Monitoring, understanding and modelling rainfall-runoff behaviour in two small residential urban catchments.

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by Thomas William Redfern.

September 2017

Declaration

This thesis is the result of my own work and includes nothing that is the outcome of collaboration, except where specifically indicated in the text. It has not been previously submitted, in part or whole, to any university or institution for any degree, diploma, or other qualification.

In accordance with The University of Liverpool guidelines, this thesis does not exceed 100,000 words.

Signed:

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Date: ____

Acknowledgements

First I would like to thank my supervisors: Dr Neil Macdonald, Dr Thomas Kjeldsen, James Miller and Nick Reynard who have all provided expertise, wisdom and inspiration throughout the four years that it has taken to produce this thesis. In particular I would like to thank Neil for his endless patience and willingness to talk on the phone or read yet another draft; James, for the hours spent driving around in Swindon, digging in the dirt and winching each other in and out of drains; Thomas, for his help with statistical and mathematical modelling and for pointing out the value of my work when I doubted myself; and Nick for always showing enthusiasm and interest even when I was interrupting something more important. Whilst having four supervisors spread across the country could be a challenge at times, I was always inspired by your collective support and dedication to science, education and research. I must also extend my thanks to colleagues at CEH Wallingford and the University of Liverpool who supported this research.

Thank you to my friends at CEH Wallingford who provided encouragement and welcome distractions during the PhD; in particular, Andrew House for our lunchtime walks, various bird watching trips and our musings about absolute nonsense regarding heavy metal and science fiction.

My eternal gratitude is extended to my Dad, Pat, Mike, Simon, Theo, Seb, Mum and Chris for reading drafts and listening to “drain talk”. It has been my dream to complete a PhD for as long as I can remember and only through your support have I achieved this goal, though I’m afraid that none of you will ever win an argument again.

To Emma and Panda you are the reason I am still alive and why I’ll always keep fighting.

To NERC who funded this work I am truly grateful and proud to have received your support.

This thesis is dedicated to the staff and volunteers of the Royal Cornwall Hospital Treliske, as well as to the memories of Pamela Davidson, Stella Redfern and Mr Timothy Christmas.

I hope I’ve done you proud.

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Abbreviations

10MINMAXINT	10 MINute MAXimum rainfall INTensity
2MINMAXINT	2 MINute MAXimum rainfall INTensity
API5	5-day Antecedent Precipitation Index
AQMAX	Peak flow rate recorded at Arley Close
ASM	Soil moisture recorded at Arley Close
BMP	Best Management Practice
BSI	British Standards Institute
CEH	Centre for Ecology and Hydrology
DCIA	Directly Connected Impervious Area
DDF	Depth-Duration-Frequency curve
DMC	Double Mass Curve
DOI	Digital Object Identifyer
DTM	Digital Terrain Model
EA	Environment Agency
EIA	Effective Impervious Area
EIDC	Environment Information Data Centre
FEH	Flood Estimation Handbook
FSR	Flood Studies Report
GIS	Geographical Information Systems
HOST	Hydrology of Soil Types
IF	Effective Impervious Factor
IPA	Individual Parcel Assessment
LiDAR	Light Detection and Ranging
MIT	Minimum Inter-event Time
NAPI	30-day Antecedent Precipitation Index
NERC	Natural Environment Research Council
OLS	Ordinary Least Squares
OSMM	Ordnance Survey Master Map
PF	Soil Storage
PIMP	Percentage Impervious
PR	Percentage Runoff
Pre1HR	Pre event 1 hour rainfall depth
Pre2HR	Pre event 2 hour rainfall depth
Pre6HR	Pre event 6 hour rainfall depth
PRGF	Greenfield Percentage Runoff
PRURB	Urban Percentage Runoff
PRurb	Urban Percentage Runoff
QMAX	Peak flow rate
REFH2	Revitalised Flood Hydrograph Method
SAAR	Series Averaged-Annual Rainfall
SMD	Soil Moisture Deficit

SOIL	Soil type (as defined by WRAP)
SuDS	Sustainable Drainage Systems
TBR	Tipping Bucket Raingauge
TIA	Total Impervious Area
UCWI	Urban Catchment Wetness Index
UDFM	Ultra-sonic Doppler Flow Monitoring
WHS	Wallingford Hydro-Solutions
WQMAX	Peak flow recorded at Winsley Close
WRAP	Winter Rainfall Acceptance Potential
WSM	Soil Moisture recorded at Winsley Close

Abstract

Monitoring, understanding and modelling rainfall-runoff behaviour in two small residential urban catchments

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Ph.D. Thesis, University of Liverpool, U.K.

Understanding the urban rainfall-runoff process is an important challenge for the hydrological sciences. Urban areas exhibit a complex mosaic of surface covers, ranging from those of an anthropogenic origin to surfaces of a disturbed natural form, which exhibit varying hydrological behaviours. The urban rainfall-runoff process is managed to reduce the risk of flooding within urban areas, whilst also considering the volume of runoff that downstream water bodies receive. Efforts to understand and manage the urban rainfall-runoff process are often hampered by a lack of rainfall-runoff data of sufficient temporal (length and/or frequency) and spatial resolution for locations of interest. Therefore, urban rainfall-runoff processes are typically estimated using hydrological models that attempt to characterise the physical nature of urban areas (using assumptions and estimates of surface hydrological behaviour), that rarely consider how small-scale variations in urban surface cover and hydraulic connectivity influence rainfall-runoff behaviour.

This thesis investigates how variations in the physical design, hydraulic form and age of two residential developments of north Swindon (Arley Close and Winsley Close) influence rainfall-runoff behaviour. Through high resolution monitoring of precipitation, drainage flows and soil moisture, a novel understanding of the complex rainfall-runoff properties of urban surface covers is developed, rejecting commonly applied, yet inaccurate assumptions regarding the total imperviousness of urban surfaces. The ability of engineering rainfall-runoff models to replicate the field study site results is assessed to develop an improved understanding of how variations in urban development patterns can be better represented within modelling tools. The implications of inaccurate rainfall-runoff modelling arising from the use of assumptions and estimates within the planning of a retro-fitted surface water drainage storage tank are assessed, demonstrating the importance of developing improved understanding of rainfall-runoff processes at small-scales within the urban environment.

Chapter 1

INTRODUCTION

The aim of this chapter is to present the context of the thesis within urban hydrology, to define the aim and objectives and describe the thesis structure.

1.1 BACKGROUND

The historic development of urban areas is strongly linked to the successful management of water; as evidenced by the ancient surface water drainage systems constructed by the Romans and Greeks (Angelakis and Spyridakis, 2010), the Victorian water management assets of London (Cook, 2001) and modern day engineering in cities such as Tokyo (Chan et al., 2012). The urban environment is characterised by a large area of surfaces of anthropogenic origin whose hydrological characteristics often differ from natural surfaces in terms of reduced permeability and increased surface runoff generation (Fletcher et al., 2013). To manage the resulting surface runoff within urban areas, hydraulically efficient surface water drainage systems that collect and route surface runoff to receiving water bodies such as streams and rivers are constructed (Butler and Davies, 2004). As a result, there are major impacts to hydrological systems caused by urbanization, identified within the scientific literature (Rose and Peters, 2001):

(i) a greater proportion of rainfall is converted to direct runoff,

(ii) lag times between precipitation and runoff are decreased;

(iii) peak flow magnitudes are increased for all but the largest rainfall events;

(iv) low flows can decrease;

(v) groundwater recharge can be altered as a result of the importation and movement of water for human use (Tubau et al., 2017), and;

(vi) water quality is degraded by effluent discharges.

The urbanisation of previously natural land cover has potential negative consequences for flood risk management, geomorphology, hydro-ecology and water resources (DeFries and Eshleman, 2004; Booth et al., 2016).

Conventional surface water drainage systems (i.e. piped systems) have a finite hydraulic capacity, which when exceeded, can lead to surface water flowing across the urban surface, potentially flooding roads, homes and businesses (Douglas et al., 2010). Intensifying rainfall patterns (due to climate change) and increasing urban development (through urban creep and additional development) is leading to an increased runoff input into existing surface water drainage systems (Swan, 2010). As a result pluvial flood risk is expected to increase (Wang et al., 2016) unless existing urban rainfall-runoff processes are better managed and mitigation measures installed into existing and new areas of urban development (Booth and Charlesworth, 2016).

Controlling the urban hydrological system in a manner that protects urban areas from pluvial flood risk, whilst also managing potential impacts to downstream hydrological systems is a challenge for engineers (Roy et al., 2008). Urban areas are constantly responding and adapting to the needs of their inhabitants, with the result that the urban land surface changes over time (Perry and Nawaz, 2008). Precipitation patterns are changing as a result of climate change (Zhou et al., 2012), with numerous and sometimes conflicting requirements for the control of flood risk and the protection of water quality and freshwater habitats (Ellis, 2013). As a consequence there are multiple objectives for managing surface water within the urban environment with management decisions requiring a thorough understanding of the complex interactions between different hydrological processes, acting on different surfaces at different scales, across the urban environment (Salvadore et al., 2015). Crucially the linkages between urban development patterns, surface water drainage design and hydrological behaviour need to be considered so that the impacts of urban development on hydrological systems can be quantified, managed and reduced (Shuster and Rhea, 2013). This objective is hampered as understanding of the urban rainfall-runoff process is restricted by difficulties in collecting and analysing hydrological data within the urban environment (Fletcher et al., 2013). Hydrologists often lack hydrological data at appropriate scales, in locations of interest, or for suitable lengths of record within urban areas (Niemczynowicz, 1999), meaning that the rainfall-runoff properties of urban areas are often estimated using hydrological models. An incomplete understanding of the processes and physical features controlling runoff generation from urban areas at different scales exists, meaning there is uncertainty in how best to describe the urban surface and its linkages to the hydrological cycle within hydrological models. As such there are a large number of methods available within the scientific literature, with considerable uncertainty in the application of appropriate methods (Salvadore et al., 2015), which leads to difficulties in the management of the urban surface water cycle (Mitchell et al., 2001).

1.1.1 Analysing and modelling urban rainfall-runoff behaviour

Current understanding of rainfall-runoff behaviour in urban areas is typically based on two key theoretical descriptions of the hydrological properties of urban surfaces:

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

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

These theoretical assumptions are used to derive descriptive statistics of urban development such as Percentage IMPervious area (PIMP) or Total Impervious Area (TIA) (Lu and Weng, 2006; Sahoo and Sreeja, 2016), or urban developments are described with categorical terms lacking physical detail e.g. residential, industrial, commercial (Herold et al., 2002). Aerial photographs, infrared imagery, satellite remote sensing and maps are analysed to produce estimates of the extent of impervious surfacing, combining areas covered by roofs, roads and other anthropogenic materials (Shahtahmassebi et al., 2016). The hydrological properties of urban areas are examined by comparing rainfall-runoff data (where available) to geospatial data that describes the extent and features of urbanisation (Ferreira et al., 2016; O'Driscoll et al., 2010), or more typically where such data are limited, the hydrological behaviour of urban areas is estimated through the use of hydrological models (Yin et al., 2016). Modelling techniques usually rely on the calibration of model parameters that link metrics describing urban development (e.g. PIMP) to rainfall-runoff behaviour, or, where such data are missing, model parameters are estimated, assumed or derived from previous work, e.g. Kjeldsen (2009) refers to Packman (1980a) to estimate surface connectivity in the United Kingdom. Whilst models can be calibrated to achieve a good performance between simulated and recorded rainfall-runoff data, model parameters at large scales are often abstract generalised mathematical representations of real world processes and features, offering little understanding of how small-scale, local processes and physical features influence the generation of surface water runoff and pluvial flood risk. Thus large-scale models and parameters are often inappropriate for the investigation of potential mitigation measures that could alleviate the impacts of urbanisation on hydrology. At smaller scales, available models are often complex and parameters difficult to estimate without detailed measured data on the urban environment, which is often missing or unavailable, and so parameter values are in practice often estimated, assumed or derived from engineering and guidance documents (Kellagher, 2013).

It is well documented that not all rainfall falling onto urban surfaces is converted into runoff at larger catchment scales (Hollis and Ovenden, 1988b; Wiles and Sharp, 2008; Awadalla et al., 2017), yet there is uncertainty about what causes losses from urban catchments and how to estimate these losses in lieu of monitored rainfall-runoff data. Not all surfaces are connected to the surface water drainage system and instead only a "Directly Connected Impervious Area" (DCIA) or "Effective Impervious Area" (EIA) has a hydraulic connection to a surface water drainage system (Carmen et al., 2016). The degree of connectivity between surface water drainage systems and surfaces plays an important role in determining the rainfall-runoff properties of urban areas (Ebrahimian et al., 2016). Controlling and reducing connectivity of surfaces is cited (Carmen et al., 2016; Walsh et al., 2005; Moore et al., 2012) as a mechanism by which the impacts of urbanisation on hydrology could be reduced, and determining accurate estimates of DCIA is acknowledged as an important factor in predicting urban hydrological behaviour (Beighley et al., 2009). However, without detailed ground assessments e.g. Lee and Heaney (2003), current methods for defining the connectivity of urban surfaces are based on estimates e.g. DCIA is equal to 70% of TIA (Packman, 1980a), or empirical equations (Sahoo and Sreeja, 2016) that show poor performance when applied to areas outside of their original derivation (Lee and Heaney, 2003). Detailed studies have shown that the connectivity of urban surfaces to the surface water drainage system is dependent on small-scale features (such as road gullies), which are difficult to measure across large areas without intensive study (Ravagnani et al., 2009). Additionally, surface scale studies have shown that a direct connection to the surface water drainage system does not necessarily convert all rainfall into runoff upon impervious surfaces (Kidd and Lowing, 1979; Hollis and Ovenden, 1988a) indicating that the rainfall-runoff properties of urban impervious surfaces are more complex than current theory allows for, e.g. urban surfaces can be considered impervious, converting a large fixed proportion of rainfall into runoff, or pervious converting little or no rainfall into runoff (Wiles and Sharp, 2008; Law et al., 2009). In summary, there is a lack of detailed understanding of what features and processes affect the rainfall-runoff properties and connectivity of surfaces within the urban environment for use in hydrological modelling and surface water management planning and as a consequence research and practical engineering decisions are often made on assumed or else uncertain model assumptions, parameters and outputs.

1.1.2 Managing urban rainfall-runoff behaviour: the need for small-scale understanding and data

In the United Kingdom, surface water management policies target event runoff volumes and peak flow rates of new urban developments to retain rainfall-runoff behaviour, in an attempt to mimic pre-development hydrological conditions (Woods-Ballard et al., 2007). A number of technologies are available to manage surface water in this way, collectively termed Sustainable Drainage Systems (SuDS) in much of Europe and Asia, or Best Management Practices (BMPs) in the USA (Fletcher et al., 2013). These technologies range from surfaces that permit infiltration, e.g. permeable paving (Alsubih et al., 2017), to storage features such as ponds and underground tanks (Martin, 1988). Whilst new developments can be designed to include SuDS, there is an urgent need to retro-fit the existing urban environment with SuDS (Macdonald and Jones, 2006) to improve the existing hydrological conditions of urbanised areas (Walsh et al., 2005) and to accommodate increased runoff generation due to climate change and urban creep (MacDonald, 2011). Retro-fitting the urban environment with new surface water drainage assets is difficult, given the competition for space within urban areas and the high costs of engineering works (Ossa-Moreno et al., 2017). Targeted retro-fitting of SuDS is required, permitting the greatest opportunity for reductions in rainfall-runoff behaviour, so as to minimise wasted effort whilst maximising reductions in hydrological impacts (Dagenais et al., 2017). Hydrologists need a detailed understanding of how rainfall is converted into runoff within different types of urban development that vary in land use, surface cover and drainage design, to appropriately target and design retro-fit SuDS.

A number of modelling tools are commonly applied to estimate the rainfall-runoff properties of new and existing areas of urban development, to plan and design surface water drainage assets, e.g. storage tanks or conveyance networks (Woods-Ballard et al., 2007). These models range in complexity and sensitivity to physical features and processes that are thought to influence the generation of runoff in urban areas and have a range of parameters that need estimating. Given the importance of the correct sizing and strategic placing of drainage assets within a surface water drainage network, it is important that modelling tools provide estimates of rainfall-runoff behaviour that are as accurate as possible (Loganathan et al., 1985). An undersized asset (conveyance pipe or tank) is unlikely to store or convey the runoff generated from an area, thus increasing the risk of pluvial flooding (Coulthard and Frostick, 2010). Oversized assets unnecessarily increase the costs of construction and land take and thus may reduce the economic efficiency of a proposed retro-fit SuDS scheme, limiting the applicability of SuDS techniques within urban areas.

There are a number of sources of uncertainty in the rainfall-runoff modelling process which may impact on surface water management planning (Lei and Schilling, 1994), yet there is limited understanding of how this uncertainty may impact on the design and feasibility of a flood risk management project. To estimate urban rainfall-runoff behaviour within surface water management planning, an assessment of surface types and extents within a new or existing urban area is made and applied to an appropriate hydrological model. Model parameter values are then estimated to reflect site conditions (Beck et al., 2017). As data is often lacking at appropriate scales (e.g. defining the rainfall-runoff properties of individual surfaces), model parameterisation is based on assumed (or guidance) values of the hydrological properties of different types of urban surface (for example see Warhurst et al. (2014), Table 1.1). Surface water management planning is therefore sensitive to the outputs of hydrological models, which itself is sensitive to the understanding of and the assumptions made to represent the hydrological properties of urban surfaces, and the rainfall-runoff processes of the urban environment.

Table 1.1: Surface categories and permeability assumptions used by Warhurst et al. (2014) to estimate the rainfall-runoff properties of urban areas in Southampton, U.K.

Urban Surface Category	**Assumed Permeable (P) / Impermeable (I)**
Brick	I
Concrete	I
Decking	I
Impermeable unknown	I
Paving	I
Other	I
Gravel	P
Lawn	P
Other vegetation	P
Trees	P
Unknown	P

1.1.3 Urban and peri-urban development: global trends to local development

Currently over 50% of the world's population lives in an urban area; by 2050 this percentage is projected to rise to 66% (UN, 2014). The proportion of the Earth's surface under urban land cover is increasing and intensifying to meet demand for housing, employment and transport infrastructure (Seto and Fragkias, 2005; Dahal et al., 2017; Tobias et al., 2016). Rapid economic development in many countries has seen rapid urban expansion, with linkages between economic activity and residential land uses in the central urban core reduced (Ford, 1999). Development to the periphery of existing urban centres (the peri-urban environment) has increased, as new economic and social trends direct development to these areas (Quarmby and Cushnie, 1989). Here, land uses such as agriculture are developed into mixed development patterns, where areas of different land uses exhibit a complex mosaic of contrasting land covers, all in close proximity (Allen, 2003).

Many of the UK's largest urban areas were developed during the Victorian or even earlier periods (Cherry, 1972). As the UK economy continues to move from an industrialised to a more services and consumer based economy the linkages between the urban core and employment are reducing as development in peri-urban areas expands (Ferm and Jones, 2016). In addition, a large component of development within the peri-urban areas of the U.K is residential housing (Gill et al., 2008) as peri-urban areas reduce the costs for new housing (vs central city locations) and peri-urban developments offer living conditions often considered preferable to city centre locations (Simon, 2008). Peri-urban residential developments are often piecemeal and occur in response to temporally changing economic and societal factors. Consequently the urban fringe of sub-urban and peri-urban areas has developed to accommodate an increasing proportion of the UK's population at different times during the 20th and into the 21st century (Champion, 2005; Stockdale, 2016).

The hydrological impacts of development within the peri-urban environment are examined in recent research (Ferreira et al., 2016; Sanzana et al., 2017; Fonjong and Fokum, 2017), as hydrologists aim to understand how development patterns over the twentieth century impact on the current hydrological system. Concurrent measurements of urban development patterns and rainfall-runoff behaviour within urbanising peri-urban areas are typically lacking over the entire course of historic development and therefore the hydrological impacts of peri-urban development are typically estimated using hydrological models (Braud et al., 2013b). There are a number of studies that have demonstrated that development within the peri-urban environment alters the rainfall-runoff behaviour of previously natural land surfaces which can increase flood risk in downstream areas (Limthongsakul et al., 2017; Bathrellos et al., 2016; Khan et al., 2016). Development in peri-urban areas poses a number of challenges for hydrologists and engineers working to quantify, manage and reduce flood risk (Sanzana et al., 2017). Representing peri-urban development within hydrological models is complicated by the complex surface cover of development and the interactions between anthropogenic and natural drainage systems (Environment-Agency, 2010). Peri-urban development is formed of a complex mosaic of land uses and land covers, which reflect the particular requirements of development and design policies during the period of construction. The arrangement of surfaces, buildings and surface water drainage system design is variable across peri-urban areas. Without detailed rainfall-runoff data it is difficult to quantify how this variability in urban design influences urban rainfall-runoff behaviour, thus making estimates of the hydrological impacts of peri-urban development uncertain (Braud et al., 2013b). A greater understanding is required of how small-scale differences of urban development design impacts on hydrological response to aid the representation of urban areas within hydrological models (Branger et al., 2013). Such understanding could also be used in the future to inform design and construction policies for new residential development in the twenty first century.

1.2 THE URBAN DEVELOPMENT OF SWINDON

The town of Swindon, 115km to the west of London is an example of a town that has experienced extensive development in peri-urban areas during the twentieth and into the twenty first century (Figure 1.1). The population of Swindon increased in a number of phases as the economic and social history of the town developed. Originally a small village, Swindon's development began during the latter part of the nineteenth century as a hub for the construction and maintenance of the UK's rail network and related industries. The population of Swindon grew in the post war era (1950s), as it was designated a "spill over" town for London, to reduce overcrowding (in central London) and aid in the supply of housing during the period (Cullingworth, 1961). Swindon also expanded rapidly during the period 1970-2000 as the central industrial core was re-developed into areas servicing commercial, financial, distribution and other services based economic activities (Brown et al., 2000). Housing developments constructed at different periods during the twentieth century accommodate a large proportion of the town's population to the peri-urban north (Figure 1.1). Each development reflects the design and planning policy of its era of construction and thus is formed of differing mosaics of surface types, housing layout, road design, green space and gardens. North Swindon is therefore characterised by a number of different residential areas with contrasting designs of the land surface and the provision of surface water drainage.

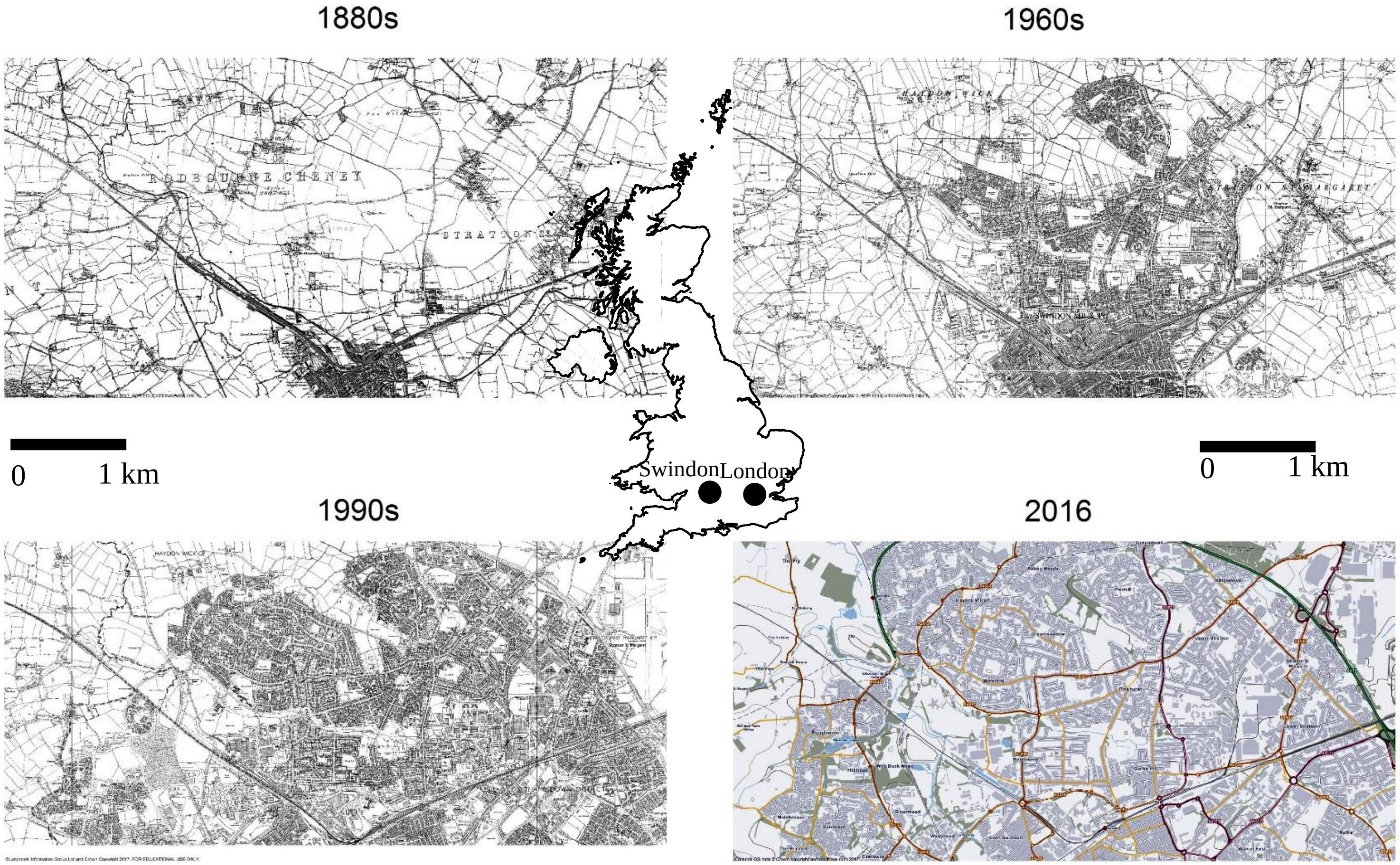

Figure 1.1: The development of the north of Swindon between the 1880s to the current day development extent with map showing location of Swindon within the United Kingdom

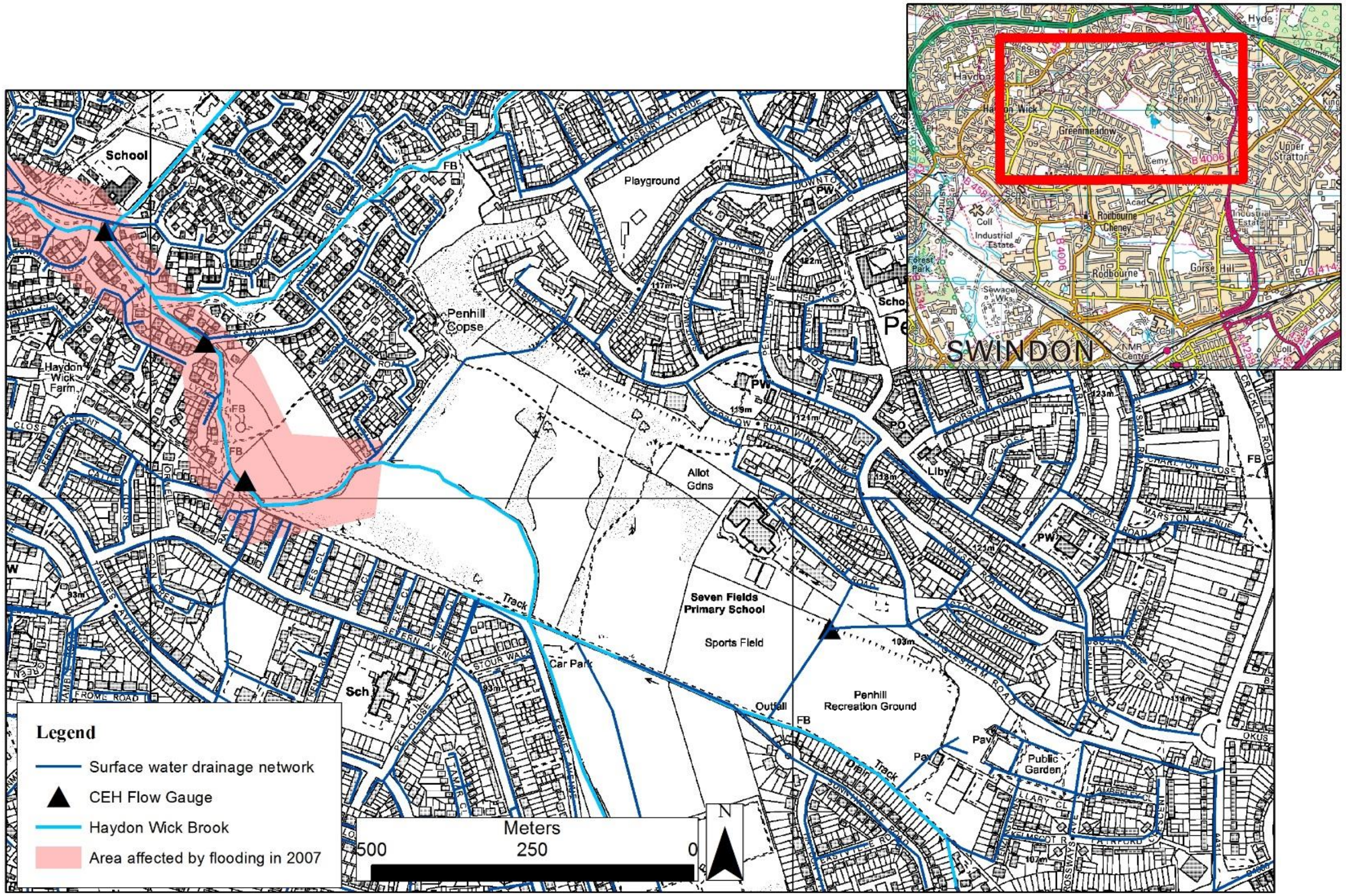

Figure 1.2: Residential development to the peri-urban north of Swindon. Areas affected by flooding in 2007 and the stream and surface water drainage networks (shapefile provided by Thames Water) shown. Contains OS data © Crown copyright and database right (2017).

