulated using the ArcGIS 10.3 Hydrology toolset in combination with manual delineation of artificial drainage areas

Site_ID	mdo	PX	PX_N	PX_{URBEXT}	PX_{N_URBEXT}	LSI	CONTAG	MESH	$PLAND_{URB}$	LPI_{URB}	TE_{URB}	ED_{URB}	$PARA\_MN_{URB}$	$PARA\_AM_{URB}$	$CONTIG\_MN_{URB}$	$CONTIG\_AM_{URB}$	$CLUMPY_{URB}$	$COHESION_{URB}$	$PLAND_{SUB}$	LPI_{SUB}	TE_{SUB}	ED_{SUB}	$PARA\_MN_{SUB}$	$PARA\_AM_{SUB}$	$CONTIG\_MN_{SUB}$	$CONTIG\_AM_{SUB}$	$CLUMPY_{SUB}$	$COHESION_{SUB}$	$PLAND_{NAT}$	$COHESION_{NAT}$
							Landscape metrics		Urban class metrics										Suburban class metrics										Green_NAT class metrics	
S1	4.42	3.88	0.59	3.88	0.30	8.09	57.48	889	16.03	10.96	53450	18.59	477	135	0.36	0.81	0.82	96.23	18.03	6.66	78650	27.36	480	171	0.36	0.76	0.76	95.1	0.76	0.47
S2	1.87	0.20	0.12	0.20	0.06	2.97	76.41	238											10.51	6.26	6100	18.86	417	271	0.39	0.61	0.69	81.4	0.00	0.00
S3	3.16	1.68	0.89	1.68	0.72	4.77	61.72	214	32.57	31.27	15800	26.42	484	108	0.34	0.85	0.85	97.68	55.77	50.79	26150	43.73	407	111	0.44	0.84	0.74	98.4	0.00	0.00
S4	1.94	1.38	0.87	1.38	0.85	3.25	68.04	199	1.53	1.05	1150	3.70	305	295	0.55	0.57	0.82	70.68	79.31	79.31	8850	28.50	80	80	0.89	0.89	0.66	99.7	9.66	0.84
S5	0.59	3.53	0.96	3.53	0.81	4.02	52.52	45	15.32	9.91	5900	27.19	440	214	0.40	0.70	0.77	85.53	62.10	38.82	10050	46.31	333	121	0.57	0.83	0.70	96.1	0.46	0.17
S6	6.00	4.28	0.73	4.28	0.59	8.79	55.45	804	18.61	13.56	75100	21.48	446	126	0.40	0.82	0.83	97.06	24.27	10.43	100400	28.72	449	129	0.40	0.82	0.81	96.0	0.62	0.47
S7	0.31	1.54	0.88	1.54	0.85	2.77	52.68	19	5.94	3.65	1250	22.83	400	400	0.44	0.44	0.70	66.01	81.74	48.86	2650	48.40	220	170	0.69	0.76	0.19	94.7	0.00	0.00
S8	1.42	1.07	0.70	1.07	0.70	2.77	52.68	19	1.50	1.50	650	3.00	277	277	0.60	0.60	0.94	74.81	72.55	70.47	7100	32.76	271	92	0.63	0.87	0.72	98.9	13.84	0.84
S9	0.41	0.66	1.00	0.66	1.00	3.10	62.34	112											99.08	99.08	100	3.67	122	122	0.83	0.83	0.00	99.9	0.00	0.00
S10	0.24	2.00	0.97	2.00	0.97	1.62	93.82	27											18.03	6.66	78650	27.36	480	171	0.36	0.76	0.76	95.1	0.00	0.00

EA_39087	10.30	3.95	0.49	1.97	0.25	11.92	55.55	1232	4.56	3.26	43500	7.47	467	168	0.37	0.77	0.81	93.58	34.05	23.95	209000	35.89	467	110	0.37	0.85	0.81	98.20	3.24	0.55
B1	4.59	1.15	0.29	0.57	0.14	8.81	50.96	360	0.71	0.15	5200	2.83	468	431	0.37	0.41	0.54	59.62	26.01	11.89	74900	40.80	456	170	0.39	0.76	0.74	93.65	12.75	0.53
B2	4.94	1.69	0.67	0.84	0.33	5.26	58.08	366	3.42	1.44	9750	7.80	465	248	0.38	0.66	0.74	78.94	43.09	41.75	37050	29.65	476	86	0.37	0.88	0.85	98.89	13.50	0.63
B3	3.83	2.76	0.84	1.38	0.42	6.56	52.81	385	15.35	13.30	25150	20.06	374	139	0.48	0.81	0.83	95.90	53.11	51.63	54000	43.06	494	96	0.36	0.87	0.78	99.24	3.87	0.64
B4	5.66	2.07	0.35	1.04	0.17	9.89	49.96	470	1.66	0.53	15000	4.46	466	291	0.38	0.60	0.68	74.27	30.68	17.11	117400	34.88	450	124	0.39	0.83	0.80	96.74	12.75	0.64
B5	7.60	1.85	0.37	0.92	0.19	10.23	50.35	571	1.91	0.63	17200	4.59	465	263	0.38	0.64	0.71	80.54	31.78	19.15	130750	34.88	456	119	0.38	0.84	0.80	97.19	11.80	0.64
B6	9.24	2.84	0.45	1.42	0.23	12.44	48.34	876	4.56	3.26	43500	7.47	467	168	0.37	0.77	0.81	93.58	34.05	23.95	209000	35.89	467	110	0.37	0.85	0.81	98.20	10.65	0.65
EA_39052	7.70	3.55	0.53	1.78	0.26	11.80	47.89	753	4.56	3.26	43500	7.47	467	168	0.37	0.77	0.81	93.58	34.05	23.95	209000	35.89	467	110	0.37	0.85	0.81	98.20	10.73	0.60

Table_APX C-8: Initial list of landscape metrics and associated values: including 5 hydrological metrics, 3 landscape metrics, 10 Urban class metrics, 10 Suburban class metrics, and 2 Green$_{NAT}$ class metrics. Blank values for certain sites indicate catchments with none of this class present.

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