The runoff generated in the residential developments to the north of Swindon contributed to flooding experienced in June 2007 in the Haydon Wick suburb of Swindon. It is estimated that up to fifty properties experienced internal flooding and nearby roads were blocked due to flood water, when runoff from the surface water drainage systems serving the residential developments and the natural components of the Haydon Wick Drainage catchment combined (Environment-Agency, 2010). Figure 1.2 shows the area affected by flooding, as well as the high density of surface water drainage systems (data provided by Thames Water), urban developments and surface water channels in the upstream area of Hayden Wick. The flooding in Haydon Wick was of a sufficient level that the Environment Agency spent ~£8m on flood alleviation works, including a flood wall and landscaping, thus demonstrating the importance of understanding and managing the rainfall-runoff behaviour of residential developments (both existing and new) in the peri-urban landscape.

1.3 CEH STUDY CATCHMENTS

Given its history of urban development and flooding the Centre for Ecology and Hydrology (CEH) are investigating how urban development patterns impact the hydrological regime of the Haydon Wick Brook (and other watercourses). CEH has monitored precipitation, river discharge and soil moisture across a gradient of catchments containing different peri-urban land uses (See Figure 1.2 for locations of flow gauges). Hydrological models that are sensitive to the degree of imperviousness within a catchment have been used to estimate the hydrological impacts following the historic development of north Swindon (Miller et al., 2014), relying on generalised relationships between catchment imperviousness, connectivity and rainfall-runoff processes derived from previous estimates and studies, e.g. 70% of impervious surfaces have a direct connection to the surface water drainage system (Packman, 1980a). A lack of monitored rainfall-runoff data at detailed small-scales within different urban areas and only a generalised understanding of how imperviousness influences the rainfall-runoff properties of urban areas, results in uncertainty in understanding how urban design and layout influences the hydrology within these catchments, and how potential retro-fit SuDS may alleviate hydrological problems.

To improve the representation of urban development of different ages and designs in future hydrological modelling and surface water management planning, this thesis improves understanding of the rainfall-runoff properties of urban surfaces and collects and analyses rainfall-runoff data from two small residential sub-catchments within north Swindon. This permits an analysis of how design and development age influences rainfall-runoff behaviour. An assessment of how uncertainty in rainfall-runoff modelling translates to the potential under-design or over-design of a retro-fit surface water storage tank is then assessed. The two monitored residential sub-catchments are nested within the larger urban catchments monitored by CEH and share similar soil and slope characteristics.

1.4 THESIS AIM AND OBJECTIVES

The aim of this thesis is to determine how the rainfall-runoff behaviour of residential development is influenced by variations in surface cover, hydraulic form and development age, assessing the implications of such differences for rainfall-runoff modelling for use in the planning of retro-fitted surface water drainage infrastructure. This is achieved through six research objectives, using an empirical approach:

(i) Undertake a review of empirical measurements of hydrological processes on common surface types in urban environments, reported within the scientific and engineering literature.

(ii) Establish a monitoring network (rainfall, runoff, and soil moisture) across two contrasting residential areas that exhibit differences in surface cover and surface connectivity.

(iii) Characterise surface cover and connectivity within the two study sub-catchments examining how variation in drainage and surface layout affects the connection between the urban surface and surface water drainage system.

(iv) Quantify differences in the hydrological behaviour of the instrumented study sub-catchments, focussing on sensitivity of rainfall-runoff behaviour to rainfall characteristics and antecedent conditions.

(v) Evaluate the ability of common hydrological modelling techniques used in surface water management planning to predict the rainfall-runoff characteristics of the study sub-catchments by examining the sensitivity of estimated runoff volumes to estimates of surface cover, model choice and model parameter value selection.

(vi) Assess the implications of different rainfall-runoff modelling outcomes in a retro-fit surface water drainage system context.

By focussing on these six research objectives, this thesis will contribute new understanding of the processes and physical features controlling runoff generation within residential urban areas for use in hydrological modelling and surface water management planning, thus making a novel and valuable contribution to the field of urban hydrology.

1.5 THESIS STRUCTURE

The thesis is presented in eight chapters, each addressing the requirements of the research objectives in turn.

Chapter 2 is a review, focussing on empirical measurements of hydrological processes on common urban surface types reported within the scientific and engineering literature. The review aims to establish the physical features and processes that exert variability on the hydrological behaviour of different types of urban surface. The chapter is presented as a journal paper that has been published in the journal Progress in Physical Geography (Redfern et al., 2016).

Chapter 3 describes the methodologies used, including the development of geospatial techniques, hydrological monitoring, data and statistical analyses and the comparison of hydrological modelling techniques.

Chapter 4 maps and defines the surface cover and surface features that exert influence on the urban hydrological system within the two study sub-catchments. The chapter develops the concept of connection efficiency as a means to understand the role that the arrangement of urban surfaces, drainage connection points and local topography has in determining the connectivity between the urban surface and the surface water drainage system. Surfaces with direct and indirect connections to the surface water drainage system are defined.

Chapter 5 analyses monitored hydrological data to compare the rainfall-runoff behaviours of the two study catchments, with particular reference to the percentage runoff and peak flow rate. The sensitivity of the rainfall-runoff performance of the two catchments to rainfall characteristics and antecedent conditions is explored through multiple linear regression modelling.

Chapter 6 models the two study catchments to assess what additional volume of runoff is produced because of urbanisation. Monitored rainfall-runoff data is used to test the ability of commonly used urban rainfall-runoff models to replicate the rainfall-runoff behaviour of the study sub-catchments. A sensitivity analysis of model choice and parameter values is used to provide advice on the application and use of models to accurately represent monitored rainfall-runoff data. The implications of inaccurate rainfall-runoff modelling are examined in a retro-fit storage tank context by estimating the increased construction costs as a result of the over prediction of runoff volumes, and undersized storage volume as a result of under prediction of runoff volumes.

Chapter 7 discusses the findings presented in Chapters 2, 4, 5 and 6 to expand their application to a wider UK and international context.

Chapter 8 presents the conclusions of the thesis.

1.6 CHAPTER STATUS AND AUTHOR CONTRIBUTIONS:

N. Macdonald, T. Kjeldsen, J. Miller and N. Reynard supported the theoretical and practical design of this thesis. J. Miller provided expertise and practical skills in establishing the hydrological monitoring equipment.

T. Redfern is the author of chapters 1, 3, 7 and 8. N. Macdonald, T. Kjeldsen, J. Miller and N. Reynard provided comments and reviewed drafts of manuscripts.

Chapter 2 is a journal paper published in Progress in Physical Geography. T. Redfern is the lead author of this paper, while N. Macdonald, T. Kjeldsen, J. Miller and N. Reynard helped to develop the methodological approach and reviewed drafts of the manuscript.

Chapters 4 and 5 will be combined into a joint paper for submission to the Journal of Hydrology. T. Redfern is the lead author of these chapters and N. Macdonald, T. Kjeldsen, J. Miller and N. Reynard helped to develop the methodological approach and reviewed drafts of the manuscript.

Chapter 6 will be written into a paper for submission to Science of the Total Environment. T. Redfern is the lead author of this chapter and N. Macdonald, T. Kjeldsen, J. Miller and N. Reynard helped to develop the methodological approach and reviewed drafts of the manuscript.

Chapter 2

CURRENT UNDERSTANDING OF HYDROLOGICAL PROCESSES ON COMMON URBAN SURFACES.

This chapter reviews empirical measurements of hydrological processes on common urban surfaces. The aim is to highlight the physical features and processes that exert influence on urban surface hydrological behaviour.

This Chapter has been published as a paper:
Redfern, T.W; Macdonald, N; Kjeldsen, T.R; Miller, J.D; Reynard, N. 2016: Current understanding of hydrological processes on common urban surfaces. Progress in Physical Geography, 40(5): 699-713

2.1 ABSTRACT

Understanding the rainfall-runoff behaviour of urban land surfaces is an important scientific and practical issue, as storm water management policies increasingly aim to manage flood risk at local scales within urban areas, whilst controlling the quality and quantity of runoff that reaches receiving water bodies. By reviewing field measurements reported within the literature on runoff, infiltration, evaporation and storage on common urban surfaces, this study describes a complex hydrological behaviour with greater rates of infiltration than often assumed, contradicting a commonly adopted but simplified classification of the hydrological properties of urban surfaces. This shows that the term impervious surface, or impermeable surface, referring to all constructed surfaces (e.g. roads, roofs, footpaths etc.) is inaccurate and potentially misleading. The hydrological character of urban surfaces is not stable through time, with both short (seasonal) and long-term (decadal) changes in hydrological behaviour, as surfaces respond to variations in seasonal characteristics and degradation in surface condition. At present these changing factors are not widely incorporated into hydrological modelling or urban surface water management

planning, with static values describing runoff and assumptions of imperviousness often used. Developing a greater understanding of the linkages between urban surfaces and hydrological behaviour will improve the representation of diverse urban landscapes within hydrological models.

2.2 INTRODUCTION

In the context of land-use and land cover change, urbanization describes the process by which natural vegetated landscapes are replaced with constructed surfaces (Shuster et al., 2005). Urban areas have expanded to provide the housing, transport and other infrastructure required by the world's increasing urban population over the 20th and into the 21st Century, and so the coverage of urban surfaces has increased and intensified in many parts of the world (Marshall, 2007).

During severe storm events, large volumes of water must navigate across the surface of towns and cities before reaching a receiving water body (Wheater and Evans, 2009). Without careful management surface water can accumulate resulting in the flooding of roads, homes and businesses, often with considerable negative economic (Sušnik et al., 2014), social (Tapsell and Tunstall, 2008) and health (Fewtrell and Kay, 2008) consequences for affected communities. Historical engineering approaches to surface water management focused on constructing drains that transfer runoff to receiving water bodies as quickly and efficiently as possible (Woods-Ballard et al., 2007). However, directly connecting the catchment stream network to urban drainage systems and runoff generating surfaces impacts on the hydrological functioning of a catchment (O'Driscoll et al., 2010), potentially increasing flood risk downstream (Hollis, 1975; Kjeldsen et al., 2013), whilst low flow regimes can be impacted by reductions in infiltration and groundwater recharge (Chung et al., 2011) with consequences for water resources and hydro-ecology (White and Greer, 2006).

Modern storm water management practices have developed away from the historical focus on removing surface water as quickly and efficiently as possible, reflecting the need to address the larger scale impacts of urbanisation on the hydrological cycle (Charlesworth et al., 2003). To reduce runoff volumes and improve urban runoff water quality, contemporary storm water management technologies aim to reduce and disconnect impervious surfaces from the storm water drainage system (Walsh et al., 2005), use pervious areas and engineered surface features to increase infiltration and therefore groundwater recharge (Hamel et al., 2013) and construct artificial areas of storage within urban catchments (Woods-Ballard et al., 2007). The legacy of extant urban developments combined with climate change and increasing imperviousness within urban areas (urban creep) means retrofitting the existing built environment with modern storm water management techniques has become a priority (MacDonald, 2011), both for local flood risk management and for the mitigation of hydrological impacts in urbanised catchments. Understanding the runoff generation processes and infiltration potential of diverse urban land surfaces is therefore a priority for the design and implementation of storm-water management policies and technologies (Salvadore et al., 2015).

Urban hydrology has been the subject of a considerable volume of research; as described in a review by Fletcher et al. (2013). Topics of research have included detecting and quantifying hydrological changes in urbanised catchments (Miller et al., 2014; Braud et al., 2013a), accounting for these hydrological changes within flood prediction models (Kjeldsen, 2009; Nirupama and Simonovic, 2007), investigating the generation of surface water flood risk within urban settings (Yu and Coulthard, 2015) and detecting the impacts of urbanisation on groundwater and base-flow regimes (Kazemi, 2011; Shepherd et al., 2006). Where available, long-term flow series can be analysed in combination with geospatial databases to attribute hydrological characteristics to urban development patterns. However, long data series within urban settings are rare with the hydrological behaviour of urban areas often predicted using hydrological modelling (Fletcher et al., 2013).

The ability of hydrological models to accurately replicate the impacts of urbanisation on the hydrological system is reliant upon the accurate representation, mathematical description and parameterisation of rainfall-runoff processes on urban surfaces (Packman, 1980b). However, no universally accepted characterisation of urban surfaces for inclusion in hydrological models exists (Shields and Tague, 2012), leading to a large number of hydrological models, with a high degree of variability in the representation of hydrological processes in urban areas (Salvadore et al., 2015). Commonly roads, roofs and other constructed surfaces are grouped together as *impervious surfaces*, with estimates of their extent determined from aerial photographs, maps (Miller et al., 2014) or remote sensing (see review by Slonecker et al. (2001)). Impervious surfaces are often assumed to prevent precipitation from directly infiltrating into the soil, converting high proportions of rainfall into direct runoff (Jacobson, 2011). Representing the hydrological behaviour of impervious surfaces is often based on estimates e.g. percentage runoff = 70%, (Packman, 1980b; Kjeldsen, 2009), theoretical assumptions e.g. infiltration= 0% (Wiles and Sharp, 2008), or the application of previously calibrated techniques linking the degree of imperviousness to hydrological behaviour (Holman-Dodds et al., 2003). Other techniques include estimating the hydrological characteristics of impervious surfaces as a function of proximity to the stream network (Franczyk and Chang, 2009), or as a function of land use (Baker and Miller, 2013). This list is by no means exhaustive and many other methods have been applied within the literature (Salvadore et al., 2015). The outputs of hydrological models are therefore sensitive to the determination of the extent of imperviousness, degree of connectivity to the surface water drainage system (Roy and Shuster, 2009) and the definition of hydrological processes on urban surfaces (Yao et al., 2016b; Beighley et al., 2009). However, there is currently no thorough understanding of hydrological processes occurring on extant urban surface types; as little research has assessed the veracity of the underlying assumptions regarding the imperviousness of impervious surfaces, or provided detailed assessments of the hydrological properties of other types of urban surface (Evans and Eadon, 2007). The aim of this study is to review empirical measurements of hydrological processes upon common urban surface types, through three objectives:

(i) Review empirical measurements of hydrological processes on common urban surfaces reported within peer-reviewed scientific literature and, where available, grey (engineering) literature.

(ii) Highlight surface types, features and processes that contribute to variability in urban rainfall-runoff and infiltration behaviour.

(iii) Discuss the implications of this review for hydrological modelling and storm water management, identifying where current understanding is lacking and where future research is required.

A detailed evidence-based description of hydrological processes occurring on urban surfaces is provided, informing future modelling and flood risk management research and policies. The aim of this study is not to provide a comprehensive discourse on all available literature, but to highlight and discuss the features, processes and variables likely to contribute to urban rainfall-runoff response and infiltration, based on evidence extracted from analysis of observations rather than predictions made using modelling systems.

2.3 REVIEW METHODOLOGY

By focusing on empirical measurements of hydrological processes on common urban surfaces, this study provides a novel approach to building understanding of the urban water cycle, complementing recent hydrological reviews focussed on modelling techniques (Praskievicz and Chang, 2009; Salvadore et al., 2015), management (Fletcher et al., 2013), impacts (O'Driscoll et al., 2010; Shuster et al., 2005) and the detection of changes within urban catchments (Jacobson, 2011). This study provides details of the observed features and processes within urban catchments that control urban rainfall-runoff response and thus offers a new insight into the hydrological performance of perceived impervious surfaces, key to managing and understanding the urban water cycle.

Relevant scientific studies and grey literature, identified through academic databases and web-based search engines (which are more likely to identify grey literature e.g. Google Scholar), are included in the review if they meet the following requirements:

(i) Studies examining roads, pavements (not permeable paving), roofs (not green roofs), driveways, paths and urban vegetated areas are targeted.

(ii) Studies that aim to determine the physical features of urban surfaces that influence hydrological behaviour (e.g. cracks, potholes, patches) are reviewed

(iii) Empirical measurements of hydrological processes (infiltration, evaporation, runoff, storage) on the urban surfaces are reported; whilst data inferred from large scale monitoring or modelling studies are intentionally excluded from the review.

(iv) Only those studies investigating surfaces within urban settings are included.

(v) Priority is given to peer reviewed scientific journals or grey (engineering) literature. Where relevant material is cited in a target paper outside of the available journals or grey literature (i.e. PhD theses), the material is assessed for relevance and inclusion.

Inevitably the reviewed materials are English language based which could limit the inclusion of some relevant studies. However, it is likely that the findings presented here are applicable to those areas supported by non-English language based hydrological communities and journals given the similarity in urban construction materials around the world.

2.4 THE HYDROLOGICAL BEHAVIOUR OF ROOFS

Roofs are typically drained via guttering to downpipes that either connect directly to the surface water drainage system, drainage features within the soil (e.g. a soakaway) or to surfaces adjacent to the building perimeter (e.g. garden, path etc.). Depending on downpipe discharge point, runoff from roofs can directly contribute to catchment runoff (via the surface water drainage system), local soil moisture and groundwater recharge or the wetting of local surfaces. Estimating the proportion of roofs with a direct connection to surface water drains requires significant effort (Lee and Heaney, 2003), which is difficult to extrapolate from catchment to catchment. Roofs have been studied for their potential to provide water for domestic grey water uses (Villarreal and Dixon, 2005), their pollutant production potential (Davis et al., 2001) and in comparison to green roofs (Bliss et al., 2009); but only a limited number of studies have specifically investigated and reported roof runoff characteristics, limiting comparative analyses. Results published in the scientific literature suggest that roofs typically convert a large proportion of rainfall into runoff, with measurements of up to 92% of rainfall shown by Farreny et al. (2011), 77% by Ragab et al. (2003a) and 57% by Hollis and Ovenden (1988b). Rainfall that is not converted to runoff in these studies is assumed to evaporate. The materials of construction (Farreny et al., 2011), slope and orientation (Ragab et al., 2003a) and total rainfall depth (Hollis and Ovenden, 1988b) influence roof rainfall-runoff behaviour, meaning that performance is highly variable between roofs (see Tables 2.1 & 2.2).

Table 2.1: Annual rainfall, runoff and evaporation estimates for six roofs studied by Ragab et al. (2003a) and average percentage runoff values recorded by Farreny et al. (2011).

		Roof	**1**	**2**	**3**	**4**	**5**	**6**
Ragab et al. (2003a)	**Annual values**	Slope (^{0})	22	22	22	50	0	0
		Orientation	N-S	E-W	E-W	N-S	N/A	N/A
		Runoff (%)	75.4	88.6	66.6	100.9	70.5	61.5
		Evaporation (%)	24.7	13.6	33.4	56.2	9.3	32.2
	Monthly Values	Max (%)	84.7	104	86.1	121	81.6	71
		Min (%)	45.7	70.5	38.3	49.4	48.2	45.6
		Mean (%)	71.1	85.6	61	90.5	66.7	58.1
Farreny et al. (2011)	**Roof material**	**Clay tiles (30^{0} slope)**	**Metal sheeting (30^{0} slope)**	**Polycarbonate plastic (30^{0} slope)**	**Flat gravel**			
	Annual average percentage runoff (%)	0.84 ± 0.01	0.92 ±0.00	0.91 ± 0.01	0.62 ± 0.04			

Table 2.2: Mean and monthly percentage runoff values recorded by Hollis and Ovenden (1988b) for roads and roofs in the south east of the UK.

	For all storms		Storms >5mm	
Month	**Mean for roads**	**Mean for roofs**	**Mean for roads**	**Mean for roofs**
Jan	6.5	47.3	20.5	125.2
Feb	6.9	49.4	10.2	37.8
Mar	1.1	47.5		
Apr	18	60.9	25.3	75.1
May	17.4	42.4	36.2	97
Jun	9.7	65	36.9	91.9
Jul	10.2	71.5	33.2	154.8
Aug	36.6	86.3		
Sep	15.6	62.1	33.1	80.6
Oct	8.3	45.1	37.9	76.6
Nov	7.8	30.1	23.7	74
Dec	8.6	58.8	25.9	90.9
Mean	11.4	56.9	28.3	90.4

2.5 THE HYDROLOGICAL BEHAVIOUR OF ROADS

Road infrastructure (e.g. roads, pavements, car parks) can represent a large proportion of urban surfaces connected directly to a surface water drainage system i.e. Lee and Heaney (2003) report that in a residential study area of Colorado (USA) 68% of directly connected urban surfaces are transport related. Road surfaces typically consist of a number of layers of materials, whose interlocking aggregates and binding materials provide a surface resistant to loading and mechanical wear. Typically constructed of asphalt, concrete or tar-macadam, an important purpose of the topmost layer (the wearing course) is to provide an impermeable barrier for water, as water ingress and movement can rapidly degrade the integrity of supporting layers and compromise the strength of a road (Dawson et al., 2009). Therefore, road surfaces are often assumed to be highly impervious, allowing only limited infiltration of water into the soil (Wiles and Sharp, 2008). Studies examining the hydrological performance of road related surfaces are available at a range of scales from <1m^2 (Ramier et al., 2004) to >100m^2 (Hollis and Ovenden, 1988b); applying methodologies that involve isolating individual surfaces and monitoring runoff in comparison to meteorological parameters (such as rainfall or temperature).

At small spatial scales, total runoff can account for a large proportion of rainfall on common road surface materials (Pandit and Heck, 2009). In tests by Mansell and Rollet (2006) on 300x300 mm slabs of concrete paving, brick paving and tar macadam surfacing, runoff is reported to represent a significant proportion of rainfall volumes for the continuous surfaces (Table 2.3) with slope and gaps influencing the hydrological behaviour. Infiltration into the road structure itself is low for all considered surfaces (2% or 0%), whilst the gaps between elements in the brick surfacing allowed on average 52% of rainfall to infiltrate into the underlying soils.

Table 2.3: Water balance components for common urban surface types from direct measurements reported by Mansell and Rollet (2006) and Ramier et al. (2004).

Study	**Surface Type**	**Runoff (Av. % of rainfall)**	**Infiltration (Av. % of rainfall)**	**Evaporation (Av. % of rainfall)**	**Infiltration through joints (% of rainfall)**
Mansell & Rollet (2006)	Flat Concrete Slab	69	1	30	
	Inclined Concrete Slab	93	2	5	
	Brick Work	9	2	37	52
	Hot Rolled Asphalt	56	0	44	
	Dense Bitumen Macadam	36	0	64	
Ramier et al. (2004)	Asphalt Concrete (deteriorated) (15% porosity)	16	58	26	
	Asphalt Concrete (5% porosity)	74	3	23	
	Asphalt Concrete (5% porosity)	73	2	25	

The permeability of asphaltic mixtures is controlled by the size and interconnectivity of pore spaces (Dawson et al., 2009). Vivar and Haddock (2007) identify that increasing porosity (a function of aggregate mix) influences the permeability of new road surfaces in laboratory experiments, where porosities over 7% show rapid increases in permeability. The deterioration of condition of surface materials can increase the permeability of a road surface, reducing the proportion of rainfall converted to runoff. By applying a specially developed urban lysimeter, Ramier et al. (2004) measured components of the water balance on three samples of asphalt concrete, of the three samples tested, one surface was more porous than the other two (15% porosity rather than 5%) arising from a deteriorated condition. On the sample with increased porosity (deteriorated condition), infiltration is reported to account for 58% of rainfall, runoff 16%, with the remaining 26% lost to evaporation. The less porous (good condition) samples evidenced infiltration rates of 2-3%, with runoff at 73-74% and evaporation at ~24% of rainfall (Table 2.3). In summary, small samples of road surfaces and newly constructed materials can convert a large proportion of rainfall into runoff, whilst infiltration is limited, but where surface condition has deteriorated infiltration can occur.

The hydrological performance of actual in-situ roads is highly variable, both in space and time. In an analysis of the rainfall-runoff performance of ten roads over 12 months, Hollis and Ovenden (1988b) report average runoff values of 11.4% for rainfall events under 5mm in depth (Table 2.2), with percentage runoff in individual months ranging from 1.1% for March to 36.6% for August. For rainfall events over 5 mm in depth the annual average increases to 28.3%, ranging from 10.2-37.9% for monthly average values. These results are surprisingly low given commonly held assumptions of the impermeability of road surfaces and may relate to the initial loss of precipitation to storage on the road surfaces (Kidd and Lowing, 1979). However, other studies have confirmed the variable conversion of rainfall into runoff upon roads (Ramier et al., 2011; Rodriguez et al., 2000). Ragab et al. (2003b) identified contradictory seasonal patterns of rainfall runoff behaviour when compared to that recorded by Hollis and Ovenden (1988b), with 70% of annual rainfall converted into runoff with a peak in winter (90%) and lower values in summer (50%). Comparing Ragab et al. (2003b) and Hollis and Ovenden (1988b) suggests that rainfall - runoff processes on urban surfaces are complex, with contradictory seasonal patterns exhibited between the two studies. Each study measured urban rainfall and runoff within the south east UK; though Hollis and Ovenden (1988b) worked within a permeable soils catchment, whilst Ragab et al.

(2003a) worked in an area dominated by clay soils, suggesting that soil type influences the urban surfaces' infiltration and runoff behaviour.

The loss of rainfall from road surfaces can be investigated through a number of field measurement techniques, making either direct or indirect measurements of infiltration, storage and evaporation. Depending on the hydrological process and type of surface studied, different units are used within the literature to report empirical results, making direct comparisons between studies challenging. Ragab et al. (2003b) used soil moisture sensors installed underneath in-situ impervious surfaces (three car parks and one road) to show that between 6-9% of annual rainfall infiltrated through the impervious surface, with evaporation accounting for between 21-24% of rainfall, with greater evaporation in summer than winter. Irrigation experiments by Hollis and Ovenden (1988a) compared the infiltration losses recorded at kerb joins and on road surfaces, where infiltration losses reported are variable between sites and over time. For road surface experiments infiltration rates range between 0.0119-0.0590 l/min/m^2, whilst for kerb experiments infiltration rates range between 0.325-7 l/min/m (Figure 2.1). A seasonal pattern of increased infiltration rates in winter months is attributed to freeze-thaw action opening pore spaces within the road surface. In some cases large volumes of water are applied before runoff occurred (from 0.5 mm equivalent rainfall depth to greater than 16.7 mm equivalent rainfall depth), indicating that initial losses of rainfall are considerable, highly variable and difficult to generalise between the studied roads. A similar irrigation experiment by Zondervan (1978) estimated infiltration rates of between 7-27 mm/hr on road surfaces, with infiltration attributed to cracks and joins in the surface, as solid road samples were taken and subjected to laboratory experiments with infiltration losses of 0.5 mm/hr recorded; supporting the findings of Ridgeway (1976) who also identified that cracks, joins and fractures in road surfacing could explain high rates of infiltration. Using a double ring infiltrometer to directly measure infiltration through road surfaces in residential and commercial areas in Austin, USA, Wiles and Sharp (2008) report that up to 20% of the annual water balance of the area could be accounted for by infiltration through impervious road surfaces, though highly variable over space, with up to a third of experiments recording no infiltration. An analysis comparing the fracture and joint apertures against the infiltration rate offered no correlation, suggesting that the sub-surface structure of surfaces and soil conditions influences infiltration, rather than the size of fracture or joint in the surface.

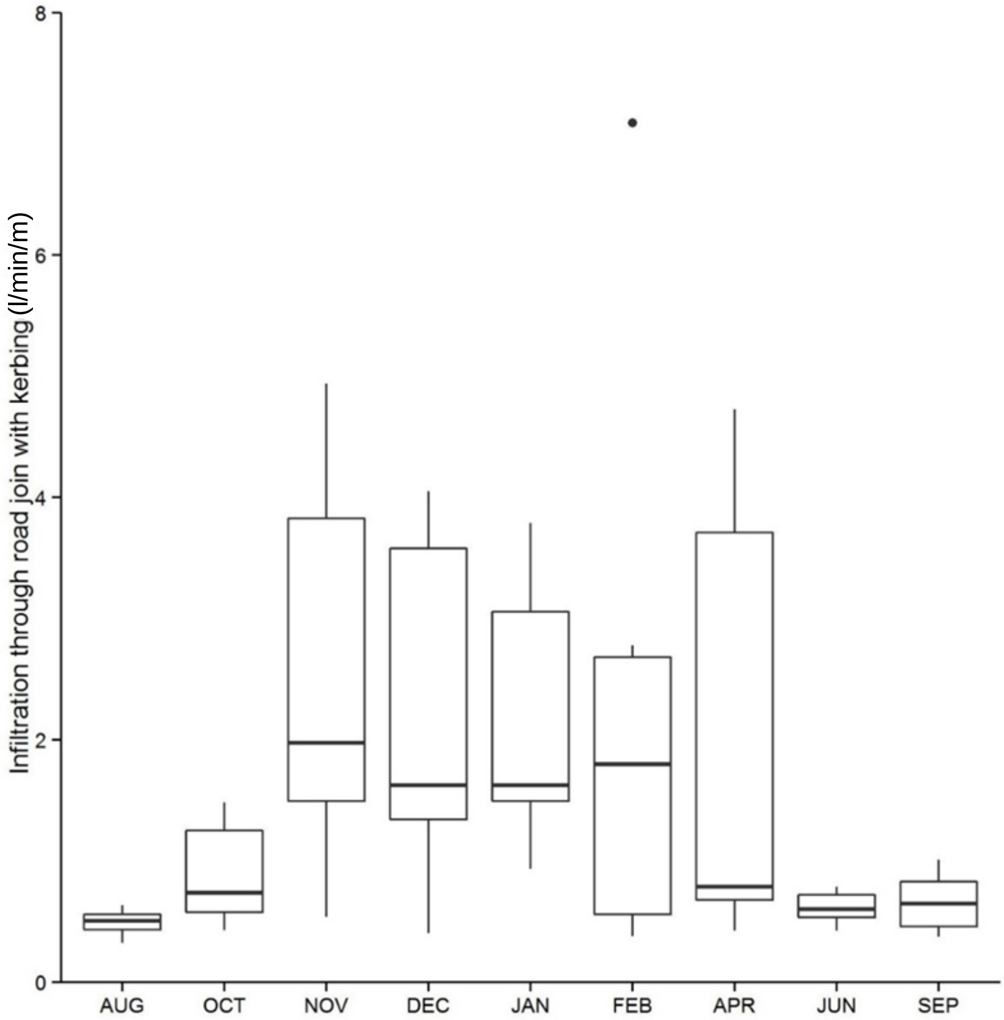

Figure 2.1: Infiltration rates recorded at road kerbsides by Hollis and Ovenden (1988a)

The age and traffic loading on road surfaces influences infiltration potential. For example, Fernandez-Barrera et al. (2008) using a “Laboratorió de Caminos de Santander” (LCS) permeameter found an eleven year old impervious asphalt and a heavily trafficked pervious asphalt to have a similar infiltration potential to that of a clay-soil grass surface (Table 2.4). Roads are often resurfaced in patches either to repair areas of poor condition (i.e. pot holes or cracks) or to cover areas that have been excavated for infrastructure trenches (e.g. water, electricity, broadband infrastructure etc.). Depending on the quality of the join between patching and extant surfacing, preferential pathways for infiltration can form with up to 8.78 l/hr/m^2 recorded around patches by Taylor (2004).

Table 2.4: Infiltration rates through common urban surface types recorded by two techniques (data taken from Fernandez-Barrera et al. (2008) and Gilbert and Clausen (2006). High LCS Permeameter results indicate low infiltration rates

	Surface type	Description of experiment	LCS Permeameter average results (s)
Barrera et al., (2008)	Reinforced Grass (concrete cells)	Clay soil	1223.86
	Reinforced Grass (plastic cells)	Sandy Soil	150.94
	Impervious Asphalt	New surface course (1 years)	>1800
	Impervious Asphalt	Old surface course (11 years)	1233.34
	Porous Asphalt	High traffic intensity	1052.01
	Porous Asphalt	Light traffic intensity	21.21
	Concrete block impervious pavement	Mortar in joints	21.77
	Concrete block pervious pavement	No fill between joints	4.55
	Metallic plate		>1800
Gilbert & Clausen (2006)	**Surface**	**Description of infiltration test**	**Infiltration rate (cm/h)**
	Asphalt	Single ring (2002)	0
		Single ring (2003)	0
		Flowing (2003)	0
	Paver	Single ring (2002)	11.8±9.5
		Single ring (2003)	10.5±5.9
		Flowing (2003)	11.4
	Crushed stone	Single ring (2002)	11.3±3.1
		Single ring (2003)	9.7±7.8
		Flowing (2003)	6

Surfaces within domestic curtilages (e.g. driveways) or public open spaces (e.g. paths) are often constructed of similar materials to road surfaces, or of non-continuous surfaces such as gravel, concrete slabs or bricks. However, they may not have direct connections to the surface water drainage system and instead may discharge to nearby permeable surfaces. Understanding the hydrology of these surfaces is important, as changes in surface types within domestic areas has been cited as a mechanism leading to increased surface water flood risk, as vegetated gardens are replaced by car parking areas (Perry and Nawaz, 2008). Grass surfaces can be reinforced to allow movement of vehicles with limited impacts on infiltration capacity (Fernandez-Barrera et al., 2008), whilst concrete paving and crushed stone surfacing have been shown to allow comparatively greater infiltration than that of asphalt (Gilbert and Clausen (2006); Table 2.4). The significance of changes in domestic surface cover is therefore likely dependant on the materials of construction and connectivity to the surface water drainage system.

In summary, roads exhibit a complicated hydrological behaviour that varies both over space and time. Whilst small samples of new road surface materials studied in laboratory conditions are shown to be highly impermeable, actual in situ roads that have been in place for a number of years are shown to allow considerable infiltration. It is likely that the hydrological properties of road surfaces change over different timescales. Over the short (minutes to months) timescale evidence suggests that between rainfall event variability can be explained in part by variations in the connectivity of pore spaces within road structures, caused by temperature related expansion and contraction; with the hydrological properties of the underlying soil also contributing to variability. Over longer timescales (years to decades) the hydrological properties of a road surface may change, as wearing and weathering processes degrade the impervious nature of the uppermost wearing course. The gradual or rapid subsidence of underlying soils may also encourage the degradation of road surfaces, by encouraging cracking and fracturing.

2.6 HYDROLOGICAL BEHAVIOUR OF URBAN GREEN SPACES AND SOILS

Urban areas contain vegetated surfaces (e.g. gardens, parks and road side verges) which need characterising in hydrological models and in storm water management planning (Law et al., 2009). This is difficult given that few studies have investigated the variability of soil hydrological properties in urban ecosystems through empirical measurements (Ossola et al., 2015). Understanding the hydrological characteristics and infiltration capacity of urban green spaces and soils is significant for the sustainable management of storm water, as urban green spaces are often cited as potential areas for storm water disconnection (Dietz and Clausen, 2008).

Typically urban green spaces are perceived as pervious surfaces or modelled with similar characteristics to more natural vegetated areas (Gregory et al., 2006). However, urbanisation can impact on the physical properties of underlying soils in a manner that impacts on the hydrological characteristics of urban green spaces through two linked systems of direct and indirect impacts (Pouyat et al., 2010). First, direct impacts include those in the immediate timescale of urban development such as the loss of vegetation, removal of top soils, importation of foreign soils and aggregates and static (buildings) and dynamic (cars and vehicles) compaction of soils (Cogger, 2005); meaning that urban soils can become highly degraded in terms of water retention capacity and infiltration potential (Pitt et al., 2008). Second, indirect impacts of urbanisation on soils involve changes in the biotic and abiotic environment that can affect undisturbed soils in proximity to urban developments, which include a changed urban climate (urban heat island effect) (Muller et al., 2014), increased soil hydrophobicity and the deposition of pollutants (i.e. heavy metals, N and S) (White and Mcdonnell, 1988). Urban development usually follows a pattern of parcelization based upon land ownership, which creates discrete parcels with separate soil disturbances and management regimes, so that soils develop differential properties over time, resulting in a complex mosaic of soil disturbance at small spatial scales (Scharenbroch et al., 2005).

Studies have shown that urban soils are more compacted than natural soils, with a larger proportion of large stones, poorer structure and less porosity with a reduced ability to hold water or allow root growth (Jim, 1998). The impact of large stone fragments on soil infiltration is complex, with the potential to increase or decrease infiltration depending on whether the stones are within the soil column or on the surface. Surface rock cover can increase soil strength, reducing the compaction as a result of loading with the potential to resist changes in soil structure (Brakensiek and Rawls, 1994). The compaction of urban soils can reduce infiltration potential, altering the proportion of rainfall that is converted to runoff (Yang and Zhang, 2011). Pitt et al. (2002) found that the modelled response of a residential development with a natural soil surface under-predicted runoff, and that urban soils had runoff behaviour similar to impervious cover. Similarly Legg et al. (1996) found that newly established residential lawns showed runoff coefficients of between 60-70%, whilst older more established lawns had coefficients of between 5-30%. The infiltration performance of an urban, compacted clay soil is shown to be similar to a saturated natural clay soil; whilst compaction reduced infiltration rates of dry sandy soils by around 90%, irrespective of antecedent conditions (Pitt et al., 2008).

Different vegetation cover can influence the hydrological properties of urban green spaces. Increased complexity of vegetation type, the properties of the litter layer, age and management regimes are all found to influence physical soil properties and infiltration capacity in urban park areas in Melbourne, Australia (Ossola et al., 2015). Woltemade (2010) identified that lawn surface condition and percentage cover of woody vegetation influenced the degree of infiltration and runoff of 108 residential lawns. However, the age of the residential development was found to significantly impact the hydrological characteristics with post-2000 development having mean infiltration rates 69% less than those developments constructed pre-2000, a similar conclusion to Legg et al. (1996). Experimental results from Bartens et al. (2008) suggest that tree growth and root development can restore natural soil hydrological characteristics to urban soils, as roots offer preferential pathways for infiltration, which over time can penetrate through heavily compacted soil layers.

2.7 DISCUSSION AND SUMMARY

This study identifies that the hydrological behaviour of urban surfaces is complex, with more infiltration than often assumed. Roads and roofs have different hydrological properties, with roofs potentially converting more rainfall into runoff (Table 2.2). Roads can degrade in condition, altering their water balance over time, reducing runoff and increasing urban infiltration. The hydrological behaviour of an urban area is therefore likely to not only be a function of total or connected impervious cover, but related to the relative proportions of surface types, their ages and condition. Future research should focus on linking the layout, age and condition of urban areas to hydrological response to aid the characterisation of urban areas for inclusion in hydrological models.

Contemporary drainage design models are typically applied at scales within urban settings where it is possible to collect highly detailed surface geospatial data. Thus, these models allow for the inclusion of detailed surface characterisations with a number of hydrological processes calculable. Whilst it is possible to estimate model parameters taking into account surface condition, the definition of suitable model parameters is difficult (unless supported by experimental data) potentially leading to poor calibration and uncertainty in model outputs (Kellagher, 2000; Evans and Eadon, 2007). This study indicates that hydrological behaviour of urban areas at small-scales is likely sensitive to the condition and type of urban surface being drained. Developing new and improved techniques to map and characterise the hydrology of different surface types and conditions will aid in their inclusion within drainage design practice. The interception of runoff on impervious surfaces by features such as cracks and fractures may disconnect impervious surfaces from the storm water drainage system, directing runoff to infiltration, meaning caution should be exerted when applying the results of small-scale experimental studies in defining the hydrological characteristics of urban surface cover at larger scales, as this could overestimate runoff potential and underestimate urban infiltration.

Design models used in engineering hydrology are typically concerned with estimating runoff, focussing on the sizing of storm water management assets at small-scales, and so are not concerned with larger scale, longer term processes such as infiltration to groundwater recharge. However, understanding the infiltration of soil water into drainage assets is of increasing importance, as this can increase the receding limb of hydrographs reducing capacity, particularly in older systems where cracking can occur in piped surface water drainage systems (Berthier et al., 2004). The data examined within this study indicates that a significant proportion of an urban area's water balance can infiltrate through road surfaces (20% recorded by Wiles & Sharpe, 2008), which may contribute to pipe infiltration. Variable hydrograph behaviour in urban drainage systems therefore is likely sensitive to a combination of rainfall, soil moisture and groundwater conditions, depending on the physical characteristics of the urban surface. This study has found that the hydrological properties of urban surfaces can change over long and short time-scales. Detailed representation of such processes could be challenging in design practice, which is often focused on event based rainfall-runoff modelling and time static parameterisation of urban surfaces (Rauch et al., 2002).

At larger, whole-catchment scales, where typically the large-scale impacts of urbanisation on hydrology are investigated, the detailed definition of impervious surface cover is less practical, but potentially of equal importance given the number of hydrological processes that build to larger-scale, long term hydrological behaviour (Salvadore et al., 2015). Evidence of infiltration through impervious surface types demonstrate that impervious covers should not be assumed to be 100% impermeable to the infiltration of precipitation. Establishing how small-scale hydrological processes (as reviewed within this study) translate into large scale hydrological behaviour is therefore a priority, in particular the trade-off between spatial-temporal resolution of data and process representation against gain in terms of predictive accuracy, i.e. model complexity vs. predictive ability. This study highlights the importance of the accurate definition of surface types and condition within urban areas, for representing urban land cover within hydrological models. It is likely that without detailed ground-truthing of impervious cover from aerial photographs and remote sensing, runoff production potential within urban settings could be overestimated if surfaces are assumed to be wholly impervious. Finding improved ways of defining surface cover at small-scales within urban areas should therefore be a priority.

Green spaces such as gardens or parkland are often considered to be permeable and therefore allow the infiltration of water (Law et al., 2009) which includes runoff from impervious surfaces on to green surfaces or *vice versa*, with some modelling techniques able to include surface interactions (Shaw et al., 2010). However, this study has found that urban green spaces and soils can be heavily degraded in their water holding capacity and infiltration potential. There is currently little guidance available on how best to represent urban pervious land cover with degraded soil properties within hydrological models (Law et al., 2009). Therefore, understanding of how urban green surfaces contribute to urban rainfall-runoff behaviour should be improved to include a better representation of the impacts of urbanisation on soil hydrological characteristics.

Increasing infiltration within urban areas is often cited as a mechanism by which the impacts of urbanisation on low flows and groundwater could be mitigated (Hamel et al., 2013), with a number of permeable pavement technologies available to increase infiltration (Scholz and Grabowiecki, 2007), whilst such technologies are also advocated as a means of reducing flood risk at local scales within urban settings (DCLG, 2014). However, this review has found evidence for significant infiltration on common urban road surfaces, particularly on aged surfaces where features such as cracks and joins offer preferential pathways for infiltration. Therefore, future research should aim to determine how effective the retro-fitting of permeable surfacing technologies is, given a more accurate description of existing urban hydrological processes on extant urban surfaces presented in this review.

The importance of understanding and managing the hydrological behaviour of urban surfaces will increase as projected changes in extreme precipitation events (Murphy et al., 2009), combined with further urban development and expanding urban surface cover will likely present greater challenges to flood and water management over coming decades (Stocker et al., 2014).

Chapter 3

METHODOLOGY

This chapter defines the methods used in the thesis focussing on research design, study site selection, geospatial methods, hydrological data acquisition and processing, event separation and analyses, statistical methods and engineering rainfall-runoff modelling techniques.

3.1 RESEARCH DESIGN

By reviewing empirical measurements of hydrological processes on common urban surface types in Chapter 2, Redfern et al. (2016) demonstrate that the hydrological behaviour of urban surfaces is sensitive to the materials of construction, condition, connectivity and slope. A greater understanding of how urban rainfall-runoff behaviour is influenced by the layout of surfaces and their connection to the surface water drainage system is needed, to inform hydrological modelling and surface water management planning. This thesis takes an empirical approach with an emphasis on the collection, analysis and interpretation of rainfall-runoff data collected from two residential sub-catchments of north Swindon, of contrasting development histories and layouts; thereby contributing to understanding of how urban design, and surface water drainage layout impacts hydrology.

3.1.1 Study sites

There are a number of variables that are known to contribute to variability in urban rainfall-runoff behaviour e.g. underlying soils (Berthier et al., 2004), the slope of surfaces (Ragab et al., 2003a) and climatic conditions (Hollis and Ovenden, 1988b) amongst others. In selecting two study sites in close proximity of comparable size, the influence of extrinsic variables in determining the rainfall-runoff behaviour of the two study sites is limited, with age and design the predominant physical difference. The two study sites reflect two periods of urban expansion in much of Western Europe (including the UK and Swindon), during the post-war 1950s and 1990s (Section 1.1.3).

The two study catchments are of homogeneous residential land use and meet the following selection criteria:

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

(ii) The study areas are of a similar size (under 1ha), of similar slopes (Appendix 4) and with similar underlying soils.

(iii) It is possible to install and maintain hydrological monitoring equipment within the surface water drainage systems that serve each study sub-catchment with appropriate practical health and safety considerations. Existing CEH rain gauges are within close proximity to the study sub-catchments and it is possible to install soil moisture monitoring equipment in secure locations in close proximity to each site.

After a number of field visits to the north Swindon area, the two sites selected for study are Arley Close and Winsley Close (Figure 3.1, Appendix 3). Winsley Close was constructed in the post-World War II era of the 1950s, within the Penhill housing estate. Winsley Close is built on the American Radburn principle, with houses grouped in small cul-de-sacs around areas of open vegetated space (Dunning et al., 1970). Access to each property is via shared pathways that link buildings to the road network, whilst few properties have private car parking spaces. Houses are grouped into small terraces around central areas of open green space with mature trees. Winsley Close was constructed as social housing following Swindon's designation as a spill over town for London in the 1950s (see Section 1.1.4), a time when car ownership was low and development planning favoured speed of construction over other considerations such as transport links or proximity to employment (Cullingworth and Nadin, 2002). Arley Close is part of the Abbey Meads housing development built during the 1990s, a period of increased car ownership (Dargay and Hanly, 2007) and like Winsley Close (1950s) is arranged into a small cul-de-sac, however there is no centrally shared open space, instead the road network constitutes the largest open shared space. Access to each property from the road network is via private pathways and driveways.

3.1.2 Health and safety training

Installation of hydrological monitoring equipment into drainage systems necessitates compliance with Health and Safety legislation, requiring the successful completion of *The Classification and Management of Confined Space Entries Course (Safety Training & Assessments Services LTD, Gloucester,* certificate in Appendix 1). This is required for entering and working within confined spaces providing training in the use of specialist health and safety equipment. At each site a safe working area is established using road cones and barriers (Blake, 2013), whilst a tripod and winch is used as a safety line for working within the surface water drainage systems (McManus, 1998); Figure 3.2. A series of site visits to north Swindon are used to identify appropriate locations to install flow monitoring equipment within the existing surface water drainage systems serving Arley Close and Winsley Close. The installation of field instrumentation is undertaken by two individuals (safety precaution), with James Miller (CEH Wallingford) supporting field installation and study site identification.

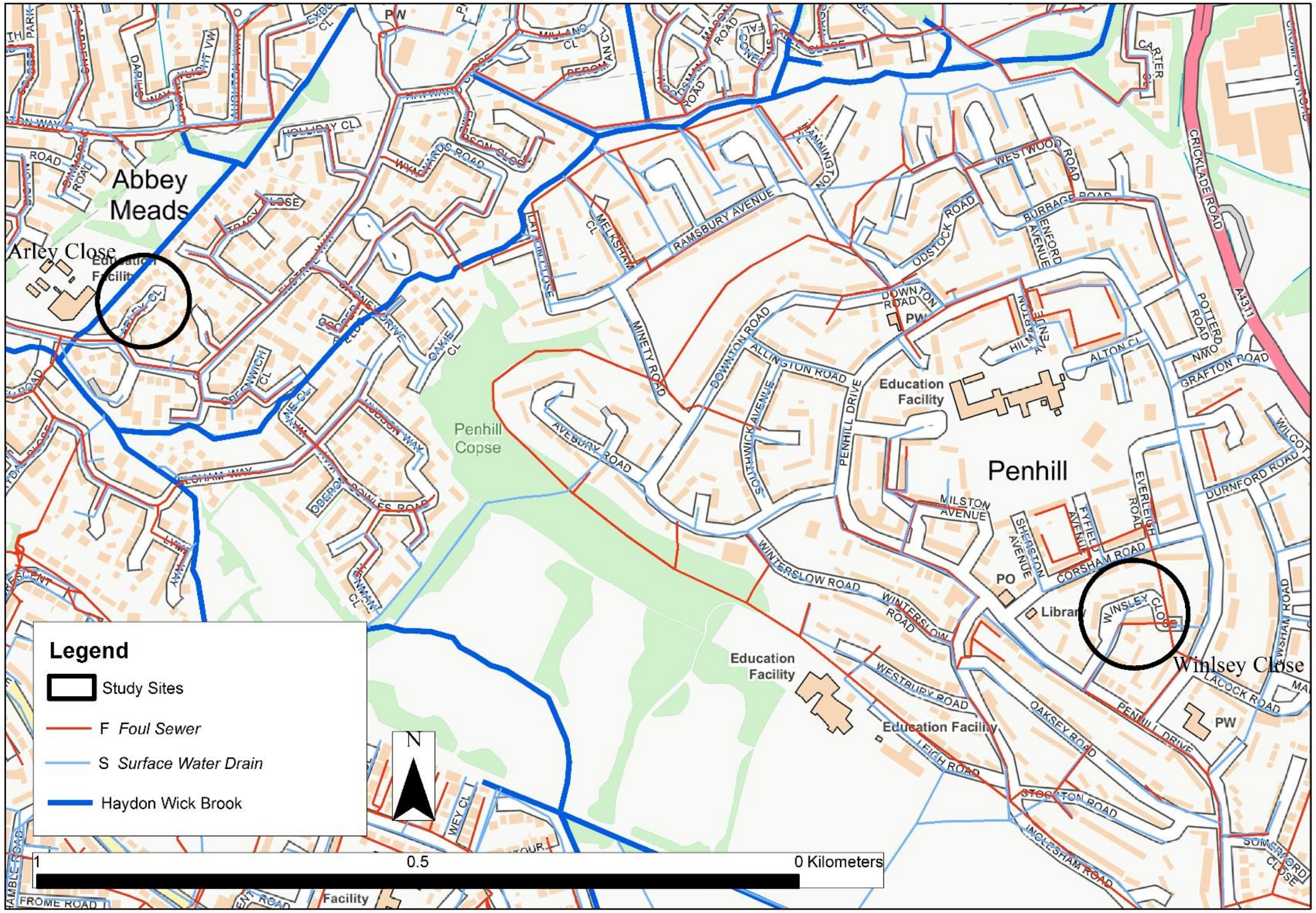

Figure 3.1: Locations of Arley Close and Winsley Close within north Swindon. Both study sites are serviced by separate foul and surface water drainage systems. Contains OS data © Crown copyright and database right 2017

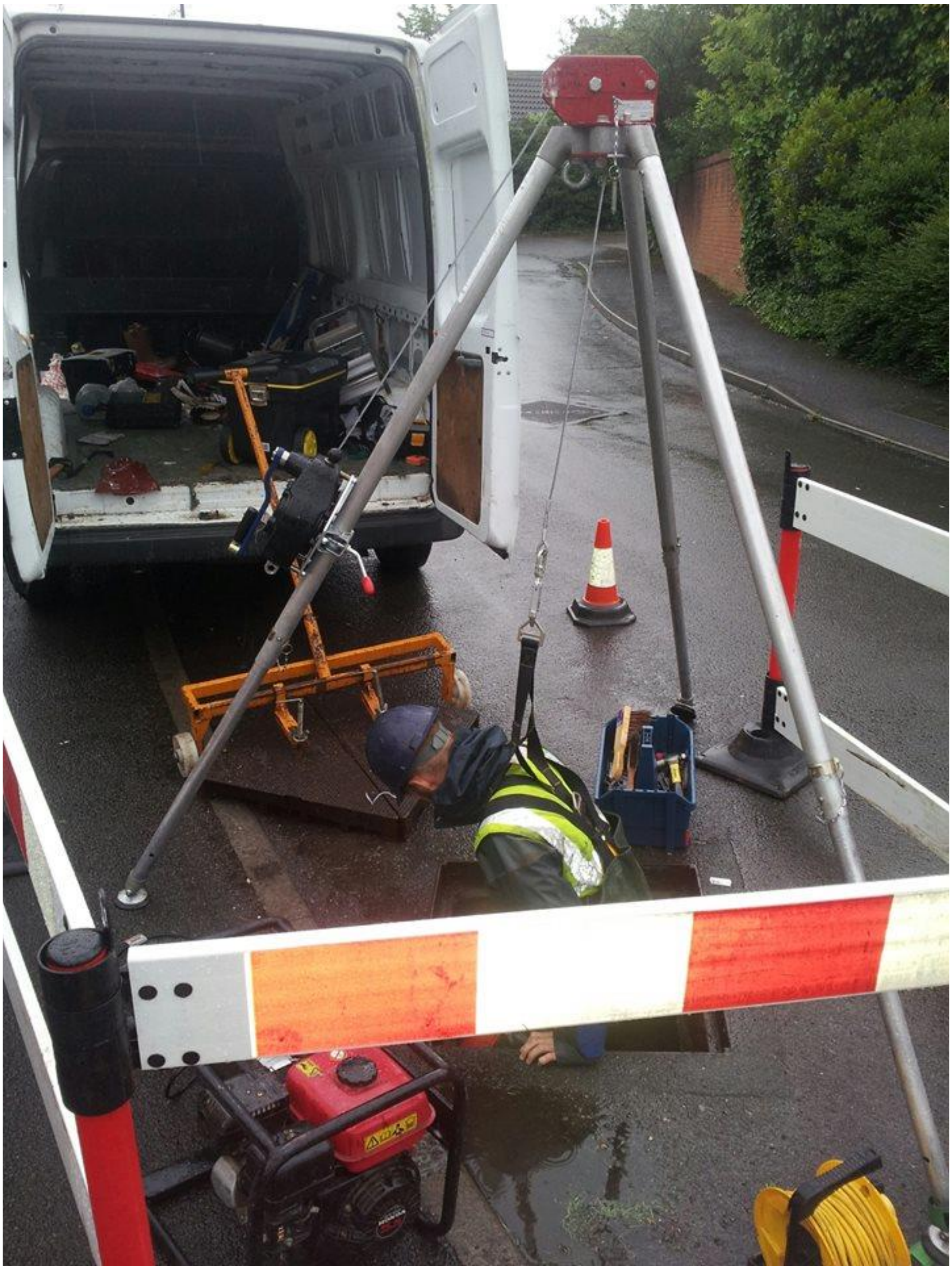

Figure 3.2: Installation of flow monitoring equipment within the surface water drainage system in Arley Close.

3.2 HYDROLOGICALLY IMPORTANT SOIL PROPERTIES

Soils are compared across the two sites by examining the Winter Rainfall Acceptance Potential (WRAP) and the Hydrology of Soil Types (HOST) of each site (Boorman et al., 1995). WRAP and HOST are pre-existing datasets derived to map hydrologically important soil properties across the United Kingdom. Each is based on an assessment of how soil properties affect hydrological processes and runoff generation, however they are sensitive to different spatio-temporal scales of hydrological processes. The WRAP classification aims to characterise the ability of soils to absorb rainfall during the timescale of a rainfall event based on an assessment of four main soil and site properties:

(i) the soil water regime,
(ii) the depth to an impermeable layer,
(iii) the permeability of soils above impermeable layer, and;
(iv) the slope of the land.

The WRAP classification classes soils across the UK into one of five categories either described as the "Winter Rainfall Acceptance Class" or "Winter Runoff Potential Class". Increasing values of WRAP value indicate a reduced ability to absorb winter rainfall and thus an increased tendency to produce surface runoff. Maps of WRAP soil types are available across the United Kingdom at up to 1:625,000 scale and there are online resources available to estimate the WRAP soil type of an area e.g. www.uksuds.com.

The HOST classification is different to WRAP in that it is based on an assessment of how soil properties affect the generation of runoff at a larger catchment scale, and thus incorporates a greater complexity, number of soil and geological properties as well as rainfall-runoff data from fluvial systems to differentiate soils. The overall objective of HOST is to assess at what depth and under what conditions water movement within a soil column becomes lateral rather than vertical (Boorman et al., 1995). Vertical flow of precipitation is likely to contribute to soil moisture and ground water recharge, resulting in low contributions to fluvial event flow response. Lateral flow is likely to contribute to interflow or surface flow processes and thus is more likely to contribute to fluvial flow responses in the immediate timescales of rainfall-runoff events. HOST categorizes soils into one of 29 classes in a gridded 1 km^2 dataset. In general terms, increased values of HOST classification indicates increased runoff potential of soils, though this not a linear system as the HOST classification incorporates a number of soil and geological features and complex process interactions that may influence soil rainfall-runoff behaviour.

Both WRAP and HOST are derived from assessments of soils and hydrogeology in non-urbanised settings. Despite this, their use is widespread within urban hydrology within the United Kingdom (Woods-Ballard et al., 2007). Soil properties in urban areas are affected by a number of processes that act across a number of different spatio-temporal scales. In addition, urban areas are characterised by a complex mosaic of land parcels, under different land ownerships and land covers (Section 2.6). The complexity of the urban environment and its particular environmental conditions may reduce the ability of large scale datasets to represent local urban soil conditions. To ascertain a greater understanding of the soil properties within Arley Close and Winsley Close and to verify that the information contained within the mapped soil properties within WRAP and HOST are representative, surface soil samples are collected and analysed.

Soil samples are taken from public vegetated surfaces in Winsley Close, and road verge areas within approximately 100 m of Arley Close since there are no publicly available vegetated surfaces within Arley Close from which soil samples can be taken. Soil samples are gathered using a closed ring t-bar auger soil sampler of 100 cm^3 volume and stored within sealed plastic bags when in transit. In total 18 samples are gathered from soils in Winsley Close, and 14 in the area surrounding Arley Close.

3.2.1 Determining the loss on ignition organic content of soils (LOI-OC)

The loss on ignition organic content is estimated using the procedure described by Nelson and Sommer (1996). The methodology is as follows:

(i) Soil samples are separated with a pestle and mortar until soil grains are approximately homogeneous (see Figure 3.3). Approximately 10g from each soil sample collected from Arley Close and Winlsey Close is placed into an aggregated sample for each site.

(ii) The aggregated sample from each study site is ground until it will pass through a sieve of <0.4 mm, stones and plant matter are removed as necessary.

(iii) The aggregated samples are placed in an oven for 36 hrs at 105^0c to dry (ensuring soils are at a baseline of zero soil moisture).

(iv) The samples are placed within a desiccator for approximately 30 minutes until cool enough to handle.

(v) The aggregated soil samples are then stirred, and approximately 5 g of soil is placed into a furnace proof aluminium tray, taking note of sample weight and the weight of the aluminium tray. In total eight sub-samples are taken from the site aggregated samples.

(vi) Each sub-sample is placed within a furnace and heated to 450^0c for 16 hours. When removed from the furnace they are cooled within a desiccator (for approximately 30 mins). Samples are reweighed once cooled.

The loss on ignition – organic content is then given by the following equation:

$$\%OC = \frac{Mpre - Mpost}{Mpre} * 100 \qquad \text{Equation 3.1}$$

Where %OC = percentage organic content, Mpre = mass of soil sample prior to furnace (g), Mpost = mass of soil sample post furnace (g).

A B

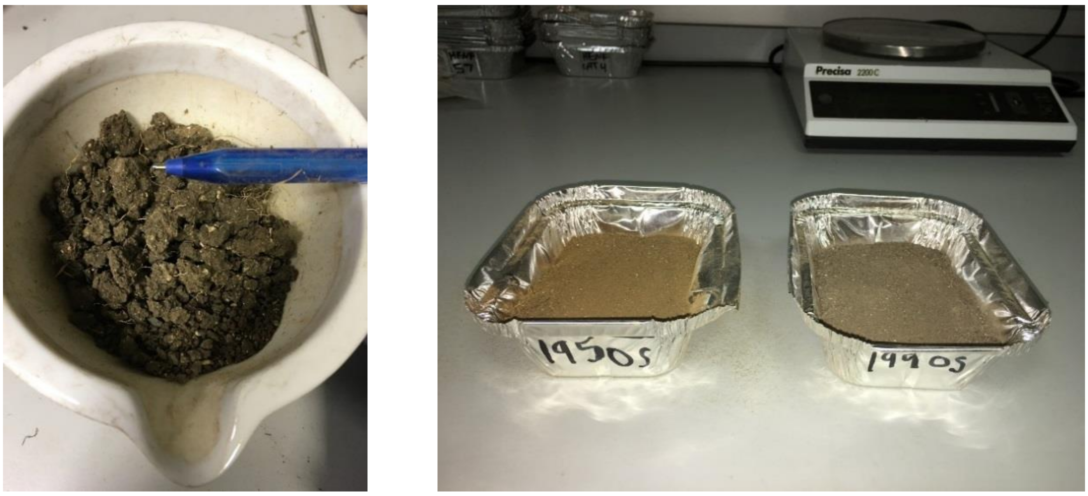

Figure 3.3: A) Homogenised soil sample (pen for scale of soil grains), B) Aggregated soil samples once ground and passed through a 0.4 mm sieve.

3.2.2 Estimating soil mineral grain size distribution

To determine the mineral grain size distribution of the soils collected from Arley Close and Winsley Close, soil samples are passed through the Mastersizer 2000, a laser diffraction particle size analysis machine (Shu et al., 2007). The methodology used is that of the CEH soil laboratory, similar to that described by Ryżak and Bieganowski (2011):

(i) A sub sample of each of the samples collected in Arley Close and Winsley Close are placed within a sterile sample tube (0.2-0.5g of soil).

(ii) 5ml of Sodium Hexametaphosphate (5%) is added, which acts as a surfactant reducing the coalescing of clay particles in suspension.

(iii) The remaining volume of the sample tube is filled with deionised water, shaken and the sample solution is left for at least one hour to suspend the mineral grains within the suspension.

(iv) The sample is passed into the Mastersizer 2000. The soil sample suspension is mixed with clean water within the Mastersizer 2000 and passed to a sample chamber between two lenses, held in position next to a laser and detector. Three measurements estimating the sample grain size distribution are made by the Mastersizer 2000 (the Mastersizer 2000 is sensitive to grain sizes from 0.02 µm up to 2000 µm).

(v) The Mastersizer 2000 estimates the % volume of a soil sample that is of a number of bands of particle size.

(vi) A .csv file is exported from the proprietary software of the Mastersizer 2000, and processed in MS Excel to determine the % of Sand (> 60 µm), Silt (2 – 60 µm) and Clay (<2 µm) particles (Natural-England, 2011).

(vii) The data are then visualised for the soil samples by plotting on the UK Soil Survey Soil texture ternary diagram via the plotrix R package (Lemon, 2006). This defines the dominant soil group within a sample based upon the proportion of grains within the sand, silt and clay definitions.

In summary, the physical characteristics of surface soil samples collected from Arley Close and Winsley Close are determined, allowing an assessment of the applicability of existing large-scale soil data to small-scale urban settings, along with the development of an understanding and comparison of how soils within Arley Close and Winsley Close may affect rainfall-runoff behaviour.

3.3 SURFACE COVER IN ARLEY CLOSE AND WINSLEY CLOSE

Urban land cover is formed of a complex mosaic of different surface types, some of which are of a solely anthropogenic origin (e.g. road) whilst others may be of a disturbed natural form e.g. park. Detailed assessments of surface type, condition and connectivity are needed to characterise the design and layout of the study sub-catchments.

A number of field and desk based investigations are performed to define surface cover within Arley Close and Winsley Close. First Ordnance Survey Master Map Topography Layer (OSMM) data is downloaded via the Digimap online service. OSMM is the most detailed, accurate and widespread dataset on the locations of buildings, roads and pavements available for the whole of the United Kingdom. The data is available free of charge for the academic and public sectors, subject to licence agreements. With its countrywide coverage, detail of the urban environment and wide availability, OSMM data is an appropriate dataset with which to begin to characterise the surface cover of the study catchments. The data is downloaded in OSGB GML file format which is then processed through the ESRI Productivity Suite to convert the GML file into an ESRI Geodatabase; a file format that is used within ArcGIS (a commonly used GIS software). OSMM is produced, managed and updated by the Ordnance Survey and is based on a structure of five interrelated layers: Topography, Address, Integrated Transport Network, Aerial Imagery, and River Network. The Topography layer is formed of features that appear in the landscape, such as buildings, land, water-bodies and roads. These features are represented either by points, lines or polygons. Each feature has a number of attributes that provide detail of physical characteristics, such as area for a polygon. The Topography layer is organised into "Themes" that allow the user to group features together based on the value of their attributes; for example, a polygon representing a road would be listed as "Manmade" under the theme "Make". This allows users to query, select and measure the urban form with a readily available and consistent dataset.

On site, Individual Parcel Assessments (IPAs) are used to first verify the data contained within the OSMM and to expand surface type classifications and detail. IPAs are defined as the practice of collecting detailed, site-specific data suitable for estimating imperviousness of individual (residential) land parcels (Keeley, 2007).

IPAs are used for collecting detailed data on the urban environment for use in surface water modelling and management (Krebs et al., 2014). The methods previously used within the literature involve the modification of existing land cover data such as maps (Lee and Heaney 2008), resident questionnaires (Keeley, 2007) and the use of high resolution remote sensing (Beighley et al., 2009). Here, maps of the study areas are annotated to demark any deviations in the land surface from the OSMM. Surface types within domestic parcels and at road sides are defined along with information on surface condition which is identified by noting defects in surface integrity (e.g. potholes or cracks). Features that could affect runoff generation such as garden walls, fences and kerbing are also recorded. The data from the IPAs are digitised onto the OSMM using ArcGIS, tracing surface boundaries with aerial photography and site notes as a guide.

3.3.1 Surface cover estimation in inaccessible locations

Both Arley Close and Winsley Close contain residential buildings that have garden areas to the front and rear of properties. It is not possible to enter rear gardens to perform site based IPAs (due to restricted access) and so aerial photography (supplied by getmapping under the PGA agreement 2003, 25 cm resolution) is digitised through visual inspection within ArcGIS into two land surface types; vegetated and semi-impervious. The semi-impervious category is chosen as it is possible to view some surfaces in Winsley Close that are block paving, rather than sealed surfaces e.g. concrete or tarmac. However, this approach is uncertain and may underestimate imperviousness, especially as it is also possible to view garden sheds and other likely impervious surfaces within rear gardens at both sites. The uncertainty of defining land cover to the rear of properties is discussed in other studies where imperviousness is defined through the interpretation and digitisation of aerial photography in urban residential settings of the UK (Perry and Nawaz, 2008; Pauleit et al., 2005). In these studies, either a conservative approach to estimating imperviousness is applied (e.g. surfaces are defined as impervious only if other surface types are discounted) or assumptions are applied e.g. non-vegetated rear garden surfaces are considered impervious. Estimates of imperviousness are likely sensitive to the methodological assumptions applied to define surface cover within residential land parcels. To determine the sensitivity of estimates of total imperviousness to the methodological assumptions applied, the total imperviousness of each catchment is estimated under three methodological assumptions:

(i) All rear-garden non-vegetated surfaces are semi-impervious (and not counted towards total imperviousness). This is termed the “Low” estimation method.

(ii) All rear-garden non-vegetated surfaces are impervious (and counted towards measurements of total imperviousness). This is termed the “High” estimation method.

(iii) 50% of all rear-garden non-vegetated surfaces are impervious. This is termed the “Medium” estimation method.

In Arley Close, the definition of front and rear garden areas is relatively straightforward as boundary features (e.g. fences) clearly demark the two areas. In Winsley Close, where there are fewer boundary features, front gardens are defined as those areas within domestic parcels that are viewable from the public highway and footpaths, whilst rear-gardens are defined as those surfaces which require access onto private land to verify surface classifications.

Digitising aerial photography to define surface cover within rear gardens is a challenging process as, depending on the time of day and the position of the aerial platform in relation to the study location at the time of image capture, shadows form across the landscape, especially in close proximity to buildings and other elevated features (such as trees) obscuring the view of the land surface. Additionally, because the photographic angle is not directly above buildings, roofs block the surfaces immediately to the periphery of building perimeters due to parallax. Surfaces are therefore defined into the vegetated and semi-impervious categories by judging the colour (green indicates vegetated, whilst grey/black indicates semi-impervious materials) and location i.e. surfaces under tree cover are assumed to be the same as surrounding surfaces within individual gardens.

It is not possible to ascertain the number or type of hydraulic drainage features that are present within rear gardens from aerial photography, other than roof drainage which is assumed to mirror the arrangement of downpipes to the front of properties. For some properties it is possible to visually verify roof drainage positions at the rear of houses from publicly accessible land, confirming that roof drainage to the rear of properties mirrors that to the front.

3.3.2 Land ownership

Though land ownership is not hydrologically important, the division between private and public land and their constituent surface types offers a descriptive structure for defining differences in residential surface layout and design, thus aiding in the characterisation of the two study sub-catchments (Perry and Nawaz, 2008). Land ownership is classified into one of two categories, defined as:

Public: land that is owned or under the regulatory authority of a public body, e.g. road or public open space.

Private: Land that is privately owned by one land owner or shared between more than one private land owner e.g. a garden serving a property or driveway.

3.4 COMPARING SURFACE CONNECTIVITY

The first step in assessing the connectivity of surfaces within Arley Close and Winsley Close is to map the locations of road gullies and roof downpipes through IPAs. Gullies within the road network are also included along with any linear drainage features (such as Aco drains). The gully and downpipe locations are digitised onto the OSMM data in ArcGIS. The connectivity of roof drainage is examined by calculating the average area drained by each roof downpipe with the following equation:

$$\overline{\begin{matrix} Roof\ Area \\ Drained \end{matrix}} = \frac{Total\ area\ of\ roofs}{No.\ Downpipes} \qquad \text{Equation 3.2}$$

The connectivity of impervious land surfaces is assessed by mapping gully drainage areas, analysing connection efficiency and examining those surfaces with direct and indirect connections to the surface water drainage system, as described below.

3.4.1 Determining gully drainage areas and surface connections

Light Detection and Ranging data (LiDAR) in the form of a Digital Terrain Model (DTM, 1m resolution) from the Environment Agency's Data.gov.uk website is used to determine the flow direction and flow accumulation of runoff across the surface of the two study sub-catchments. The DTM is a raster dataset where each grid cell has x and y coordinates for location as well as a z coordinate for elevation. The DTM is a processed data format derived by the Environment Agency from raw LiDAR data that removes surface features that obscure the land surface, for example trees. The data is available at a range of resolutions for different locations in the UK; and according to the Environment Agency website is currently available for 72% of England's land surface, focussing on urban and coastal areas. All of the Environment Agency's LiDAR products are available free of charge, for academic, public sector and commercial purposes (Environment-Agency, 2016).

The DTM is used to map which land surfaces connect into which drainage gully with the following methodology:

(i) The flow direction tool of ArcGIS is used to derive the flow direction of each grid cell of the DTM (Figure 3.4). This method assigns a flow direction to each cell of the DTM by calculating the maximum slope between each grid cell and its eight surrounding neighbouring cells. The flow direction is then assigned to the direction of maximum slope.

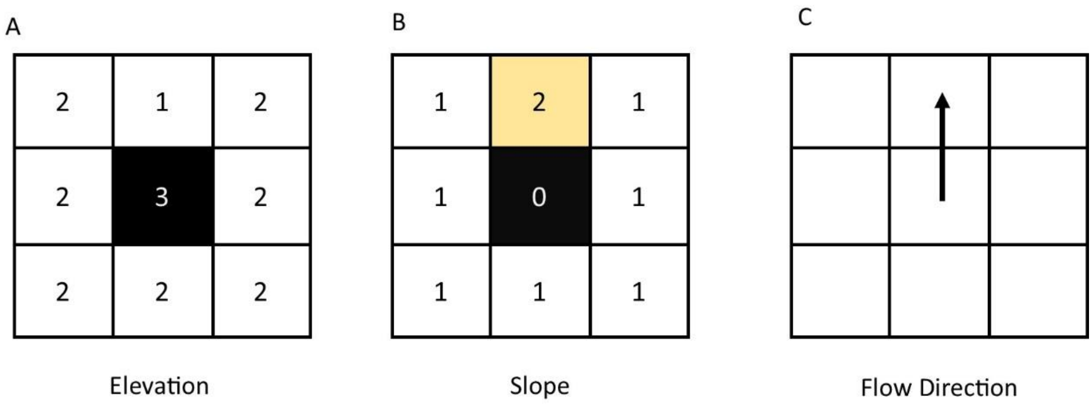

Figure 3.4: Flow direction tool takes a DTM as input (A), calculates the slope between each grid cell (B) before assigning a flow direction to the direction of maximum slope (highlighted in yellow in B, drawn as arrow in C). This diagram presents the process for the central square highlighted in black.

(ii) The flow accumulation tool is used to map how surface flow coalesces across the surface (Figure 3.5). The flow accumulation tool takes the output of the flow direction tool as an input and then counts the number of cells that flows into each cell. By altering the colour ramp of the resulting raster dataset it is possible to see how surface flow is generated (Jenson and Domingue, 1988).

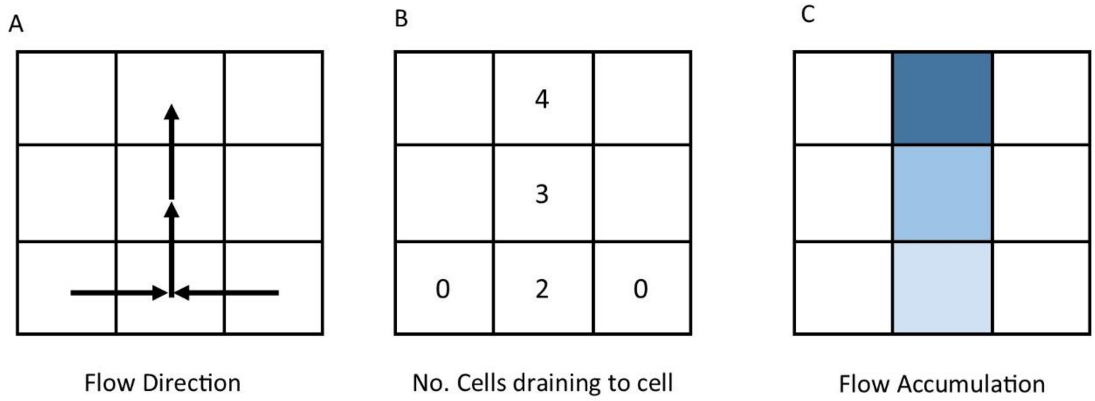

Figure 3.5: Flow accumulation tool takes the output of the flow direction tool (A) and counts the number of cells that flows into each cell (B). Cells are then coloured across a colour ramp allowing the user to investigate how surface flow is formed (C).

The ArcGIS tools are based upon the methods described by Jenson and Domingue (1988), which are designed for the large-scale estimation of catchment boundaries for fluvial catchments. To verify the results of the LiDAR processing and assess the ability of these tools to map surface flow generation in small urban areas the flow accumulation output is plotted onto the OSMM data along with the locations of the drainage gullies. In addition, photographs of surface flow (when present) are taken during site visits and compared to the flow accumulation output.

Drainage areas for each gully within Arley Close and Winsley Close are digitised, using the flow accumulation output to guide gully area definition. By tracing the flow accumulation across the urban surface it is possible to visually determine which surfaces drain and connect into which drainage gully.

3.4.2: Connection efficiency

Losses occur from urban surfaces via infiltration through cracks and joins, storage in surface depressions and evaporation to the atmosphere (Section 2.5). The longer precipitation spends on the urban surface and the greater the distance that surface runoff must travel to enter the drainage system, the greater the opportunity for these losses to occur (Ramier et al., 2011). The closer a surface is to a connection point (e.g. road gully), the more efficiently that surface will contribute runoff as there is less opportunity for losses from a surface when the drainage distance, and therefore residence time is reduced. A catchment characterised by lots of small areas in close proximity to hydraulic connection features will have increased connection and drainage efficiency to that with large areas and fewer connection points (all other variables being equal). A new method is developed to compare the connection efficiency of Arley Close and Winsley Close to determine how the connectivity of the study surface water drainage systems are controlled by the layout of surfaces and hydraulic connection points, as no methodology currently exists specific to small urban catchments. The method is similar to the concept of a Time-Area diagram, where a catchment is characterised into a graph, showing the area drained vs the time it takes for an area to drain to a point of interest (Butler and Davies, 2004). Here the method finds the sum of connected surface cover at different distances from drainage connection gullies, using the processed LiDAR data from Section 3.4.1 and several simple tools within ArcGIS, with the following methodology:

(i) Each gully drainage area determined in 3.4.1 is split into a 0.5x0.5m raster dataset, which is converted to a point dataset (where the points are placed at the centre of each raster cell).

(ii) The "points distance" tool in ArcGIS is used to determine the distance of each drainage area point to its corresponding drainage gully (Euclidean distance is used here, note a more advanced method could be developed to take into account routing pathways, however at the small catchment scale examined here this is unnecessary due to the short travel distances).

(iii) The drainage distance point data is ordered and the maximum distance identified (giving max drainage distance of each gully), with the data sorted into 1m interval bins.

(iv) The total number of cells in each 1m bin is calculated.

(v) The total number of cells in each distance bin is multiplied by $0.25m^2$, to determine the area drained versus the distance away from each gully for the irregular drainage area polygons.

The area connected is plotted against the distance from a gully, aggregated for all catchment gullies and compared across the study catchments. If the area connected vs distance plot is skewed to the left (lower distance) then the catchment is characterised by more efficient connections, i.e. there is a greater connected surface area in close proximity to drainage gullies. If the plot is skewed to the right (longer distances) then the catchment is characterised by less efficient connections, i.e. less connected surface area in close proximity to drainage gullies. The method is intended to produce an understanding of the comparative connection characteristics of the two study sub-catchments, not to provide a single descriptive statistic describing each catchment. Therefore, the outputs of the method are used to compare the catchments through visual inspection of the area vs. distance plots (Section 4.4.1).

3.4.3 Direct and indirect connections to the surface water drainage system

Currently, urban impervious surfaces are regarded as being either connected or disconnected to a surface water drainage system within urban hydrological theory and surface water management planning (Roy and Shuster, 2009). Those surfaces that drain directly to a hydraulic connection point (e.g. road gully) as well as those that drain indirectly (e.g. via a connected surface) are regarded as having the same connection properties (Lee and Heaney, 2003). However, Chapter 2 (Section 2.5) illustrates that joins between surfaces and roadside kerbing can be areas where losses occur from impervious surfaces (e.g. roads, paths). It is unlikely that surfaces with direct and indirect connections to the surface water drainage systems contribute runoff to surface water drainage systems with the same efficiency. Therefore, the definition of surface connectivity is expanded within this thesis to include three categories of connectivity:

(i) Directly Connected Impervious Surfaces: Those surfaces that have a direct connection to a hydraulic entry point to the surface water drainage system (e.g. a road with at least one drainage gully).

(ii) Indirectly Connected Impervious Surface: Surfaces that do not have a direct connection to the surface water drainage system and instead contribute runoff to the surface water drainage system by draining onto a Directly Connected Impervious Surface.

(iii) Non-connected Impervious Surface: Surfaces that do not have a connection (either direct or indirect) to the surface water drainage system, instead draining to nearby permeable surfaces.

The digitised surface information and hydraulic entry data collected in Sections 3.4.1-3.4.2 are used to manually determine surfaces with direct connections (i.e. a surface served by at least one entry point) and indirect connections (i.e. those surfaces where surface runoff must flow across another surface before connecting to the surface water drainage system). Defining the connectivity of surfaces to the rear of residential properties is difficult, given the uncertainty in defining surface cover and the presence and locations of hydraulic entry points to the rear of properties described in Section 3.3.1. Therefore, connectivity of impervious surfaces to the rear of properties is defined under two assumptions to examine how sensitive estimates of surface connectivity are to the method/assumptions applied within the hydrological literature:

(i) Impervious surfaces to the rear of properties are connected to the surface water drainage system, a similar assumption to that applied by Lee and Heaney (2003),

(ii) Impervious surfaces to the rear of properties are not connected to the surface water drainage system (a more conservative approach).

Using these assumptions, it is possible to explore how sensitive calculations of total imperviousness and connectivity are to some of the assumptions and methods used in the literature to examine and characterise surface cover within urban areas.

3.5 ESTABLISHING A HYDROLOGICAL MONITORING NETWORK

A hydrological monitoring network is established to measure runoff and soil moisture within the study catchment areas. The hydrological monitoring is conducted between May 2014 and December 2015 (approximately 18 months) in conjunction with concurrent rainfall monitoring undertaken by CEH (see Section 1.3). The placement and maintenance of monitoring equipment within the urban environment is difficult. A number of technical, security and safety considerations (see Section 3.1.2) are required in addition to ensuring the scientific quality, value and integrity of the data.

3.5.1 Installation of Stingray 2.0 portable level-velocity loggers

To monitor flow within the surface water drainage systems of Arley Close and Winsley Close, Ultrasonic Doppler Flow Monitoring (UDFM) devices are installed into the pipe network serving each study area. UDFM is a standard method for the measurement of flow within non-surcharged pipes and open channels (Blake and Packman, 2008). The equipment works by means of an acoustic signal that is emitted by a sensor into the oncoming flow of water. The acoustic signal reflects off on-coming bubbles and debris within the water column and the change in frequency of the returning acoustic signal is used to estimate flow velocity. A pressure sensor provides concurrent measurements of water depth; which together with the velocity data is used to estimate flow volume per unit time:

$$Q = V * A \quad \text{Eq. 3.3}$$

Where Q = discharge (m^3/s), V = Velocity (m/s) and A = the cross sectional area of flow (m^2) (Hamill, 2011).

Equation 3.3 requires that the geometry of the monitored section of pipe or channel is known and constant. Therefore, UDFM devices are placed within a structure of known and constant geometry. At both Arley Close and Winsley Close, UDFM devices are placed within the surface water drainage pipes (of 225mm diameter) draining each area. The cross-sectional area of flow within the circular pipes at water depth h is calculated with equation (3.4):

$$A = r^2 \cos^{-1}\left(\frac{r-h}{r}\right) - (r-h)(\sqrt{2rh - h^2}) \quad \text{Equation 3.4}$$

Where A = the cross-sectional area of flow, r = the radius of pipe, and h = the height of flow within the pipe recorded by the UDFM equipment.

The Stingray 2.0 Portable level-velocity logger (Greyline instruments) is a self-contained unit, comprising a battery and logger box, cable and sensor head. The sensor head emits and detects the acoustic signal as well as housing a pressure transducer for water depth measurements (Figure 3.6). The system is supplied with a clip, used for affixing the sensor to the bottom of surface water drainage pipes. Access is gained to each surface water drainage system via manholes within the roads serving each study catchment (Figure 3.2). The geometry of the bottom of each manhole is unknown, given the rough shape of the cement that embeds the pipe into each manhole. To place the sensor in a position with known and constant geometry, metal plates are used to affix the sensor head onto the bottom of drainage pipes upstream of the access manhole, with the following methodology (Figure 3.6):

(i) The manufacturer supplied sensor clip is glued to a thin, rigid metal plate.

(ii) The sensor head is attached to the clip.

(iii) The sensor is pushed by around 10cm upstream of the manhole into the surface water drainage pipe, leaving the non-sensor end of the metal plate within the access manhole.

(iv) The non-sensor end of the metal plate is screwed to the bottom of each surface water drainage pipe within the access manhole.

(v) Cabling is clipped to benching in the manhole ensuring it does not interfere with the flow within the pipe or manhole.

(vi) The logger and battery box is placed on the top step iron of the manhole, within easy reach of the surface.

(vii) After a trial period of two weeks with logging interval set to 10 seconds (after which the equipment malfunctions due to depleted batteries) the logging interval is set to 30 seconds. This provides a battery life of approximately one month.

(viii) A brush on a long pole is used to clean the sensor head each time data is downloaded from each site (every two to four weeks) during the monitoring period.

Figure 3.6: Installation of Stingray 2.0 UDFM equipment in surface water drainage manholes; (left) the installation of the sensor within the pipe upstream of the manhole; (right) the storage of cabling and data logging box.

3.5.2 Verification of the surface water drainage system via manual acoustic method

To confirm connections between surface drainage features (gullies and roof downpipes) and catchment surfaces to the surface water drainage system, a manual acoustic methodology is used. The method is based on the observation that when a vehicle passes over a manhole cover or drainage gully connected to the surface water drainage system of an open manhole, a distinct noise echo can be heard within the manhole, that is distinguishable to the sound that travels above ground. Therefore, by striking manhole covers and gully gratings with a hammer it is possible to check the connectivity to a test manhole. This method is applied to each study sub-catchment. One person remains at the manholes where the Stingray 2.0 flow loggers are installed, whilst another strikes each manhole and gully cover within the study sub-catchments with a hammer. If an echo is heard within the surface water drainage system then this confirms that the gully or manhole is connected and if no sound echo is heard then the gully/manhole is not connected to the monitored system. This method is used to establish the catchment boundary and connected hydraulic features within the study sub-catchments. Figure 3.7 shows the catchment boundaries defined within Arley Close and Winsley Close respectively. An area to the west of Winsley Close was originally thought to be included within the catchment drained by the monitored surface water drainage system, however upon checking the connectivity of surfaces through the manual acoustic method, it was determined that this area of Winsley Close connects to the monitored surface water drain downstream of the monitored point and was therefore omitted from the catchment boundary definition (Figure 3.7, D). The catchment area for Arley Close is 4982m^2 (0.4982 ha) and 6690m^2 for Winsley Close (0.6690 ha).

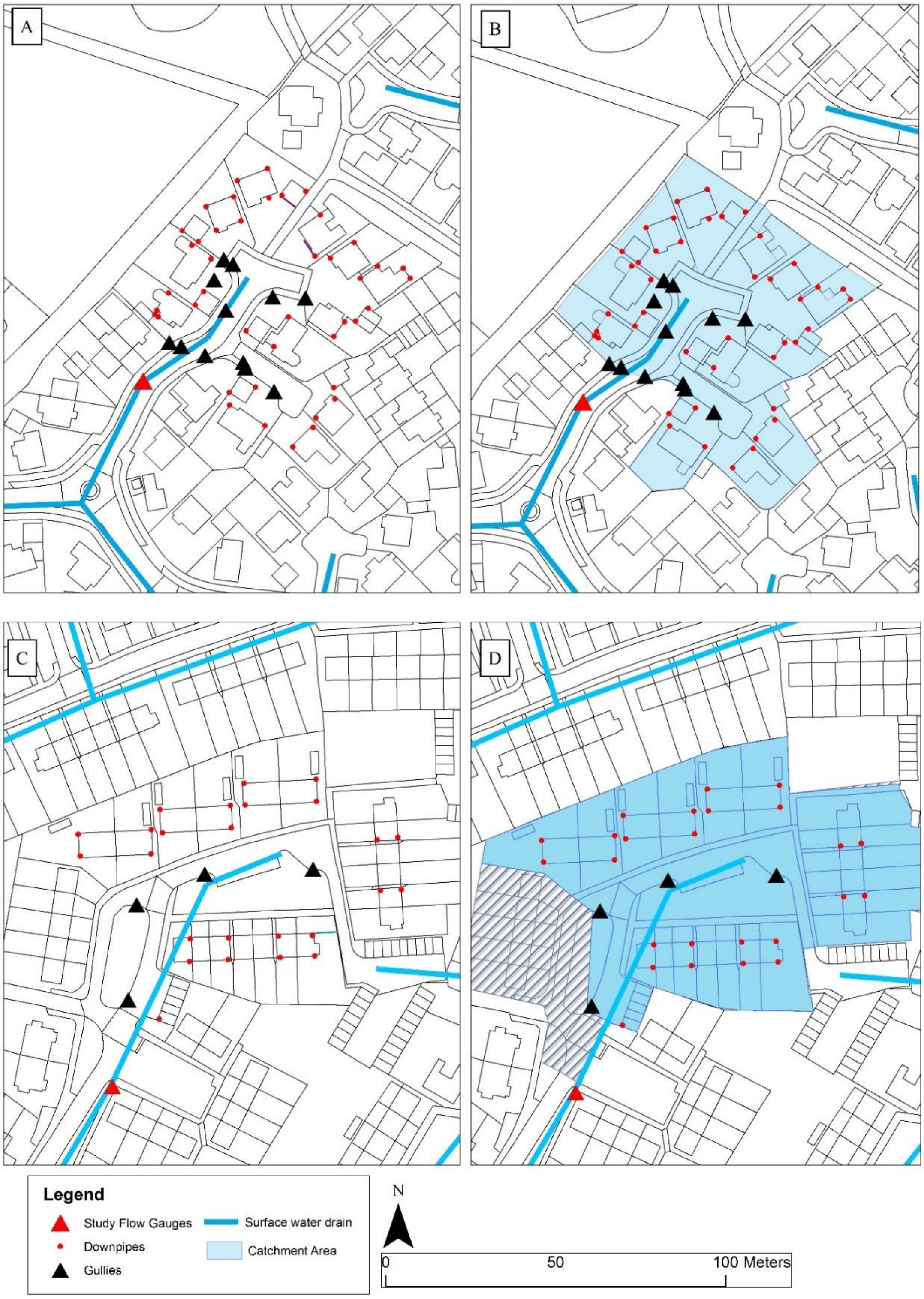

Figure 3.7: Catchment areas for (A,B) Arley Close, and (C,D) Winsley Close. D shows an area to the west of Winsley Close that is removed following the application of the manual acoustic method.

3.5.3 PR2 soil moisture profile probes

Two PR2 soil moisture profile probes with DL6 loggers (Delta-T devices) are used to record the temporal variability (1hr) of soil moisture at six depths into the soil column (100mm, 200mm, 400mm, 600mm, 800mm and 1000mm) each in close proximity to the study sites. The PR2 is a capacitance-sensor based probe that converts measures of soil electric permittivity to estimates of soil moisture content through a manufacturer supplied calibration curve (Qi and Helmers, 2010). A data logger records values of soil moisture (m^3/m^3) on an hourly basis and the data is stored within the data logger and downloaded every 2-4 weeks. Selecting suitable sites for installing the soil moisture profile probes that are both secure and in locations of relevance to the study locations is challenging, as no suitable sites are available directly within the study catchments (due to a lack of secure locations). School grounds are selected as they provide more secure limited access locations with one probe installed in the garden area adjacent to the car park at Catherine Wayte Primary School, approximately 200m to the west of Arley Close and the other in the playing fields of Swindon Academy, approximately 300m to the north of Winsley Close (see Figure 3.8). The probes are installed by boring a 1m deep hole and installing an access tube, following manufacturer guidelines. This is a plastic tube that is placed within the soil to create a neutral boundary between the soil and probe. The access tube is inserted into the bored hole, and the PR2 probe inserted into the access tube. The DL6 logger is placed within a lockable box, and secured on a concrete slab adjacent to the PR2 probes (See Figure 3.9). The access tube allows for the easy removal and maintenance of the PR2 probe whilst also acting as a barrier between the probe and the soil (to protect against rust). The presence of the access tube does not affect the measurements of soil moisture made by the PR2 probe as the electrical signal can pass through the access tube without interference.

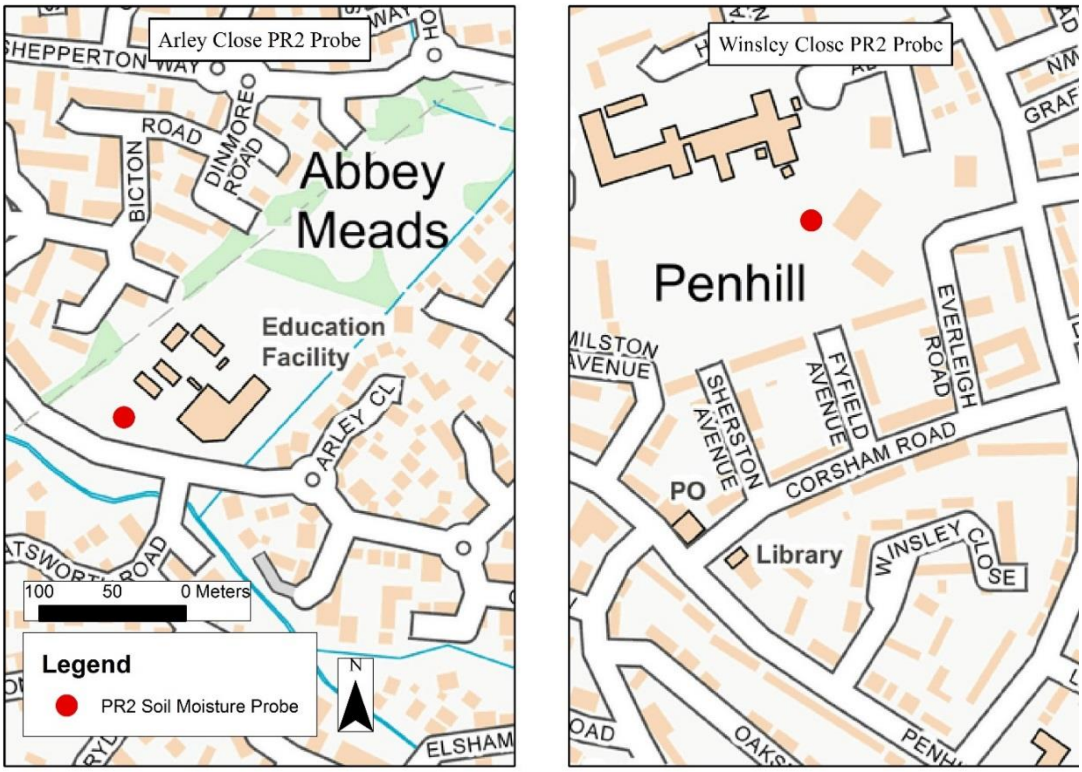

Figure 3.8: Positions of PR2 soil moisture probes at (left) Arley Close and (right) Winsley Close. Contains OS data © Crown copyright and database right 2017

The standard manufacturer's calibration between readings of soil permittivity and soil moisture is used for PR2 soil moisture monitoring, as:

(i) Soil sampling is required for site specific probe calibration (requiring the digging of a deep trench, Silva Junior et al. (2013) which is a destructive process (i.e. soils are removed from site) and therefore not appropriate on private land (schools).

(ii) It is not possible to remove calibration soil samples from close proximity to the PR2 probe without altering the overall performance of the PR2 probe, thus reducing the efficacy of any calibration and soil moisture monitoring exercise.

Figure 3.9: Soil moisture monitoring. left) the installed PR2 probe at Swindon Academy (close to Winsley Close), right) field trials with the TDR300 probe.

3.5.4 Spatial measurements of soil moisture: TDR 300

As it is not possible to install PR2 soil moisture probes directly within the two study sites or produce a site specific calibration (Section 3.5.3), a Field Scout TDR300 mobile soil moisture probe (Spectrum Technologies, Inc.) is used along with a GPS locator (Garmin 72H) to record surface soil moisture readings at 1-2 m spacing within the vegetated surfaces of the study catchments, every two to four weeks within the monitoring period. The TDR300 soil moisture probe can be calibrated to site specific conditions within Arley Close and Winsley Close, and through comparison of data collected between the PR2 and TDR300, the PR2 data can be validated. In Arley Close there is minimal green space with public access, therefore the area where data is collected is extended to vegetated surfaces within approximately 100m of Arley Close within the wider Abbey Meads housing development. The TDR300 probe is a small and light piece of equipment that allows for mobile surface readings of soil moisture. The TDR300 links to a GPS tracker that records longitude and latitude when a soil moisture reading is taken. The TDR300 probe uses the principle of time domain reflectometry to estimate volumetric soil moisture content (Brevik and Batten, 2012). The TDR300 is supplied with three different rod lengths, allowing the user to estimate the average soil moisture across the surface at 76mm, 125mm and 225mm depths, when the required rods are inserted into the TDR300. Field trials with the TDR 300 examined the ease with which each rod length could be inserted into urban soils (Figure 3.9). Rod lengths over 76mm bend and deform as they enter the soil column, rendering the results of the TDR300 inaccurate and unreliable as the measurements recorded are dependent on the amount of deformation in the rods. Therefore, a rod length of 76mm is chosen as this results in the least amount of rod deformation.

The TDR300 is supplied with two calibration curves defined by the manufacturer. One curve is designed for soils with high clay content, and the other low clay content. Given that the TDR300 is designed for applications in well sorted agricultural soils and that the aim of the TDR300 measurements is to verify the PR2 measurements within Arley Close and Winsley Close, an additional calibration is performed in the urban soils within the study sub-catchments. A method adapted from Penna et al. (2009) derives separate calibration curves for each of the two study sites:

(i) Soil samples (100 cm^3) are extracted from the surface of vegetated surfaces within the study sub-catchments after a reading is taken with the TDR300 under the normal (low clay) manufacturers calibration. The soil samples are placed within sealed zip bags and taken to the soil processing laboratory of CEH (Figure 3.10).

(ii) The soil samples are weighed, oven-dried at 105°C for 24h and weighed again.

The volumetric soil moisture content within the soil sample is defined by Equation 3.5:

$$VSMC = \frac{(Mass_{wet} - Mass_{dry})/density\ of\ water}{Volume\ of\ soil\ sample} \qquad \text{Equation 3.5}$$

Where VSMC = Volumetric Soil Moisture Content (m^3/m^3), $Mass_{wet}$ and $Mass_{dry}$ = mass of soil sample before and after drying, = the density of water=1000kg/m^3 and the volume of the soil sample is 100cm^3.

Calibration surface soil samples are collected during wet and dry conditions, at each site in summer and winter of 2014 and 2015. A calibration curve is then derived for both Arley Close and Winsley Close by plotting the TDR300 readings against the soil moisture values derived from the soil sampling described above. Each calibration curve is then used to convert TDR300 readings to estimates of soil moisture content collected during the field monitoring campaign.

Figure 3.10: Soil sample processing through CEH soil laboratory.

3.5.5 Rainfall data collection: links to CEH hydrological monitoring network

Precipitation monitoring is undertaken by the Centre for Ecology and Hydrology (CEH) for the study monitoring period. This data is used as it is not possible to place precipitation monitoring equipment directly within Arley Close and Winsley Close given the lack of secure and suitable locations. Raw data collected by CEH is processed to determine estimates of precipitation at two minute resolution for Arley Close and Winsley Close with the following methodology.

The Environment Agency (EA) maintains a Tipping Bucket Rain (TBR) gauge at the Swindon sewage treatment works to the south west of Swindon. The EA rain gauge has data collected and managed under guidance provided by BSI Standards publication 7843-2:2012 (Code of practice for operating rain gauges and managing precipitation data) and 17898:2014 (Code of practice for the management of observed hydrometric data). TBRs are formed of a cylindrical housing, with a funnel at the top that collects and routes precipitation to a tipping bucket mechanism in the centre of the rain gauge. The tipping bucket mechanism gradually fills as rain is collected, and once full tips to empty a bucket, before refilling as a rainfall event continues (Shaw et al., 2010). A data logger records the number of times that the tipping bucket mechanism tips during a user defined time period and thus rainfall intensity over time is monitored. The EA TBR produces data at a 15 minute resolution.

CEH placed three TBRs within north Swindon as part of wider monitoring work described in Section 1.3. The CEH TBRs are also maintained to relevant BSI standards. The CEH TBRs have a tipping mechanism that is sensitive to 0.2mm of precipitation depth and record tips at 2 minute resolution. The CEH TBRs provide rainfall data at a higher temporal resolution than the EA gauge and are in locations of closer proximity to the study sites (see Figure 3.11). The Vygon TBR is placed within the grounds of Vygon Ltd, in an industrial estate to the north of Swindon. The Penhill TBR is placed within a garden area at Seven Fields Primary School, and the Pinehurst TBR is placed within a secure oil separator operated by Thames Water. The CEH TBRs are placed within locations that are less secure and where vegetation is less managed than the EA TBR and thus there is missing data during the monitoring period due to vandalism and the overgrowth of vegetation. To derive a complete rainfall series for Arley Close and Winsley Close the rainfall time series from each of the potential study CEH rain-gauges is compared to the data collected at the Environment Agency gauge using Double Mass Curves (DMC).

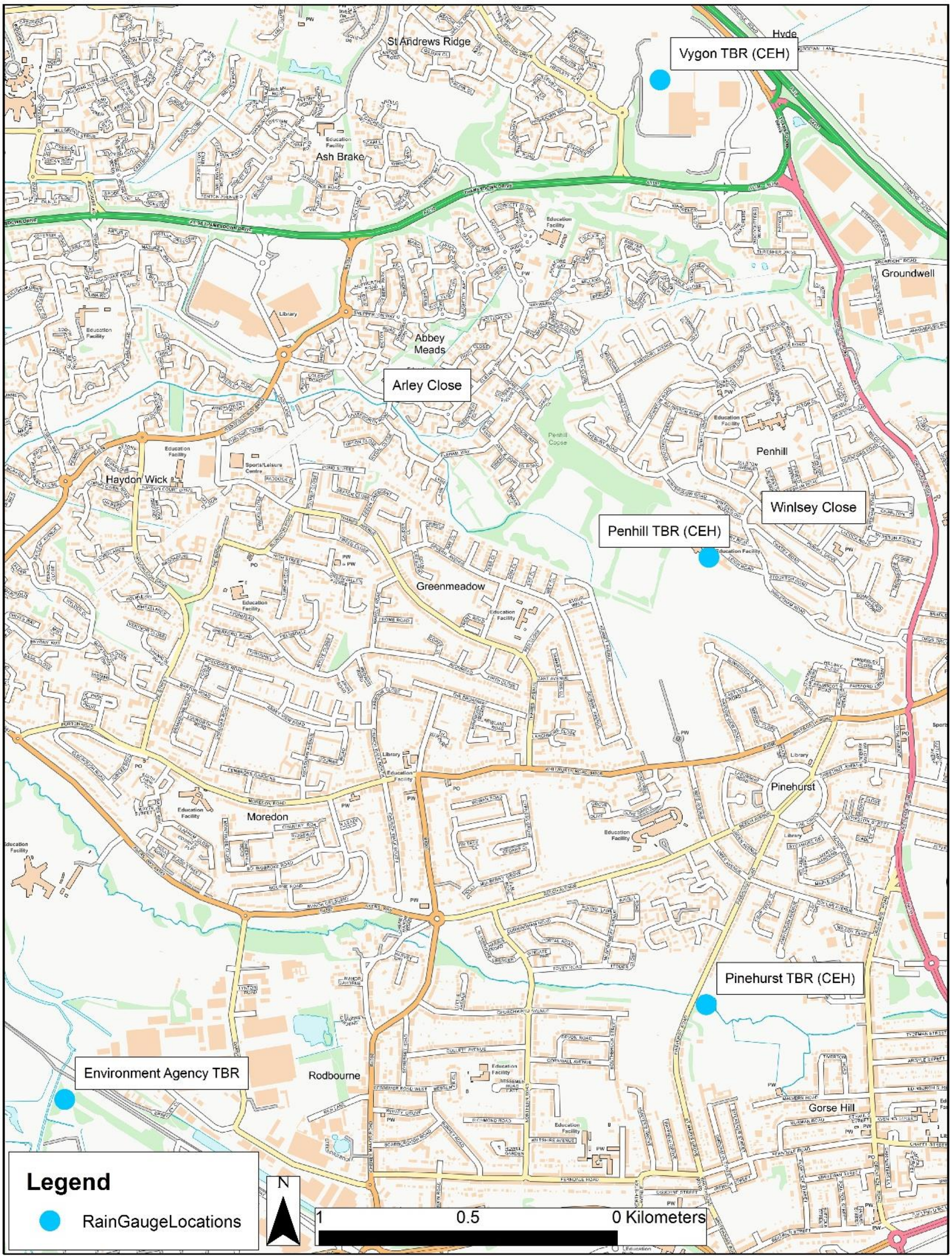

Figure 3.11: Rain gauge locations in relation to Arley Close and Winsley Close.

Between November and December 2015 an additional TBR gauge is placed in a secure location approximately 200m to the west of Arley Close (adjacent to the Arley Close PR2 soil moisture probe, Figure 3.8) to examine:

(i) whether there is variation in the timing of rainfall at Arley Close and the other study rain gauges; and,

(ii) whether there is variation in the depth of rainfall received.

This is achieved by comparing the rainfall series collected at Arley Close and the Pinehurst gauge, through DMCs (Kohler, 1949).

3.6 DATA STORAGE, PROCESSING AND QUALITY ASSURANCE

Data from each piece of monitoring equipment is downloaded to a field laptop and saved in a proprietary data format supported by each field instrument. The raw data is then exported from each piece of software and saved within a Microsoft Access database. As new data files are downloaded and stored, the additional data is added to the Access database. The TDR300 data files are combined into a single data set using a script written in the R programming language. The rainfall data is provided by CEH as a .csv file at 2 minute resolution for each potential study gauge described in Section 3.5.5 and 15 minute resolution for the Environment Agency rain gauge. To access, visualise and process monitored data, the R programming language is used via the RODBC package for connecting R to an Access database (Ripley and Lapsley, 2017) or by directly importing a data .csv file into an R environment.

The data collected by each type of hydrological monitoring equipment has a number of errors which need correcting with site calibrations required to produce data that are as accurate and specific to Arley Close and Winsley Close as possible. This Section outlines the analytical approaches to correcting any errors or required site specific calibrations required for Arley Close and Winsley Close.

3.6.1 Deriving rainfall data series for Arley Close and Winsley Close

To determine any loss of data or systematic errors in rainfall data collection by the CEH TBRs, Double Mass Curves (DMC) are used to compare the rainfall data series collected by the CEH TBRs and the EA TBR. DMCs plot the accumulated sum of one time series of rainfall data against another (Searcy and Hardison, 1960). Deviation from a straight line, or a change in slope indicates that there is a systematic difference in the recording of rainfall between two sites, assuming that the two recording sites receive similar rainfall during a study period and can therefore highlight instrument errors or other problems (e.g. the overgrowth of vegetation) (Khemani and Murty, 1973). At high temporal resolutions this may result in a stepped line appearance, as precipitation events move from one rain gauge to another, though this stepped shape is lost at lower temporal resolutions.

The location of the rain gauges away from Arley Close and Winsley Close result in variable durations between precipitation and runoff at the study sites, to asses this a gauge is placed near Arley Close for one month, during November – December 2015 in an attempt to characterise the relationship between precipitation recorded in the rain gauge at Arley Close and that at the other study rain gauges. By computing DMCs for gauges placed at Arley Close and that at Penhill (the CEH gauge with closest proximity to Winsley Close, Figure 3.11), against the complete record of precipitation recorded at Pinehurst, it is possible to derive an estimate of precipitation that is location specific to Arley Close and Winsley Close.

3.6.2 Velocity-depth corrections for flow monitoring: defining and identifying errors

Several error types are identified by Blake and Packman (2008) in velocity-depth measurements recorded with UDFM equipment. Table 3.1 identifies errors, their description and how they are isolated and corrected within the data series collected at Arley Close and Winsley Close.

Table 3.1: Velocity and depth data error types, their description and how identified in the velocity-depth data set recorded at Arley Close and Winsley Close with Stingray 2.0 UDFM equipment.

Error Type	Description	Identification method	Error correction method
Equipment malfunction and depleted battery errors.	Equipment can malfunction and batteries can deplete to voltages below levels that are required for operation. Such occurrences appear in a data series as either a period of no/missing data, or unexpectedly high or highly variable readings of either velocity or depth.	Visual inspection of data time series and cross reference with field notes of malfunction.	Removed from data series
Missing depth data due to low flows.	The sensor of the Stingray velocity-depth logger is 25mm thick. Therefore accurate readings of depth are gathered when flow exceeds 25mm. Under 25mm the sensor head is still able to make velocity readings whilst recording 0 for depth. Therefore, this error is evidenced by readings of velocity with zero depth.	Select query where Velocity = >0 and Depth readings = 0.	Infill depth data using a generalised linear model for a "clean" period of velocity and depth data (Hydro-Logic, 2014).
Spurious readings of depth and velocity caused by debris.	Debris within the pipe alters the hydraulic conditions within close proximity to the sensor. This can alter the depth-velocity relationship in the immediate location of the sensor, thus altering the collection of velocity/depth data. This error manifests itself as spuriously high, or low values of velocity within data.	Visual inspection of depth-velocity scatter plot	Use the generalised relationship between velocity and depth, to correct spuriously high readings of velocity or depth if identified within series.

A script in the R programming language is written specifically to visualise, detect and correct errors within the velocity-depth data. Figure 3.12 illustrates the different types of error within monitored data at Winsley Close. Point 1 on Figure 3.12 illustrates that there are velocity readings with no recorded depth, point 2 shows spuriously high readings of velocity and point 3 shows where the main body of data exists that can be generalised to determine the relationship between velocity and depth for data correction and infilling.

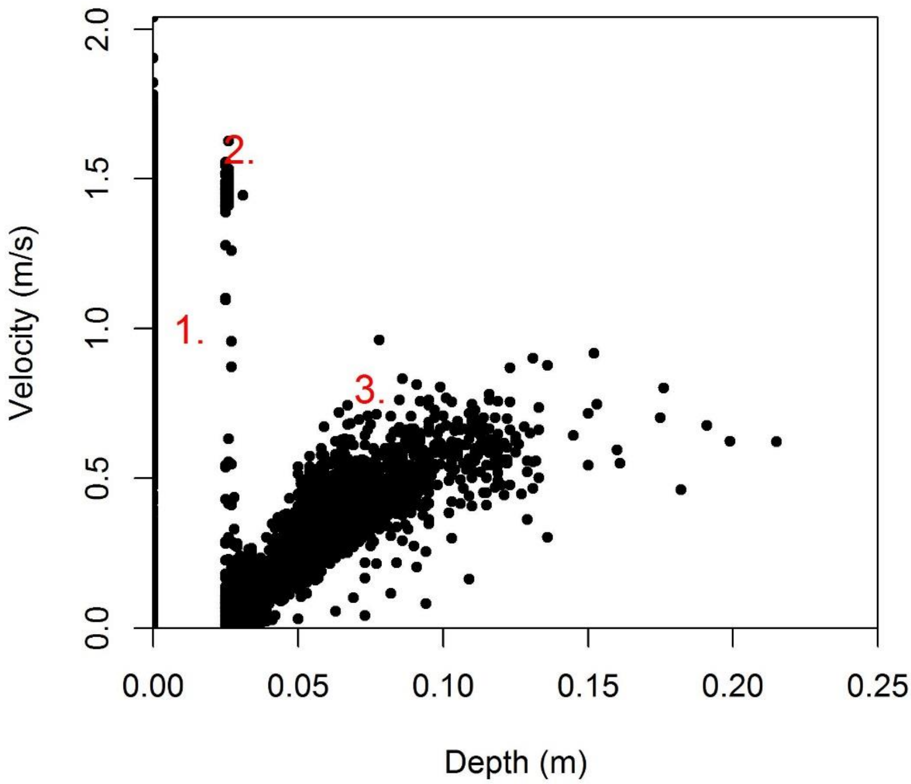

Figure 3.12: Raw velocity and depth measurements from Winsley Close with errors identified as 1. Readings of velocity with no measurements of depth, 2. Spuriously high readings of velocity for depth and 3. Region of consistent relationship between velocity and depth

3.6.3 Errors encountered with PR2 soil moisture monitoring equipment

Two types of errors occur with the soil moisture monitoring performed with the PR2 profile probes; vandalism and rusting. On two occasions the PR2 probes are missing data within the time series due to vandals lifting the probes out of the soil causing damage. In addition, moisture within the PR2 access tubes leads to periods where the PR2 probes rust, and thus data is lost during these periods. To infill an estimate of soil moisture during periods of missing data, soil moisture is estimated by linear interpolation between known values. An uplift is applied to data after October 2015 in Arley Close to account for a drop in readings again caused by vandalism. After August 2015 the PR2 probe at Winsley Close is over-sensitive to soil moisture which results in an increase in data variability and maximum readings of soil moisture outside of the range previously recorded at either site. To address this, a DMC is constructed between the PR2 series collected at each site, and the original data is adjusted post August 2015 at Winsley Close PR2 to ensure a consistent relationship between the two monitoring devices.

3.7 DEFINING AND EXTRACTING RAINFALL-RUNOFF EVENTS FOR ANALYSIS

3.7.1 Rainfall-runoff event definition

When analysing rainfall-runoff behaviour of a hydrological system it is possible to examine data at a range of temporal scales. For example Kadioglu and Şen (2001) compare both monthly totals of rainfall and runoff as well as individual rainfall-runoff events to explain how seasonal changes in runoff behaviour relate to fine scale sensitivity of a catchment to variability in rainfall characteristics and antecedent conditions. Event-based methodologies therefore offer the opportunity to understand how a catchment responds to changes in physical drivers (e.g. rainfall intensity) over time. Event-based analyses of rainfall-runoff data are used extensively within the scientific literature for different catchment types and locations, e.g. mountainous, South Korea (Kjeldsen et al., 2016); arid, Oman (McIntyre et al., 2007); urban, Korea (Maniquiz et al., 2010), and are used to determine the sensitivity of hydrological behaviour to a number of physical characteristics including rainfall intensity (Dunne et al., 1991) and soil moisture (Fitzjohn et al., 1998).

Extracting rainfall-runoff data for individual events from a time series of data can present difficulties. Event flow (flow arising from rainfall) needs separating from baseflow (flow derived from ground water or other slow runoff generating pathways or simply runoff from a previous event) and a definition of when one event finishes and another begins is needed (Blume et al., 2007). There are therefore two methodological processes that are defined before an event based analysis is completed:

(i) The Minimum Inter-event Time (MIT): this defines a fixed rainless period that elapses between rainfall events. The MIT is exceeded before a new event is identified within time series of rainfall data (Dunkerley, 2008a).

(ii) Baseflow separation: either graphical or analytical approaches to separate rainfall generated runoff from baseflow, thus deriving direct event runoff (Blume et al., 2007).

Event extraction and baseflow removal is performed through data analysis and visualisation with the following techniques through the writing of specific code in the R programming language.

3.7.2 Defining the Minimum Inter-event Time (MIT):

Rainfall is a highly variable phenomena where intensity and total volume vary over the duration of an event (Huff, 1967). There are long periods of time with no rainfall between different rainfall events (Acreman, 1990) and the length of this inter-event rainless period varies. The Minimum Inter-Event Time (MIT) is a time period chosen within an analysis of rainfall data that is exceeded before a new rainfall event is extracted from a time-series of data (see Figure 3.13). Choosing an appropriate value of MIT is a compromise between two conflicting requirements of event-based rainfall-runoff analysis:

(i) The need for independent rainfall events; meaning that the rainfall-runoff behaviour of one event is not unduly influenced by a previous event;

(ii) The need for high resolution data that allows for insightful descriptions of rainfall characteristics (Aryal et al., 2007).

The shorter a MIT value chosen, the more events extracted from a time series of rainfall, and the smaller and shorter duration those events (capturing detail of events, with potentially less independence between events). Longer values of MIT lead to fewer events of greater duration and depth being isolated from a rainfall data series (thus capturing a reduced detail of within event rainfall characteristics, but with potentially greater independence between events, see Figure 3.13). Dunkerley (2008b) show that MIT values selected within the literature range from 3 minutes to 24 hours, and that often there is little justification of how or why specific periods of MIT are chosen within studies. An analysis by Dunkerley (2008a) of MIT values for a rainfall data series demonstrates that the choice of MIT values affects the average rainfall intensity (as duration and total event depth changes) and that large values of MIT can reduce the information about rainfall event variability as data is averaged over longer time periods. Therefore Dunkerley (2008a) recommend that MIT values are chosen in connection with the purpose and scale of hydrological study.

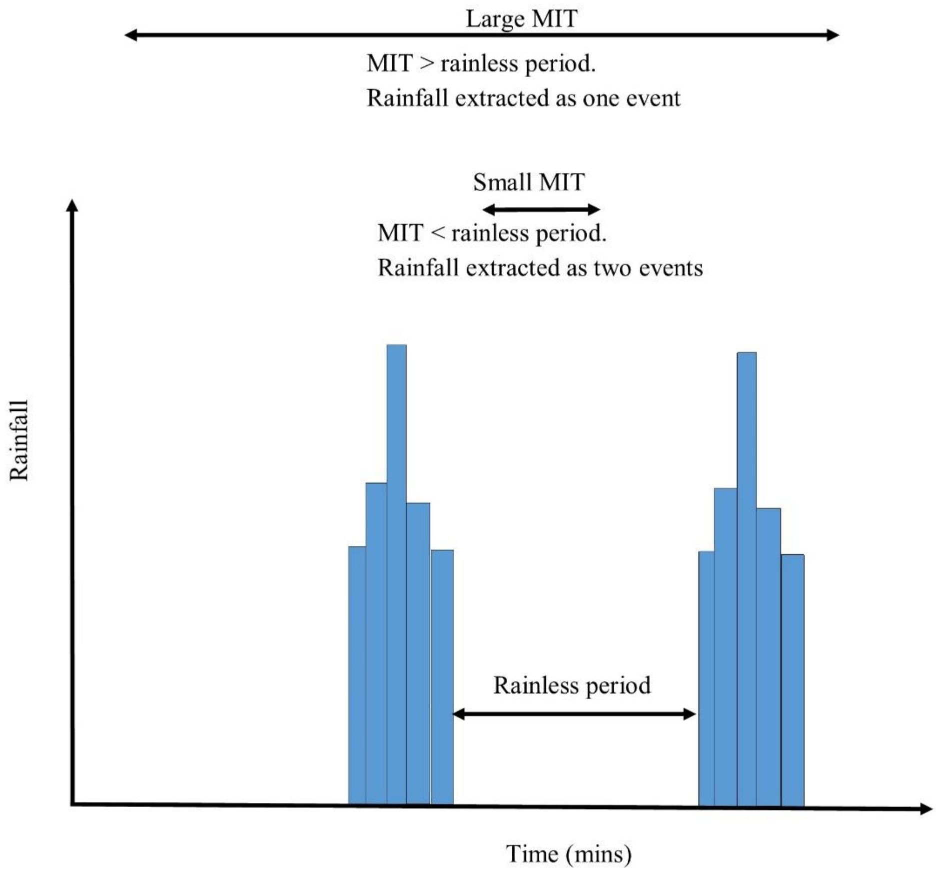

Figure 3.13: The relationship between rainfall data, the Minimum Inter-event Time (MIT) and the number of events extracted from a rainfall series.

The objective of this analysis is to extract rainfall-runoff events from continuous time series, permitting rainfall-runoff performance of the study sub-catchments to be examined and compared. It is important that the choice of MIT in this study retains a high resolution of data about each rainfall and runoff event. As this study also includes an assessment of how antecedent conditions affect rainfall-runoff performance (e.g.

the collection of soil moisture data) it is not as important to retain highly independent rainfall events. As both study sites are relatively small (under 1ha), heavily urbanised and served by a surface water drainage system, it is likely that the rainfall-runoff response of both catchments will be in the order of minutes, rather than hours; therefore the MIT duration should also be in the order of minutes. A process of trial and error is used to examine how the choice of MIT value affects the extraction of rainfall-runoff events from the monitored data collected at Arley Close and Winsley Close. A number of MIT durations are tested (15-60 minutes) and the resulting rainfall-runoff events extracted are plotted and examined, with an MIT of 30 minutes selected for this study as it maximises the separation between rainfall-runoff events, whilst retaining a high resolution describing event durations, intensities and depths.

3.7.3 Base flow separation

The flow recorded within a hydrological system is formed of two conceptual components: the base flow (flow derived from groundwater or previous events) and event runoff (flow derived from direct runoff during or following an event). The separation of a hydrograph into baseflow and runoff is required, so that the catchment response to precipitation and antecedent conditions can be determined. There are a number of techniques available within the literature to perform baseflow separation, based on either a graphical interpretation of hydrographs (Guillemette et al., 2005) or a conceptual understanding of the underlying physical processes that generate runoff within a catchment (Furey and Gupta, 2001; Kjeldsen, 2007). According to Blume et al. (2007) there are two major difficulties in base flow separation:

(i) identifying the point in time when event flow starts and ends and hydrographs consist entirely of base flow; and,

(ii) the progression or interpolation of the base flow hydrograph during an event.

Despite its importance to the characterisation of events, few studies in urban hydrology actually define or justify the choice of base flow separation techniques. For example, the event based analysis reported within Maksimovic and Radojkovíc (1986) and Kidd and Lowing (1979) have no discussion of event separation.

The catchments in this study are comparatively small and heavily urbanised and the surface water drainage system at each site only drains the study area and do not contain drainage of non-urbanised or additional areas upstream. The hydrological response of the studied surface water drainage systems is highly sensitive to rainfall as they only contain flow when there is rain (i.e. the flow in the pipes is ephemeral). Therefore, minimal base flow removal is required, as it is unlikely that flow within the drainage system is derived from any source other than surface runoff (e.g. aquifers or groundwater). Where there is flow within the drainage system prior to an event, this is assumed to be the contribution of local soil drainage from previous events, which Berthier et al. (2004) demonstrate can extend the tail end of events. This hydrograph separation technique is presented in Figure 3.14, with the following rules applied to extract event runoff from hydrographs:

(i) When there is no flow within the studied drainage system before a rainfall event, the end of the event runoff is deemed to occur when the hydrograph reaches a threshold level lower than 0.1 l/s (due to turbulence at low flow rates and the sensitivity of monitoring equipment).

(ii) When there is flow within the drainage system before an event, the event ends when the recessional limb reaches the pre-event flow value (after the rainfall event).

(iii) The base flow hydrograph is interpolated using a straight line between the start and end points of the event hydrograph.

Where pre-event flow is variable, due to turbulence in flow conditions within the pipe network and the monitoring equipment's high sensitivity, the pre-event flow is defined as the 15 minute average flow before rainfall occurs.

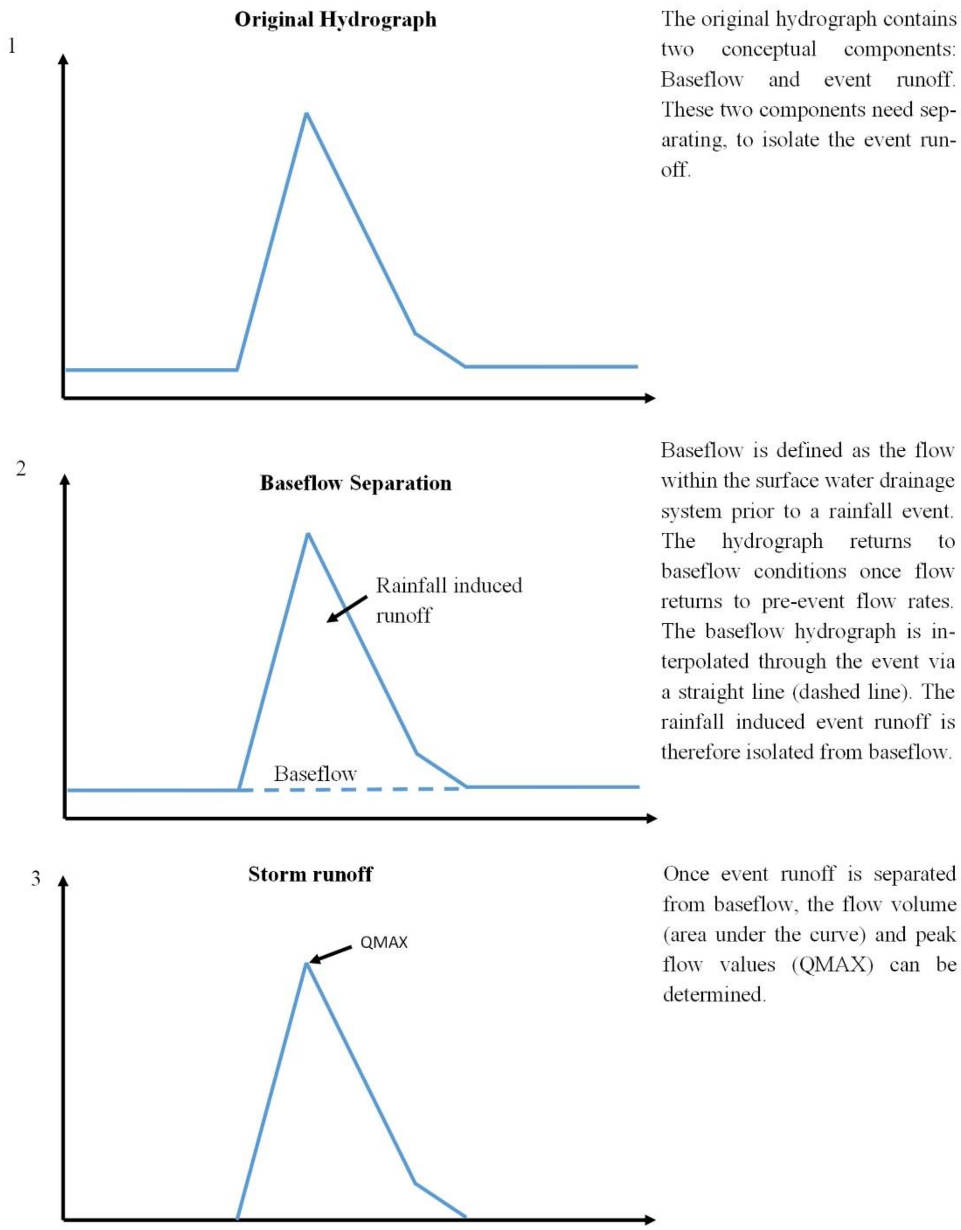

Figure 3.14: Hydrograph separation technique used to remove base flow from runoff response.

3.7.4 Event selection

Comparing time series of rainfall and runoff data is complicated by a series of potential factors. Rainfall does not fall in constant patterns, instead the intensity of rainfall changes throughout the duration of an event. Depending on the sensitivity of the runoff producing system under study, fluctuations in rainfall can produce variations in runoff production. This behaviour may not be linear and it may change over time as catchment and event conditions change. Consequently, there can be considerable uncertainty involved in determining which rainfall input produces subsequent runoff behaviour. To reduce uncertainty not all rainfall-runoff events are included within analyses. Rather, events are selected based upon their characteristics with a target set of characteristics defined before analysis begins. The following criteria are used to either include or exclude an event from analysis:

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

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

(iii) There must be rainfall, runoff and soil moisture data for the event at both Arley Close and Winsley Close.

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

By constraining analyses to events that meet these selection criteria, uncertainty in determining which rainfall input produces subsequent runoff output is reduced.

3.7.5 Determining peak flow rates and percentage runoff

There are two key descriptive metrics that describe the characteristics of event runoff hydrographs; the percentage runoff and peak flow rate (Goldshleger et al., 2009). Percentage Runoff (PR), sometimes referred to as the runoff coefficient, is defined here as the proportion of rainfall that falls on a catchment that ends up as event runoff within the surface water drainage system. PR is often quoted as a percentage and is used extensively within the literature to examine the rainfall-runoff behaviour of a number of catchments of different types (Rodríguez-Blanco et al., 2012; Merz et al., 2006; Norbiato et al., 2009). PR is derived using the following methodology:

(i) Total rainfall volume is calculated for a rainfall event by multiplying the total event rainfall depth by catchment area.

(ii) Event runoff volume is calculated for an event by summing the flow ordinates in an event hydrograph and then multiplying by 30 seconds, noting that the runoff data are collected at 30 second intervals (Section 3.5.1).

(iii) Total runoff volume is divided by total rainfall volume and multiplied by 100 (Equation 3.6).

$$\text{Percentage Runoff } (PR) = \frac{\Sigma Q*30}{P*Area} * 100\% \qquad \text{Equation 3.6}$$

Where Q is the flow ordinates (l/s) from a hydrograph, P is total event rainfall depth (mm) and *Area* is the catchment area (m^2).

Peak flow rate (QMAX) is the maximum flow within a surface water drainage system during an event, it is stated as the volume per unit time and its units are related to the scale of catchment under study (for example m^3/s might be used for large catchments whilst l/s for small catchments). QMAX is an important descriptor of surface water response that has implications for downstream hydraulic capacity and flood risk management. Consequently QMAX is the target of much of the UK's surface water management policies and legislation, with design standards aimed at retaining pre-development QMAX conditions (Woods-Ballard et al., 2007). QMAX is determined for each studied rainfall-runoff event by use of simple functions within the base version of the R programming language e.g. max(x), where (x) is a vector of flow ordinates of a given event.

3.7.6 Deriving event descriptive metrics

For each of the sampled events from Arley Close and Winsley Close, descriptive metrics are derived through the analysis of the rainfall and soil moisture data collected during the monitoring campaign. Table 3.2 details these descriptive metrics, their definition and units. The metrics are split into two categories, describing either the characteristics of the rainfall event, or the antecedent wetness of the catchments prior to a rainfall event.

Those metrics within the antecedent conditions grouping are derived either from an analysis of the rainfall or soil moisture time-series of data (for example the pre event 1hr rainfall depth), or else require the use of previously published equations to derive descriptive metrics that are shown to correlate to urban rainfall runoff behaviour (API5, SMD and UCWI, Kidd and Lowing (1979)). By deriving these descriptive metrics of each event, it is possible to investigate the sensitivity of the urban rainfall-runoff process within Arley Close and Winsley Close and how this sensitivity may be influenced by their respective designs through multiple linear regression, as described in the next Section (Section 3.8). Example code and an outline of the coding methods used within the thesis for data manipulation and processing are outlined in Appendix 2.

Table 3.2: Descriptive metrics for rainfall-runoff events sampled from Arley Close and Winsley Close. Metrics are split into rainfall characteristics and antecedent conditions groupings.

	Variable Name	Definition	Units
Rainfall Characteristics	**Depth**	Total event rainfall depth	mm
	Duration	Total event duration	Minutes
	2MinMaxInt	Maximum 2 minute rainfall intensity	mm/2minutes
	10MinMaxInt	Maximum 10 minute rainfall intensity	mm/10minutes
Antecedent Conditions	**API5**	Antecedent (5 day) Precipitation Index (see 3.9.2.1)	mm
	SMD	Soil Moisture Deficit (see 3.9.2.1)	mm
	UCWI	Urban Catchment Wetness Index (see 3.9.2.1)	mm
	Pre1HR	Pre event 1 hour rainfall depth	mm
	Pre2HR	Pre event 2 hour rainfall depth	mm
	Pre6HR	Pre event 6 hour rainfall depth	mm
	ASM/WSM	Soil moisture recorded by PR2 probes, ASM = Arley Close, WSM = Winsley Close.	m^3/m^3

3.8 LINEAR REGRESSION MODELLING

Multiple linear regression modelling is a statistical method that estimates how a number of explanatory variables predict a response variable, where the relationship between the response and explanatory variables follow a consistent, linear, additive relationship (Weisberg, 2005). The linear regression equation takes the form:

$$\hat{Y} = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 \ldots \beta_p \cdot X_p \qquad \text{Equation 3.7}$$

Where Y is the response variable, β_0 is the estimate of the intercept with the y-axis (i.e. the value of Y when the explanatory variables are zero), X_1, X_2....X_p are the explanatory variables, and β_1,β_2 ....β_p are the regression coefficients.

To estimate the values of the regression coefficients (β_1,β_2 ....β_p) the multiple linear regression model is fitted using the Ordinary Least Squares method (OLS) by minimising the error between the predicted values of Y and the observed values of Y. This simple form of the linear regression model can be interpreted as follows (Field et al., 2012):

"*A per unit increase of X_1 is equal to a β_1 increase in Y, where the other explanatory variables are held constant.*"

Linear regression analysis is used extensively within the scientific literature to examine the sensitivity of rainfall-runoff response in a number of different catchment types to various physical variables (McIntyre et al., 2007) and forms the basis of much of the statistical flood prediction work in the United Kingdom (Kjeldsen and Jones, 2009).

The aim of regression analysis within this study is to examine the sensitivity of runoff characteristics as described by the metrics of QMAX and PR (Section 3.7.5) at Arley Close and Winsley Close, to variations in rainfall characteristics and antecedent conditions as defined in Section 3.7.6. The analysis is not intended to produce models that could be used for prediction outside of this study (for say drainage design), but rather as a tool to develop a greater understanding of how urban design influences event based rainfall-runoff behaviour. It is important that the modelling strategy used reflects this objective for analysis. Two objectives are used to constrain the regression modelling and establish the modelling strategy:

(i) The modelling procedure investigates how rainfall-runoff behaviour of the two study sites is sensitive to antecedent conditions and rainfall characteristics.

(ii) Models are interpretable, have physical relevance and allow for comparison between the two study sites.

With these two statistical modelling objectives it is possible to define the model fitting procedure, the hypothesis testing framework, the assessment of model fit, residual analysis and explanatory variable selection methodologies.

3.8.1 Model fitting method

The Ordinary Least Squares (OLS) regression model fitting procedure is used to estimate the regression coefficient values. Figure 3.15 (A) shows a scatter plot between two variables of hypothetical dummy data, *X* and *Y*. The OLS fitting method estimates values for the regression coefficients (in the case of this simple linear regression β_0 and β_1) so as to minimise the sum of the difference between the values of *Y* estimated by a model and the data values of *Y*. OLS is chosen as *Y* (the dependant variable) is continuous and the modelling strategy aims to maximise the physical interpretation of the regression modelling, reducing the applicability of methods such as Partial Least Squares regression or Principle Components regression (Craven and Islam, 2011; Wold et al., 1984). Figure 3.15 (B) shows the residuals, the difference between the recorded and predicted values of *Y* for a given model (red vertical lines). The OLS fitting procedure minimises the sum of the residuals across the range of the values of *X* and *Y*.

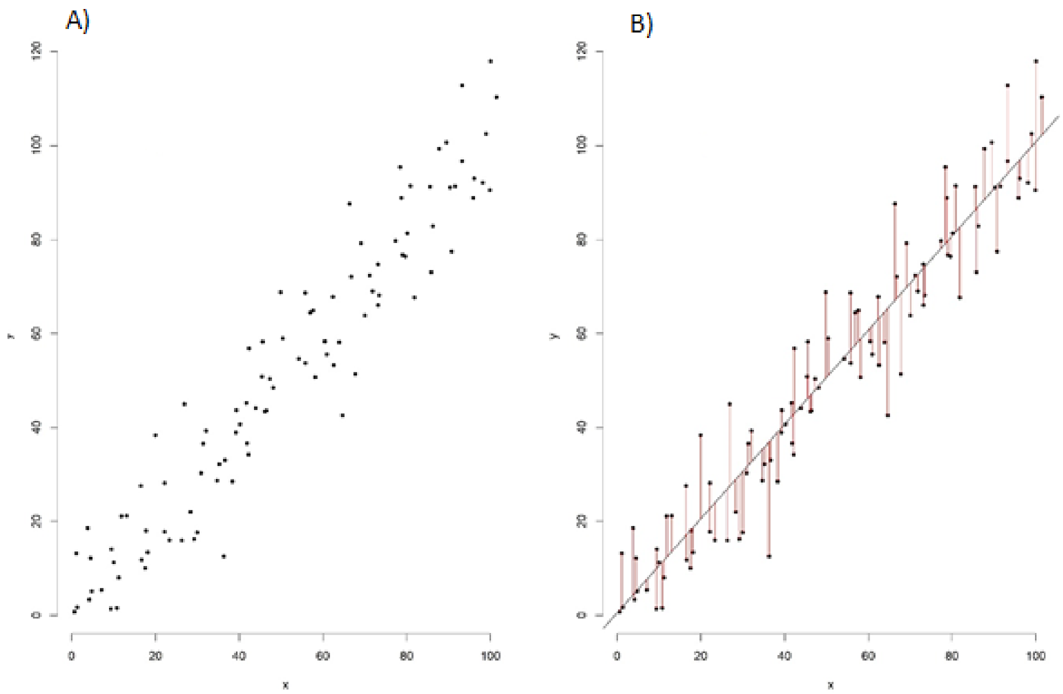

Figure 3.15: A) Scatter plot between two dummy variables, B) a linear regression model fitted by means of ordinary least squares and residuals between model and observed data (red vertical lines).

3.8.2 Hypothesis testing framework:

If there is a linear relationship between an explanatory variable (X_p) and Y, then the value of β_p does not equal zero (James et al., 2013). The linear regression modelling procedure computes a significance test of this observation by establishing a Null hypothesis (denoted by H_0) that states that the value of each regression coefficient is equal to zero i.e. there is no relationship, whilst the alternative hypothesis (denoted H_a) states that the slope is not equal to zero:

H_o: There is no effect of X_p on Y, $\beta_p = 0$.

H_a: There is an effect of X_p on Y, $\beta_p \neq 0$.

Linear regression modelling tests the Null hypothesis by means of a t-test. The value of β_p is determined via the OLS methodology (Section 3.8.1), along with the standard error (a measure of the accuracy of the coefficient estimate). The *t*-statistic is computed by dividing the regression coefficient estimate by the coefficient standard error. The test t statistic is then compared to the t distribution and a P value deduced.

The P value describes the likelihood that the Null hypothesis is true given the data sample. The user then decides a critical value of P (termed the alpha value) that will indicate whether the Null hypothesis should be rejected (and the alternative hypothesis accepted) or accepted (rejecting the alternative hypothesis). An alpha value of 0.05 is used here as the criteria for rejecting the Null hypothesis. Therefore a P value less than 0.05 is required to reject the Null hypothesis and declare the regression coefficient estimate as statistically significant (James et al., 2013).

3.8.3 Assessment of model fit: the coefficient of determination

The coefficient of determination is a measure of the fit between a regression model and the modelled dataset. It is calculated with the following equation:

$$R^2 = 1 - \frac{\sum(\hat{y}_i - \overline{y})^2}{\sum(y_i - \overline{y})^2} \qquad \text{Equation 3.8}$$

Where R^2 = the coefficient of determination, $\hat{y}_i$ = the regression estimate for y value i, $\overline{y}$ = the mean of all values of y and y_i = the *i*th value of y. The coefficient of determination is the proportion of the variation in the dependant variable (Y) that is explained by the linear model. For multiple linear regression (i.e. when there is more than one explanatory variable) an adjusted coefficient of determination is used:

$$R^2_{adj} = 1 - (1 - R^2)\frac{n-1}{n-p-1} \qquad \text{Equation 3.9}$$

Where R^2_{adj} = the adjusted R^2 value, R^2 is defined in equation 3.8, n is the number of observations and p is the number of explanatory variables in a multiple linear regression model. Adjusted R^2 is used in place of R^2 for multiple linear regression as R^2 values will increase with an increase of variables added to a model, regardless of how much of a better representation of a dataset a model is. Therefore R^2 can provide a misleading interpretation of multiple regression analysis results, whereas the adjusted R^2 value only increases if there is an improved fit between model and data with the addition of an additional explanatory variable (James et al., 2013).

3.8.4 Residual analysis

Analysing the residuals of a regression model is an important step in assessing and confirming that linear regression modelling is an appropriate method for describing the relationship between explanatory and dependant variables. The residuals are the difference between modelled and recorded data (shown as vertical red lines on Figure 3.15 B).

The residuals of a multiple linear regression model should be:

(i) normally distributed,

(ii) with no systematic pattern (random scatter about zero),

(iii) homoscedastic (i.e. of equal variance across the range of fitted values),

(iv) with no outlying values of increased leverage (James et al., 2013).

Deviation from the above requirements indicate that the relationship between the response and explanatory variables does not conform to a consistent, additive, linear relationship. In this case data transformations may be required, or a more complex model structure (say quadratic terms added). Residual analysis is completed using a series of four plots that test the above conditions in turn (Figure 3.16).

A plot of residuals against the fitted values of a regression model indicates whether there is any systematic pattern within the residuals. The "Residuals vs Plotted" plot should show a random scatter of data points, with no trends or curves visible (Figure 3.16).

The "Normal Q-Q" plot compares the distribution of the residuals of a regression model against that of a theoretical normal distribution to check for conformity. If the residuals conform to the normal distribution then the points plot on a straight line. Large-scale deviations from a straight line indicate that the dataset deviates from the normal distribution (Figure 3.16).

The "Scale-Location" plot checks that the residuals are homoscedastic. The residuals are normalised and scaled to convert all residuals to the same sign (all positive) and plotted against the fitted values. The data points should plot in a random scatter of equal variance across the fitted values. If the variation of the standardised residuals increases, decreases or follows a curve this indicates that the residuals are heteroscedastic and thus breach the need for homoscedasticity (Figure 3.16).

The “Residuals vs Leverage” plot examines the leverage of each point within a dataset. Leverage describes the amount by which one data point influences the estimate of a regression coefficient. An outlying data point “pulls” the regression line towards it, to minimise the residual and this “pull” has an undue influence on the regression coefficient estimates in comparison to all the other points in the dataset, reducing how representative of the whole dataset a regression line is. A measure of leverage is the Cooks Distance (Cook, 1977; Chatterjee and Hadi, 1986) which examines the effect of deleting each data point from a dataset, refitting the regression model and examining the change in coefficient estimate. Here it is judged that all data points should have a Cook’s distance less than 1, as a Cook’s distance greater than 1 indicates that a data point is an outlier, with increased leverage, and thus is having an undue effect on the regression coefficients (Weisberg, 2005). Lines are plotted on the “Residuals vs Leverage” plot to indicate Cooks distance values of 0.5 and 1. Points are plotted onto the plot and the modeller can examine the Cook’s distance of each point (Figure 3.16).

If any of the residual analysis plots indicate deviations from the assumptions of linear regression modelling, then the regression modelling process is repeated either with a more complex model structure, or with transformed dependant and/or explanatory variables. The rules used to interpret regression coefficient values are then adjusted accordingly.

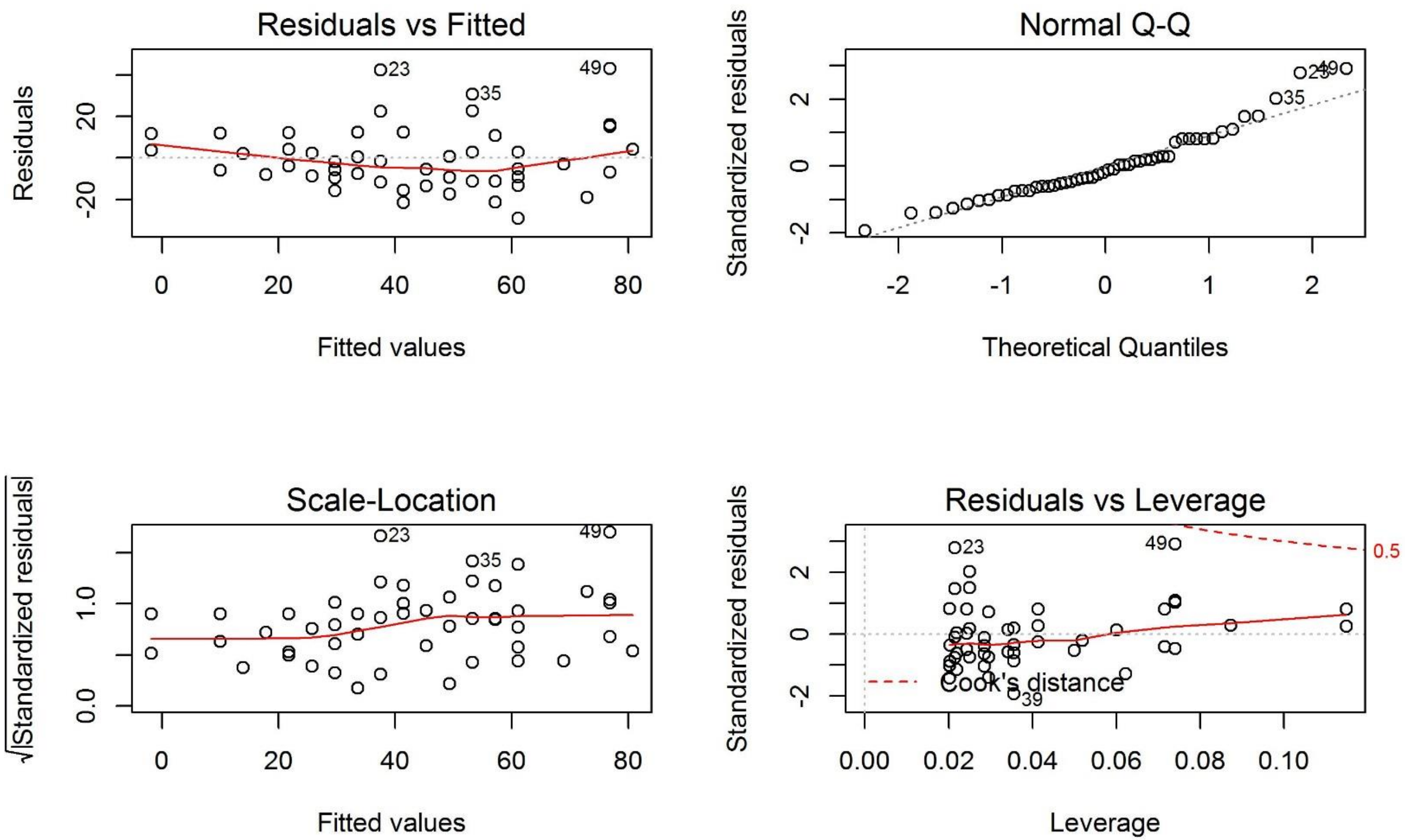

Figure 3.16: Diagnostic plots for example regression model illustrating the four residual analysis plots drawn by the base regression functions of R.

3.8.5: Variable selection method

Rainfall event characteristics and metrics describing antecedent conditions are available for regression modelling (Table 3.2). Antecedent indices and rainfall characteristics describe similar, but subtly different properties of an event, and some are correlated to each other. Understanding the collinearity between explanatory variables in a regression model is important, as the aim of this modelling exercise is to maximise the physical relevance of the regression models to identify the sensitivity of rainfall-runoff behaviour to rainfall characteristics and antecedent conditions. Using explanatory variables that are correlated within regression modelling creates a number of problems (Kroll and Song, 2013):

(i) Estimated regression coefficients of one variable depends on which other explanatory variables are already included within a model.

(ii) The contribution of any one explanatory variable in reducing the error sum of squares depends on which other explanatory variables are already in the model.

(iii) Hypothesis tests for regression coefficients may yield different conclusions depending on which explanatory variables are already in the model.

The problems of collinearity in regression modelling are particularly acute in studies with small sample sizes (Kroll & Song, 2013), therefore an explanatory variable selection method is applied that excludes combining variables with high collinearity. To achieve this a correlation matrix (whereby the Pearson correlation coefficient (James et al., 2013) between each of the explanatory variables is estimated) is used to examine the correlation between explanatory variables, and a variable selection method is applied that minimises the correlation between explanatory variables used within a model.

Through careful selection of explanatory variables and detailed analysis of model residuals, the sensitivity of rainfall-runoff behaviour in Arley Close and Winsley Close to rainfall characteristics and antecedent conditions is examined. This provides a basis to understand how the comparative differences in design and age of the two study developments influences rainfall-runoff behaviour.

3.9 APPLYING UNDERSTANDING OF RAINFALL-RUNOFF BEHAVIOUR IN ARLEY CLOSE AND WINSLEY CLOSE TO HYDROLOGICAL MODELLING AND SURFACE WATER MANAGEMENT PLANNING

In the United Kingdom, when urban development is planned, engineers, hydrologists and regulatory authorities work to national policies and guidelines for the provision and design of surface water drainage systems (Woods-Ballard et al., 2015). These policies aim to retain a rainfall-runoff behaviour post development that mimics pre-development greenfield conditions (for new urban developments) or else, aim to reduce runoff volumes and flow rates of existing urban areas (for brownfield re-development or the retro-fitting of surface water drainage systems). To achieve this the runoff volume of an urban development is estimated under two conditions:

(i) greenfield (a site under pre-development non-urban surface cover), and,

(ii) urban (describing an area that is developed).

The additional runoff volume generated following urbanisation is managed on site, either through long-term storage (with a heavily restricted outflow rate) or through infiltration or grey water uses (e.g. garden watering). To estimate the additional runoff volume generated from a development site following urbanisation, equation 3.10 is used:

$$Vol_{xs} = RD \, . A . (PR_{URB} - PR_{GF}) \qquad \text{Equation 3.10}$$

Where Vol_{xs} = the excess runoff volume generated following urbanisation, RD = the rainfall depth for the 100-year 6-hr event, A = catchment area, PR_{URB} = the percentage runoff from a development once urbanised, and PR_{GF} = the percentage runoff from a site under the pre-development greenfield condition (a simplified equation to that described by Woods-Ballard et al. (2007)).

The rainfall depth (RD) for a design event is generated from Depth-Duration-Frequency (DDF) curves published as part of the Flood Studies Report (NERC, 1975) and Flood Estimation Handbook (CEH, 1999). Catchment area (A) is derived from assessments of catchment information and drainage areas. PR_{URB} and PR_{GF} need estimating for an area, given the lack of monitored rainfall-runoff data at appropriate scales within urban catchments and this is completed using urban hydrological models.

The initial planning process for retro-fit surface water drainage systems is therefore as follows:

(i) Estimate catchment area based on development site information.

(ii) Estimate rainfall depth of the 100-yr 6-hr event based on Depth Duration Frequency curves.

(iii) Estimate greenfield percentage runoff value (PR_{GF}) using appropriate modelling tool

(iv) Estimate urban percentage runoff value (PR_{URB}) using appropriate modelling tool

The costs of storing excess runoff volumes on site following urbanisation in a retrofitted storage tank can then be estimated using published cost estimates produced by Stovin and Swan (2007). Assuming that storage is in the form of a reinforced concrete tank, a cost estimate is £500/m^3 (a central cost estimate as Stovin and Swan (2007) produce a range of values of potential costs). This cost estimate does not incorporate the purchasing of land or other potential secondary costs. The process described here is only considering runoff volumes generated from an urbanised area, not flow rates, and only a simple estimate of construction costs. However, this analysis is pertinent as it reflects the types of analyses that engineers undertake in the planning of a surface water management project (e.g. Warhurst et al. (2014)) and the first stage in many linked hydrological-hydraulic models is to estimate runoff volumes, and the second stage is to apply routing procedures to estimate peak flow rates and hydrograph shape (Kidd and Lowing, 1979), meaning that estimates of flow rate are sensitive to the estimation of runoff volumes.

Given the reliance of the surface water management planning and engineering design process on hydrological modelling, designing and managing the urban rainfall-runoff process is sensitive to the outcomes of modelling tools and any uncertainty involved in representing the urban rainfall-runoff process within models. There are a number of sources of uncertainty in measuring and estimating the urban rainfall-runoff process within hydrological models, including defining surface cover (Section 3.3), surface connectivity (Section 3.4) and choosing parameter values to reflect site conditions (e.g. materials, surface condition etc.).

To examine and quantify how uncertainty in hydrological modelling influences surface water management planning, the additional urbanised runoff volume from Arley Close and Winsley Close is calculated using PR values estimated from current industry-standard modelling tools for PR_{GF} and PR_{URB} and compared to storage estimates derived from estimating PR_{URB} as the average event PR value from the monitored rainfall-runoff data collected and analysed in Arley Close and Winsley Close. Uncertainty in PR_{URB} modelling, derived from uncertainty in estimating surface cover and connectivity, the choice of urban rainfall-runoff model and parameter value selection is explored by use of a decision tree and a sensitivity analysis of the UK Variable Runoff model. The methodological process is as follows:

(i) Estimate PR_{GF} for Arley and Winsley Close, using the plot scale ReFH2 method.

(ii) Estimate required storage volumes and construction costs of a storage tank in Arley Close and Winsley Close by assuming that PR_{URB} is equal to the average PR value derived from monitored rainfall-runoff events.

(iii) Examine uncertainty in modelling PR_{URB} values by applying methodological assumptions to estimate surface cover in available rainfall-runoff models. Construct a decision tree and apply two scenarios to quantify the upper and lower bounds of potential modelled PR_{URB} values, required storage volumes and cost estimates. Compare these to those derived from monitored rainfall-runoff data in method (i) above and estimate the increased costs of construction resulting from the over-prediction of PR_{URB}, or the under design volume through the under prediction of PR_{URB}.

(iv) Examine how uncertainty in deriving estimates of connectivity and choosing appropriate model parameters to reflect site characteristics affect the estimation of PR_{URB} values, storage volumes and cost estimates by conducting a sensitivity analysis on the UK Variable Runoff Model.

The following Sections describe the urban and greenfield rainfall-runoff models applied to estimate PR_{GF} and PR_{URB}, as well as the methods used to assess uncertainty in model parameterisation to reflect surface cover, condition and connectivity. The urban rainfall-runoff models described here are those recommended for use by Woods-Ballard et al. (2007), a document more widely known as the SuDS Manual, as this is the main document used in UK surface water management planning for the design of Sustainable Drainage Systems. It should be noted that Woods-Ballard et al. (2007) was updated in 2015 (Woods-Ballard et al., 2015), with several of the methods described here removed. They are included here as a number of the urban rainfall-runoff models are still available in drainage design software and because a large number of urban catchments will have been assessed using the methods described by Woods-Ballard et al. (2007) between the two editions of the document being published.

3.9.1 Plot scale estimates of greenfield percentage runoff (PR_{GF})

The plot-scale Revitalised Flood Hydrograph method (ReFH2), described by Kjeldsen (2007) and WHS (2016) is used to estimate the greenfield Percentage Runoff of Arley Close and Winsley Close (PR_{GF}). A full technical description of the model is given by Kjeldsen (2007), so this Section describes how the model is applied to Arley Close and Winsley Close. ReFH2 is implemented in software produced by Wallingford Hydro-Solutions. The model is parameterised by querying the FEHweb (www.fehweb.ceh.ac.uk) service to download point catchment characteristics for Arley Close and Winsley Close (where each query point is placed in the centre of each study catchment). The ReFH2 software contains a rainfall modelling tool based upon the Depth-Duration-Frequency curves reported in the Flood Studies Report (NERC, 1975) and Flood Estimation Handbook (CEH, 1999). These are used to derive a precipitation event for the 100-yr 6-hr event. The rainfall is input into the ReFH2 rainfall-runoff model and the output of the ReFH2 software is a hydrograph containing both direct runoff, baseflow and the total flow of the two flow components. It is possible to determine the percentage runoff from this output by:

(i) Calculating the total rainfall volume for an event by multiplying the total rainfall event depth by catchment area.

(ii) Calculating the total direct runoff volume for an event.

(iii) Dividing the direct runoff volume by rainfall volume and multiplying by 100.

The output of applying the ReFH2 model with the above methodology is to generate the PR_{GF} parameter in Equation 3.10.

The plot-scale ReFH2 method is currently applied within UK engineering design practice for greenfield estimation. Other greenfield methodologies are available, however, they are not applied in this study as the focus is on assessing urban modelling tools and a number of the other available methods have been discredited in other research (Faulkner et al., 2012).

3.9.2 Urban percentage runoff estimation methods (PR_{URB})

Historically many models have been developed to represent the urban rainfall-runoff process within hydrological, hydraulic and engineering design calculations. These models are available within commercially available software and are used for surface water drainage design calculations on a routine basis (MicroDrainage, 2011). Here their formulation is taken from Woods-Ballard et al. (2007) and the models are implemented by developing MS Excel spreadsheets.

Current methods for runoff modelling split the above ground (hydrological) and below ground (hydraulic) phases of runoff generation in urban areas to represent the different processes that control runoff generation on urban surfaces, and the hydraulic routing of runoff through surface water drainage systems (Kellagher, 2000). The *Wallingford Procedure*, described by Kidd and Lowing (1979) is a methodology developed in the UK for designing and simulating surface water drainage systems. The method is implemented in a number of different software packages that are used extensively in the UK engineering industry to design and simulate new and existing surface water drainage systems (e.g. Microdrainage, InfoWorks etc.). The above ground, hydrological phase of the modelling process calculates the percentage runoff (PR_{URB}) of an event and the below ground hydraulic phase routes runoff volume into an event hydrograph. This study focusses on the various above ground hydrological models for percentage runoff estimation that are available.

3.9.2.1 Original Fixed UK Runoff Model

The original rainfall-runoff model derived in 1979 for the above ground phase of runoff generation is a regression model (Equation 3.11) linking the percentage runoff of an event to metrics describing the percentage imperviousness of a catchment (PIMP), the antecedent wetness of an event (UCWI) and the soil type (SOIL) as defined by the Winter Rainfall Acceptance Potential (WRAP) (Kidd and Lowing, 1979).

$$PR = 0.829 * PIMP + 25.0 * SOIL + 0.078 * UCWI - 20.7 \qquad \text{Equation 3.11}$$

Measurements of PIMP can be made through the analysis of surface types within urban areas, whilst SOIL values are derived through the analysis of published maps (Kellagher, 2013). The Urban Catchment Wetness Index is derived by the following equation:

$$UCWI = 125 + 8 * API5 - SMD \qquad \text{Equation 3.12}$$

Where API5 = five day antecedent precipitation index (mm) and SMD = soil moisture deficit (A data set currently produced by the UK Met Office (MetOffice, 2017)).

Event specific values of UCWI are derived using the following method for simulation purposes:

(i) Sum the rainfall depth totals for each of the five days prior to an event.
(ii) The API5 for 09:00 of the day of an event is given by:

$$API5_9 = \sum_{n=1,5} P_{-n} C_p^{n=0.5} \qquad \text{Equation 3.13}$$

Where P_{-n} = rainfall depth on day *n* before an event and C_p = a decay coefficient of 0.5.

(iii) The API5 at the time of an event is then given by:

$$API5 = API5_9 C_p^{(t'-9)/24} + P_{t'-9} C_p^{(t'-9)/48} \qquad \text{Equation 3.14}$$

Where t'= Time (hours) of the beginning of an event, and P_{t-9} = rainfall depth between time t' and 09:00.

(iv) The soil moisture deficit (SMD) for an event is then calculated from:

$$SMD = SMD_9 - P_{t'-9} \quad \text{Equation 3.15}$$

Where SMD_9 = Soil Moisture Deficit at 09:00 on the day of an event and $P_{t'-9}$ = rainfall depth between time t' and 09:00. The SMD describes the depth of rainfall required to return soil storage to field capacity (Butler and Davies, 2004). The UCWI is therefore a weighted metric of the wetness of the preceding five days before an event, where the rainfall closest to the event has the greatest influence on UCWI values. Design values of UCWI have been recommended for areas across the UK, in relation to the Standard Averaged Annual Rainfall (SAAR) for both winter and summer conditions and these are used in design practice (Kellagher, 2000).

3.9.2.2 New Variable UK Runoff Model

An alternative runoff model, called the Variable UK Runoff Model (or "New" Runoff model) was devised in 1990 to account for increased wetness and runoff generation as rainfall-runoff events elapse. The model was developed by John Packman of CEH, however no single paper reports its development and thus a direct citation is not possible. The Variable UK Runoff Model is recommended over the original regression equation in modern surface water modelling guidance, however, both models are still available within surface water drainage design software packages and are widely used (Woods-Ballard et al., 2015). The UK Variable Runoff Model is sensitive to the fact that not all impervious surfaces are connected to the surface water drainage system as the model contains an Effective Impervious Factor (IF) parameter to split impervious surfaces into connected and disconnected surfaces. Non-connected surfaces are lumped together with permeable surfaces and the runoff generated from these surface types increases as an event elapses and the catchment wetness increases. The percentage runoff from the connected surfaces remains unchanged throughout an event (assumed to be 100%). The Variable UK Runoff Model takes the form:

$$PR = IF * PIMP + (100 - IF * PIMP) * \frac{NAPI}{PF} \quad \text{Equation 3.16}$$

Where PR = Percentage Runoff (%), IF = the effective paved area factor (%), PF = soil storage depth and NAPI = the 30 day antecedent precipitation index (similar to

API5, over a longer preceding period). Design values of NAPI and PF are available in design guidance, whilst PIMP and IF need estimating based upon assessments of surface cover and connectivity.

3.9.2.3 ReFH2

An urban extension to ReFH2 (Section 3.9.1) described by Kjeldsen (2009) includes a method to estimate the impacts of urbanisation on runoff volume generation. The urban extension splits an urban area into two components, (i) rural and (ii) urban, and a runoff volume is defined from a design event for each component. The urban percentage runoff is modelled with Equation 3.17 (simplified from the equations described in Kjeldsen 2009):

$$PR = PIMP * IF * PRurb \qquad \text{Eq. 3.17}$$

Where PIMP = the percentage impervious area, IF = the proportion of impervious surfaces connected to a drainage system and PRurb = the percentage runoff of connected impervious surfaces. Default design values are used to represent large-scale urban development within fluvial catchments (PIMP=30%, IF = 70% and PRurb=100%) and whilst the urban extension is intended for the large-scale estimation of the impacts of urbanisation in fluvial catchments the method is also recommended for use on plot scale assessments of runoff (Woods-Ballard et al., 2007; WHS, 2016).

3.9.2.4 SuDS Method

A simple method for estimating the additional runoff volume following urbanisation of a development plot is described by Kellagher (2013). Here the volume of runoff that must be attenuated on site (either through infiltration or storage) for an urban development is estimated using Equation 3.18, this is a version of Equation 3.10 under specific assumptions, and here it is termed the “SuDS Method” given that its details are provided within the SuDS design manual (Woods-Ballard et al., 2007):

$$Vol_{xs} = RD * A * 10 * \left[\frac{PIMP}{100}(\alpha 0.8)\left(1 - \frac{PIMP}{100}\right)(\beta SPR) - SPR\right] \qquad \text{Equation 3.18}$$

Where:

Vol_{xs} = Extra runoff volume resulting from urbanisation (m^3)
RD = rainfall depth for the 100yr 6hr rainfall event (mm)
$PIMP$ = percentage impermeable area (as a proportion)
A = Catchment area (ha)
SPR = SPR index for the SOIL or HOST class (this specifies the percentage runoff from permeable surfaces).
α = proportion of impervious surfaces connected to the surface water drainage network
0.8 = assumed percentage runoff from connected impervious surfaces
β = proportion of pervious surfaces connected to a surface water drainage system.

Equation 3.18 has been copied directly from Woods-Ballard et al. (2007), however inspection of the equation indicates that the text contains a typographical error, therefore, the following modification is made (Equation 3.19) within this study:

$$Vol_{xs} = RD * A * 10 \left[\left(\frac{PIMP}{100}(\alpha 0.8) + \left(1 - \frac{PIMP}{100}\right)\beta SPR\right) - SPR\right] \quad \text{Equation. 3.19}$$

Where parameter values have the same meaning as those in equation 3.18.

To apply this model, the areas of connected and disconnected impervious and pervious surfaces are determined and the percentage runoff from impervious surfaces estimated (default value of 0.8). This model includes the SPR_{HOST} catchment characteristic from the FEH (CEH, 1999) to represent the likely percentage runoff of a development site under greenfield conditions. It is possible to modify the equation to include an alternative greenfield model so that SPR is derived from ReFH2 as follows:

$$Vol_{xs} = RD * A * 10 \left[\left(\frac{PIMP}{100}(\alpha 0.8) + \left(1 - \frac{PIMP}{100}\right)\beta_{REFH2}\right) - PR_{ReFH2}\right] \quad \text{Eq.3.20}$$

All parameters are identical to those defined for equation 3.18 and PR_{ReFH2} is the greenfield percentage runoff as defined by the plot scale ReFH2 method described in Section 3.9.1.

3.9.3 Parameterising urban rainfall runoff models

The parameter values that need defining for each urban rainfall-runoff model, their description and methods for defining their value are summarised in Table 3.3. The different models share a number of parameters that need estimating based on assessments of catchment spatial data (PIMP, IF), whilst some parameters are estimated from design guidance (UCWI, NAPI, PF etc.). Each of the four models need an estimate of the percentage impervious area (*PIMP*) whilst the SuDS method, the UK Variable Runoff model and REFH2 require an estimate of surface connectivity (IF), which is represented as a proportion of PIMP with connections to the surface water drainage system.

There is uncertainty in estimating the PIMP value in Arley Close and Winsley Close given the difficulties of defining surface types within rear gardens (See Section 3.3 for description). Selecting a parameter value to represent surface connectivity is also difficult, given that connectivity is defined in terms of those surfaces with direct and indirect connections (Section 3.4) and overall surface connection efficiency. There are a range of methods that have been applied to define connectivity within urban hydrology studies. For example Lee and Heaney (2003) assume that indirectly and directly connected surfaces should be considered connected, whilst Perry and Nawaz (2008) assume that some semi-impervious surfaces (concrete slab patios) are impervious and connected. Estimates of PIMP and IF are therefore sensitive to the methodological assumptions used for their definition from geospatial data and it is therefore likely that estimates of PR_{URB} and the estimated required runoff storage volume are similarly affected by assumptions applied in geospatial methods.

Table 3.3: Summary table of urban rainfall runoff models, parameter values, description and estimation methods

Model	Parameter	Description	Method
Fixed PR	*PIMP*	Percentage Impervious Area	Inspection of spatial data
	SOIL	Based on WRAP	Published maps
	UCWI	Measure of antecedent wetness	Design guidance
Variable PR	*PIMP*	Percentage Impervious Area	Inspection of spatial data
	IF	The connectivity of impervious surfaces	Inspection of spatial data or design guidance
	NAPI	Measure of antecedent wetness	Design guidance
	PF	Soil storage depth	Design guidance
ReFH2	*Area*	Catchment area	Inspection of spatial data
	PIMP	Percentage Impervious Area	Inspection of spatial data
	IF	The connectivity of impervious surfaces	Inspection of spatial data or design guidance
	PR_{urb}	Urban surface percentage runoff	Estimated value
SuDS	*PIMP*	Percentage Impervious Area	Inspection of spatial data
	α	The connectivity of urban surfaces	Inspection of spatial data or design guidance
	PR_{urb}	Urban surface percentage runoff	Estimated value
	β	The connectivity of green surfaces	Inspection of spatial data or assumed value
	PR_{rural}	Green surface percentage runoff	Derived from greenfield rainfall-runoff modelling

3.9.4 Uncertainty in urban percentage runoff modelling

To examine how uncertainty in urban rainfall-runoff modelling translates into a range of potential estimates of required runoff storage volume, a decision tree is constructed to visualise the potential modelling outcomes based on methodological assumptions regarding surface cover, connectivity and rainfall-runoff model choice. Two scenarios that estimate the upper and lower bounds of the uncertainty range are applied to quantify the range of possible values of $PR_{URB,}$ runoff storage volume and construction costs that could be produced. A number of sources of uncertainty in modelling the percentage runoff of Arley Close and Winsley Close are considered, including:

(i) Defining surface cover and connectivity,

(ii) choosing an appropriate urban rainfall-runoff model, and;

(iii) choosing model parameter values to reflect site conditions.

To explore and assess how uncertainty in defining surface cover and choosing rainfall-runoff models affect estimates of $PR_{URB,}$ runoff storage volumes and estimated construction costs, a decision tree is used to visualise the linkages between methodological assumptions and model choice to design outcomes. A decision tree shows in diagrammatic form how a series of decisions can lead to a number of different outcomes (Magee, 1964). A decision tree grows from a single starting node and expands in a tree like pattern of additional nodes and branches. Nodes mark the points at which a decision or assumption is made, whilst branches show possible alternative choices that can be made at each decision node. Figure 3.17 shows a simple example of a decision tree, where two decisions (black circles) with two different choices can be made (black lines) leading to four possible outcomes (white circles).

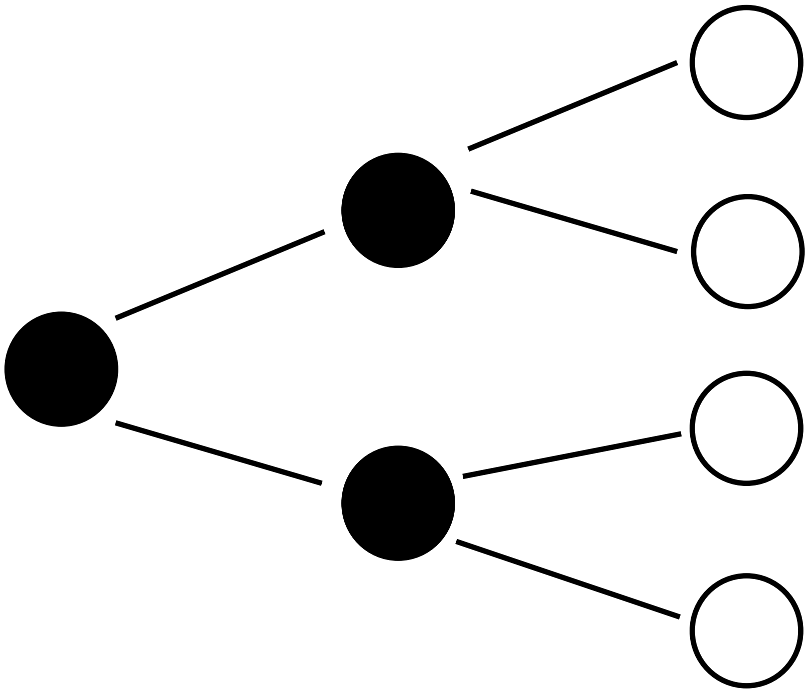

Figure 3.17: A simple example of a decision tree. The user starts at the left hand start node and moves to the right of the diagram. At each node (black circle) a decision is made between two choices (black lines, branches) and over the course of two decisions there are four possible outcomes (white circles).

Decision trees are widely used in the business management literature to understand the complexity of making multiple decisions where there is uncertainty in events and outcomes (Consigli et al., 2017). Their use here is intended to visualise and explore how choices made in terms of methodological assumptions regarding surface cover, connectivity and rainfall-runoff model produce a range of outcomes in terms of values of PR_{URB}, required runoff storage volume and estimated construction costs. The range of uncertainty is quantified by testing two scenarios designed to define the upper and lower limits of potential modelling outcomes:

(i) The first scenario aims to find the maximum storage estimate that could be produced from the surface water management modelling process for each site. This assumes the High PIMP value defined in Section 3.4 and 100% connectivity between impervious surfaces and the surface water drainage system, a highly conservative scenario but one that is recommended in surface water management planning for the initial sizing of surface water drainage assets (Kellagher, 2013).

(ii) The second scenario attempts to find the minimum volume of storage that is possible to be estimated at each site, by assuming the low PIMP value in Section 3.3. and assuming that only surfaces with a direct connection to the surface water drainage system contribute to runoff (Section 3.4).

Whilst these two scenarios occupy the extremes of choices that could be made in a modelling exercise, without appropriate understanding of the urban rainfall-runoff process they are plausible design modelling outcomes.

3.9.5 Representing connectivity within the UK variable runoff model

A sensitivity analysis is conducted to explore the uncertainty of representing the surface connectivity of Arley Close and Winsley Close within a design rainfall-runoff model, the UK Variable Runoff Model. This model is chosen as a result of its simplicity (it can be easily executed in MS Excel), sensitivity to imperviousness and connectivity and its prevalence as a method within surface water drainage design in the UK (Woods-Ballard et al., 2015).

Connectivity is typically considered as a binary process in current urban hydrology theory, i.e. an impervious surface is either connected or disconnected to a surface water drainage system (Kong et al., 2017). Section 3.4 expands this simplistic understanding of connectivity to include connection efficiency and defines surfaces with direct and indirect connections. Directly and indirectly connected surfaces are likely to contribute different amounts of runoff to the surface water drainage system given that joins and gaps between surfaces lead to losses from storage, evaporation and infiltration (Chapter 2, Section 2.5). The connectivity of surfaces is currently represented within the UK Variable Runoff Model as a proportion of the total imperviousness of a catchment:

$$Connected\ Surfaces = IF * PIMP \qquad \text{Equation 3.20}$$

Where IF = effective impervious area factor, and PIMP = the percentage imperviousness of a catchment.

A sensitivity analysis of the New UK Runoff Model is used to assess the sensitivity of modelled PR_{URB} values to values of IF and PIMP. The PIMP value is then set to the MEDIUM value defined in Section 3.3 and a number of methods of defining connectivity (IF) are tested to determine the accuracy of PR_{URB} predictions. The sensitivity analysis methodology is as follows:

(i) The model parameter values of NAPI and PF are set to 17 and 200 respectively at the start of each event.

(ii) Values of PIMP are increased between the LOW, MEDIUM and HIGH methods for each site, defined in Section 3.3.

(iii) The values of IF are increased from 0 (no connectivity) to 1 (full connectivity) by 0.1 and PR_{URB} calculated.

(iv) A three dimensional scatter plot is used to visualise the sensitivity of PR_{URB} to values of PIMP and IF.

(v) Values of PIMP are then set to the MEDIUM value and values of IF are then derived using the following methods:

Method 1: Standard values of IF are used from guidance documents based on surface condition: 0.75 for "good" condition surfaces, 0.6 Fair and 0.45 Poor, Woods-Ballard et al. (2007).

Method 2: IF is defined as the proportion of PIMP with a direct connection to the surface water drainage system (i.e. a surface with at least one hydraulic connection to the surface water drainage system, defined in Section 3.4).

Method 3: IF values are adjusted until the PR_{URB} output from the model matches the mean PR value from the observed events.

The values of PR_{URB} derived from the different values of IF defined under Methods 1 and 2 are compared to those derived under Method 3, and the resulting runoff volumes calculated through Equation 3.10.

The sensitivity of hydrological models to the uncertainty of understanding and defining surface cover, connectivity and rainfall-runoff processes within urban residential catchments is therefore quantified. This allows a discussion of how residential land covers can be better represented within commonly applied rainfall-runoff models. The succeeding chapters report the results of applying the methods described here.

Chapter 4

DEFINING SOIL PROPERTIES, SURFACE COVER AND CONNECTIVITY WITHIN ARLEY CLOSE AND WINSLEY CLOSE

This chapter compares the soil properties, surface cover and surface connectivity of Arley Close and Winsley Close, reporting the results of new methodologies to compare the overall connection efficiency and those surfaces with direct and indirect connections to the surface water drainage system.

4.1 INTRODUCTION

Hydrologists need a consistent and hydrologically relevant methodology with which to define urban surface cover and surface connectivity, so that different types of urban development can be represented within hydrological models and surface water management planning. Quantifying and understanding the different ways in which urban surfaces connect to the surface water drainage system and defining different types of urban surface cover that exhibit a range of hydrological behaviours with detail at small-scales remains a scientific and engineering challenge (Yao et al., 2016a). There is a lack of studies examining the physical features and processes within urban areas that control the connection of the urban surface to the surface water drainage system, increasing the uncertainty of representing urban areas within hydrological models. For example, Kjeldsen (2009) relies on large scale estimates of connectivity (70% of surfaces are connected) to represent urban areas within a flood prediction model, whilst others demonstrate the complex and non-linear relationship between imperviousness and connectivity (Lee and Heaney, 2003).

The connectivity of surfaces is often estimated with a simple definition that relates connectivity to the presence or absence of a surface water drainage system (Sahoo and Sreeja, 2016), or via empirically derived equations relating imperviousness to connectivity (Sutherland, 2000). However the actual connectivity of surfaces is dependent on the presence of hydraulic entry points (such as road gullies) whose spatial distribution varies across the urban landscape (Prichard et al., 2009); in addition surface features such as kerbing affect the generation of runoff on urban surfaces (Ozdemir et al., 2013). It is likely that the efficiency by which runoff can enter the surface water drainage system is sensitive to the types of surface being drained, their condition and the physical arrangements of surfaces in relation to drainage connection points (Redfern et al., 2016). These are small-scale features and processes (for example road gullies are smaller than 0.5 m^2) that are difficult to detect in aerial photographs or satellite remote sensing and thus require detailed study to record their occurrence (Wiles and Sharp, 2008; Keeley, 2007). Whilst such intensive detailed study may be impractical across large catchment scales, the understanding gained from small-scale studies could be applied to estimation methods of surface connectivity at larger scales. In addition, in the United Kingdom at least, there are a number of legislative and policy drivers that may increase the availability and resolution of data on the locations and types of surface drainage features (e.g. Section 21 of the Flood and Water Management Act 2010). With greater understanding of the connection process, hydrologists and engineers will be better placed to quantify hydrological impacts in urbanised catchments and design the urban environment in a manner that reduces such impacts, warranting further study of the surface cover and connectivity of urban surfaces within Arley Close and Winsley Close.

This chapter reports the results of applying methods described in Sections 3.2-3.4, which define surface soil characteristics, surface cover and connectivity of surfaces within Arley Close and Winsley Close, building on readily available data with detailed site visits. The chapter examines how representative large-scale soil maps are of small-scale soil properties within urban areas. In addition an assessment of how the number and type of drainage connection points impacts overall connectivity of the urban surface is made by applying a novel methodology (Section 3.4.2).

Ordnance Survey Master Map data (OSMM), Light Detection and Ranging data (LiDAR) and aerial photography are combined in a GIS environment and site based Individual Parcel Assessments (IPA) are used to define surface cover and connectivity within Arley Close and Winsley Close (Section 3.3 – 3.4). The chapter culminates in the definition of not just the surface cover and connectivity, but explores the efficiency of connections, comparing surfaces with direct and indirect connections to the surface water drainage system.

4.2 RESULTS

The methods used to define and characterise surface soils, surface cover, drainage layout and surface connectivity are defined in Sections 3.2-3.4. Here the results are reported and comparisons are made between Arley Close and Winsley Close.

4.2.1 Soil properties

Initial investigations into the soil properties of Arley Close and Winsley Close focus on examining hydrologically relevant soil maps for each area (Section 3.2). Both sites are defined as soil type 4 under the Winter Rainfall Acceptance Potential (WRAP) classification of soils. This indicates a low infiltration potential and thus soils that have restricted drainage properties and high runoff. However, the WRAP classification map is only available at a maximum scale of 1:625000 and is thus a coarse dataset with which to assess soils at the small plot scale (Section 3.2). The Hydrology of Soil Types (HOST) map is also examined at each site. Arley Close is defined as HOST type 25, whilst Winsley Close is close to the boundary between two 1km^2 grid squares for two different classes, 2 and 25 (Figure 4.1). It is therefore uncertain as to which category Winsley Close should be defined into, demonstrating the difficulty of using large-scale mapping products to define the soil types of small-scale urban development areas. HOST types 2 and 25 have different hydrological properties (Table 4.1) and thus it is important to examine in greater detail the soils present within Arley Close and Winsley Close.

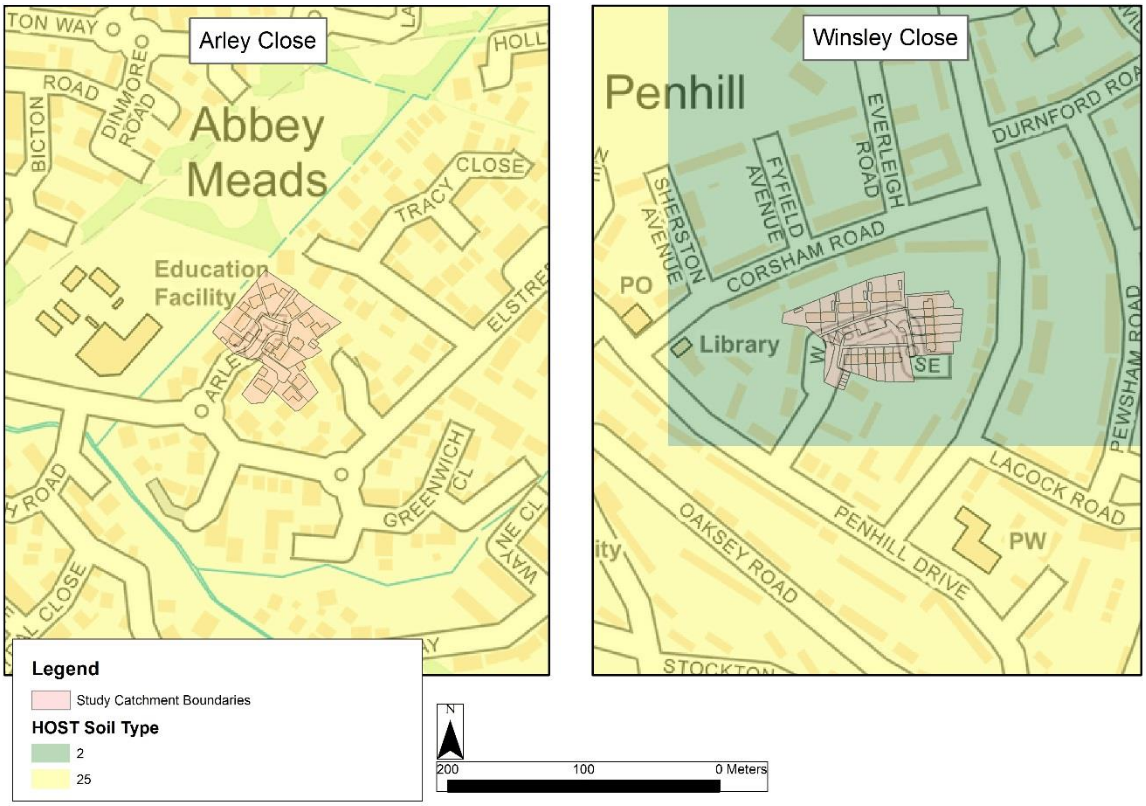

Figure 4.1: Dominant HOST soil classifications for Arley Close and Winsley Close. Arley Close is within HOST class 25, Winsley Close is close to the boundary between HOST class 2 and 25. Contains OS data © Crown copyright and database right 2017

Table 4.1: Hydrological descriptions of HOST classes 2 and 25 (Boorman et al., 1995).

HOST Class	Description
HOST 2	Free draining permeable soils on 'brashy' or dolomitic limestone substrates with high permeability and moderate storage capacity.
HOST 25	Slowly permeable, seasonally waterlogged soils over impermeable clay substrates with no storage capacity.

Soil samples collected in Arley Close and Winsley Close are processed through the soil laboratory of CEH to estimate organic content, bulk density and mineral grain size distribution (Section 3.2.1 - 3.2.2). The loss on ignition organic content of soils in Arley Close is less than half that evidenced at Winsley Close (Table 4.2) whilst the mean bulk density of soils is similar between sites. An analysis of the variation in soil characteristics amongst the samples collected at both sites is not possible given the limitations of deriving an aggregated soil sample for each site (see Section 3.2.1).

Table 4.2: Average % organic content and bulk density for soil samples taken from Arley Close and Winsley Close

	Arley Close	**Winsley Close**
% Organic matter (mean)	7	19
Mean Bulk Density (g/cm^3)	0.86	0.91

Figure 4.2 plots the percentage of sand, silt and clay for all the surface soil samples taken at Arley Close and Winsley Close against the UK Soil Classification system described by Natural-England (2011). The surface soils for each site are similar, predominantly grouped in the Light Silts and Light Loams category.

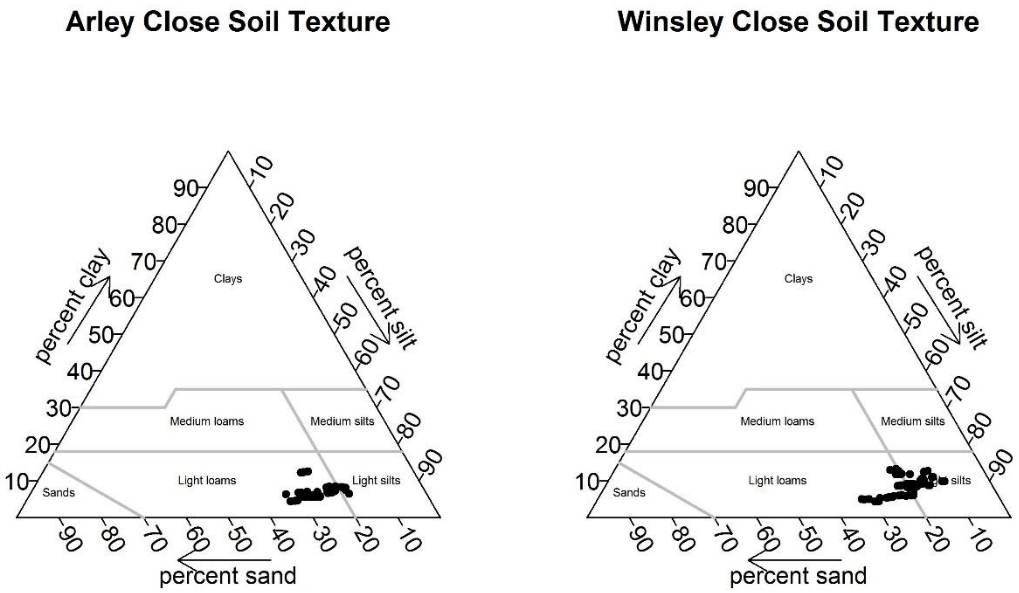

Figure 4.2: Soil grain size analysis for surface soil samples taken from Arley Close and Winsley Close (Drawn using the Plotrix R package, (Lemon, 2006)).

This demonstrates that even though the HOST classification system suggests differences in soil properties at the larger 1km^2 grid scale surrounding each site, the actual surface soil properties that may influence short term event based rainfall-runoff behaviour of both sites are similar. It is unclear whether this similarity in soil characteristics is derived from historic soil generating processes, or from the importation of similar soils into the study sites during construction. Examining soils from deeper within the soil column may have allowed for a greater understanding of soil properties within the study sites, however this is not possible here given the limitations of working upon private land.

The increased organic content of the soils collected in Winsley Close (Table 4.2) is likely a result of the mature tree cover within the vegetated surfaces where soil samples are taken, in comparison to the roadside verge areas with predominantly grass vegetation in Arley Close. In addition, surface soils in Winsley Close have been in-situ since the 1950s and thus have had a longer time to accrue organic matter without disturbance than Arley Close, where the surface soils were established during construction in the 1990s. Given the similarity of surface soil characteristics, it is unlikely that there is a significant difference in the contribution of soils to the rainfall-runoff behaviour of each site.

4.3. SURFACE COVER: OSMM AND IPAS

Site based, Individual Parcel Assessments (IPAS) build upon data contained within the Ordnance Survey Master Map (OSMM) topography layer to define surface cover within the domestic and roadside areas in each study sub-catchment (Section 3.3). Figure 4.3 illustrates the extra detail that is collected via the IPAs in roadside and domestic areas. For both sites the majority of surface cover is defined as General Surface within the OSMM (around 65%, Figure 4.4) and as a consequence IPAs are required to effectively characterise the two catchment areas since OSMM does not define surface cover within domestic or road side areas accurately.

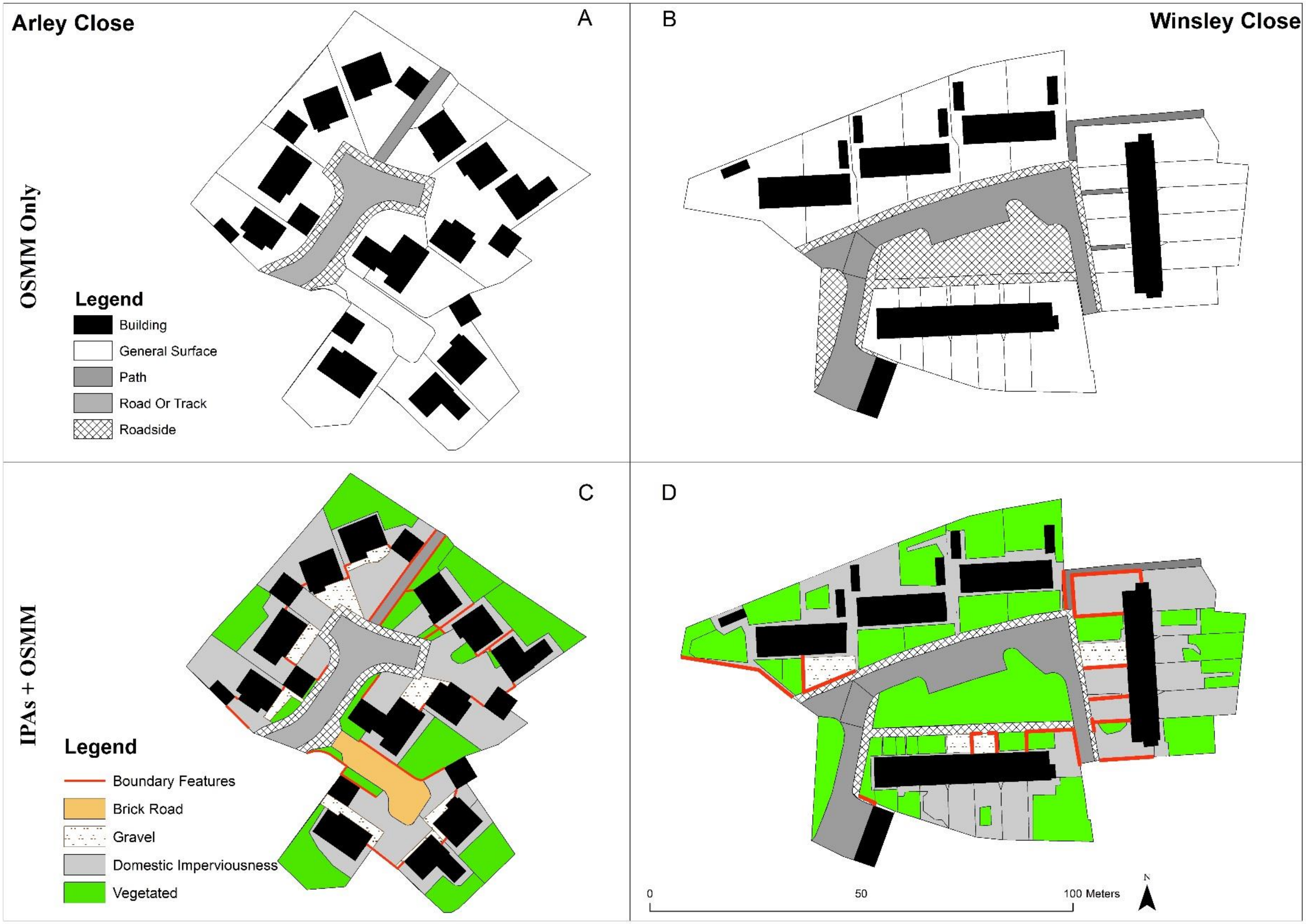

Figure 4.3: Catchment maps with (A,B) OSMM data and (C,D) more detailed surface definitions following IPAs

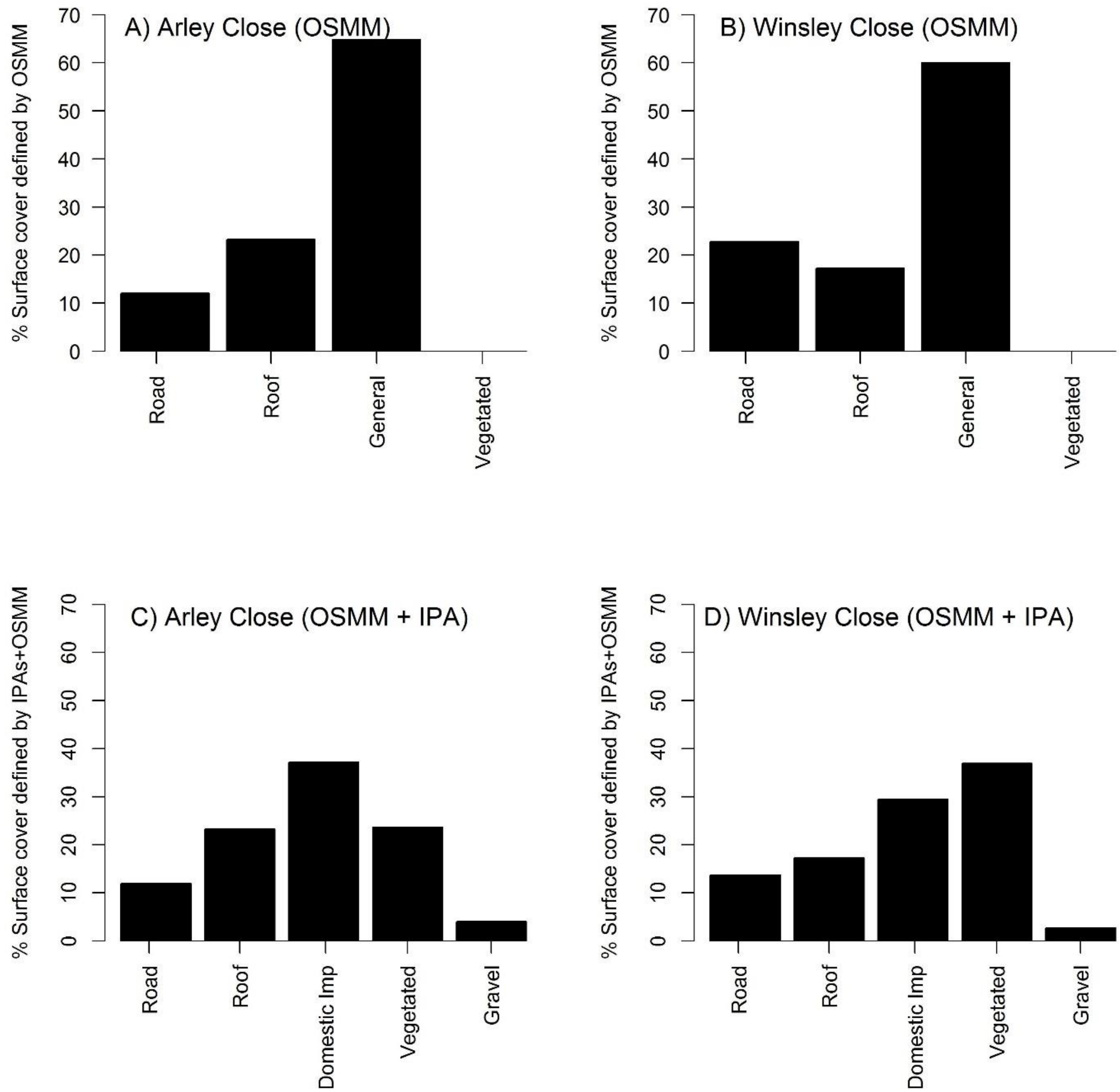

Figure 4.4: Surface cover comparisons between Arley Close and Winsley Close. Plots A and B are defined from OSMM data alone whilst plots C and D contain data from IPAs. Note that in figures C and D, Domestic Impervious includes both impervious and semi-impervious surface definitions.

The OSMM data identifies the locations of buildings accurately in both areas and whilst roads are identified accurately within Winsley Close, in Arley Close an area of road is incorrectly identified as general surface. All road surfacing is tarmac within Winsley

Close, whilst Arley Close contains 183 m^2 (approximately 38% of total road surfacing) of brick paved surfacing, with cement mortar fill between brick elements. No serious defects in surface condition are recorded in either area, although Winsley Close does contain some areas of minor cracking to road and pavement surfaces, likely a function of the increased age of surfaces within Winsley Close. However, surface defects only cover a small proportion of the catchment and are small defects.

Figure 4.4 (C,D) shows that when taken as a whole the classification of surface covers within the two study areas are fairly similar in terms of the proportion of each catchment that is roofed, road related surfacing, semi-impervious or vegetated. By analysing surface locations (e.g. private vs public land, Section 3.3.2) in more detail it is possible to determine how the two catchment areas differ (Figure 4.5). Arley Close contains a greater proportion of both private and roofed areas, whilst Winsley Close contains a greater proportion of public areas. The public areas within both study sites contain a majority of road related surfacing; Arley Close contains 98% whilst Winsley Close contains 65%. As a consequence 35% of public land within Winsley Close is vegetated, whilst only 2% of public land in Arley Close is vegetated. Both study areas have similar splits in the private areas between front and rear gardens in residential parcels (Arley Close 62% rear gardens; Winsley Close 64% rear gardens).

In Winsley Close front gardens are 45% vegetated surfaces whilst in Arley Close only 13% of front gardens are vegetated. Front gardens in Arley Close are of predominantly impervious surfacing (65%) with 22% of surfacing made of semi-impervious cover (gravels). In Winsley Close 41% of front gardens are impervious, leaving 14% of surfacing semi-impervious. Both sites have a similar split in terms of surface cover within rear gardens with Arley Close containing 54% vegetated, 46% semi impervious and Winsley Close 41% vegetated, 59% semi impervious cover. In summary the greatest differences between Arley Close and Winsley Close are in the surface covers within public areas and front gardens.

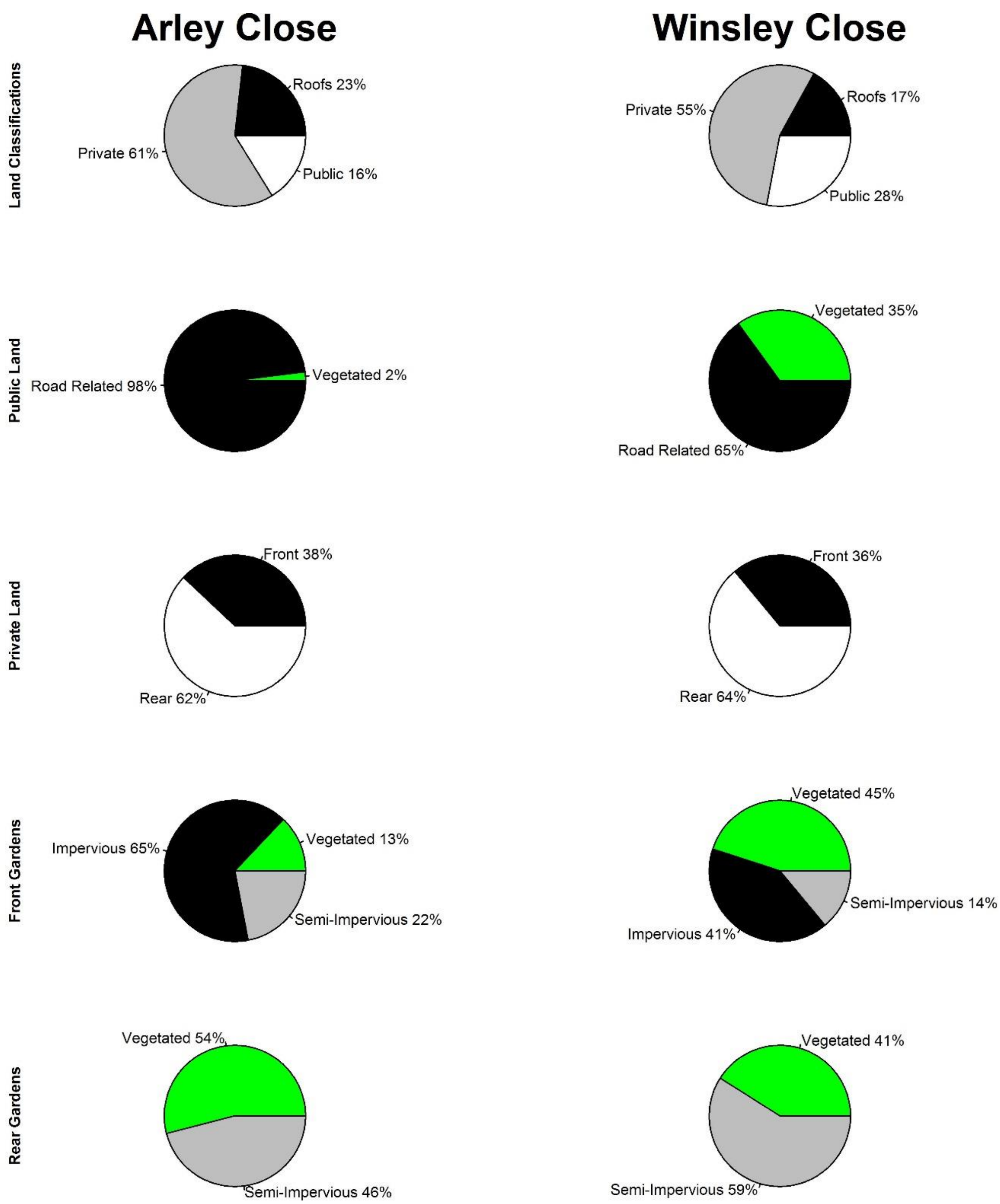

Figure 4.5:Land surface classifications for both sites. Note rear garden non-vegetated surfaces are classified as semi-impervious (there is uncertainty as to whether these surfaces are impervious or semi-impervious, Section 3.3.1).

There is uncertainty in both Arley Close and Winsley Close as to whether rear garden non-vegetated surfaces are impervious or semi-impervious cover (see Section 3.3.1) and therefore the total impervious area in each study area is calculated under the three methodological assumptions described in Section 3.3.1:

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

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

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

The results of this are presented in Table 4.3 for Arley Close and Table 4.4 for Winsley Close.

Table 4.3: Calculation of total impervious area and PIMP for Arley Close under three assumptions regarding the imperviousness of non-vegetated rear garden surfaces (Section 3.3.1)

Method i (HIGH)		**Method ii (LOW)**		**Method iii (MEDIUM)**	
Arley Close	**Area (m^2)**	**Arley Close**	**Area (m^2)**	**Arley Close**	**Area (m^2)**
Roofs	1156	Roofs	1156	Roofs	1156
Road related	782	Road related	782	Road Related	782
Domestic Impervious (front garden)	753	Domestic Impervious (front garden)	753	Domestic Impervious (front garden)	753
Domestic Impervious (rear garden)	862			Domestic Impervious (rear garden)	431
Sum, (PIMP)	3553, (71%)	Sum, (PIMP)	2691, (54%)	Sum, (PIMP)	3122, (63%)

Table 4.4: Calculation of total impervious area and PIMP for Winsley Close under three assumptions regarding the imperviousness of rear garden non vegetated surfaces (see Section 3.3.1).

Method i (HIGH)		**Method ii (LOW)**		**Method iii (MEDIUM)**	
Winsley Close	**Area (m^2)**	**Winsley Close**	**Area (m^2)**	**Winsley Close**	**Area (m^2)**
Roofs	1150	Roofs	1150	Roofs	1150
Road related	1218	Road related	1218	Road related	1218
Domestic Impervious (front garden)	540	Domestic Impervious (front garden)	540	Domestic Impervious (front garden)	540
Domestic Impervious (rear garden)	1389			Domestic Impervious (rear garden)	695
Sum, (PIMP)	4297, (64%)	Sum, (PIMP)	2908, (43%)	Sum, (PIMP)	3603, (54%)

Arley Close contains a larger PIMP in comparison to Winsley Close for all three methodological assumptions tested. However estimates of PIMP are more variable at Winsley Close because of the increased surface cover within Winsley Close that is digitised as semi-impervious within rear gardens.

4.4: SURFACE CONNECTIVITY: DRAINAGE CONNECTION POINTS

Within Arley Close and Winsley Close the position and type of hydraulic connections between urban surfaces and the surface water drainage system is determined through site based Individual Parcel Assessments (Section 3.4). The number of road drainage gullies, roof downpipes and linear drainage features that are recorded in each study area are detailed in Table 4.5. Arley Close has nearly three times the number of drainage gullies in comparison to Winsley Close (11 vs 4) and the gullies are located on both private and public surfaces. In comparison, Winsley Close only has drainage gullies upon public surfaces, meaning that there are no gullies draining private driveways or paths.

Table 4.5: Number of drainage gullies, roof downpipes and linear drains in Arley Close and Winsley Close.

Gullies	**Arley Close**	**Winsley Close**
Number	11	4
No. Private	6	0
No. Public	5	4

Roof Downpipes	**Arley Close**	**Winsley Close**
Number	43	25
m^2/Downpipe(Roof)	27	46

Linear Drain	**Arley Close**	**Winsley Close**
No. of linear drains	2	1
Total Length	12	7

In Winsley Close, the gullies are located exclusively at the road side, along the lines of kerbing that surround road surfaces (Figure 4.6). Whilst this pattern is replicated in Arley Close for those gullies within the road network (public surfaces), in private areas the gullies are in a number of locations, where instead of kerbing, driveways for example exhibit a camber that shapes surfaces towards drainage gullies (Figure 4.6). Roofs in Arley Close have a greater number of roof downpipes connecting roof drainage into the surface water drainage system (43) in comparison to Winsley Close (25) - Table 4.5. Despite the smaller overall catchment area of Arley Close (Section 3.5.2) there are a greater number of drainage connection points on roofs, public and private land.

4.4.1 Land surface connectivity: characterising drainage areas

LiDAR data in the form of a Digital Terrain Model (DTM) is analysed to produce an estimate of the flow direction and flow accumulation on each surface within Arley Close and Winsley Close (Section 3.4.1). The output of the LiDAR DTM analysis (Figure 4.6), illustrates how the topographic surface of each study area influences runoff generation. The flow accumulation ArcGIS output is displayed on top of the OSMM and IPA data with a blue colour ramp. The flow accumulation raster dataset shows the number of cells of the DTM that flows into each cell (the darker blue a raster cell is coloured, the greater the number of cells that flows into it). It is possible to trace how runoff will flow across the urban surface by tracing the colour ramp across the accumulation raster from light to dark blue (Figure 4.6). The areas of darkest blue line up with the locations of drainage gullies, allowing an assessment of which surfaces drain into which gully. Drainage areas are digitised for each gully (Figure 4.8) and drainage lengths and drainage areas for each gully calculated and compared (Figure 4.9). The location of the generation pathways as predicted by the processed LiDAR data are verified by site observation (Figure 4.7). The puddling and flow accumulation in the photograph of Figure 4.7 is well replicated in the ArcGIS output, demonstrating the toolset's skill in estimating surface flow direction and accumulation on the urban surface.

Flow accumulation in rear gardens is ignored as this is unlikely to be accurate given the presence of non-impervious surface types and features that would restrict the generation of runoff such as garden walls, fences and other boundary features.

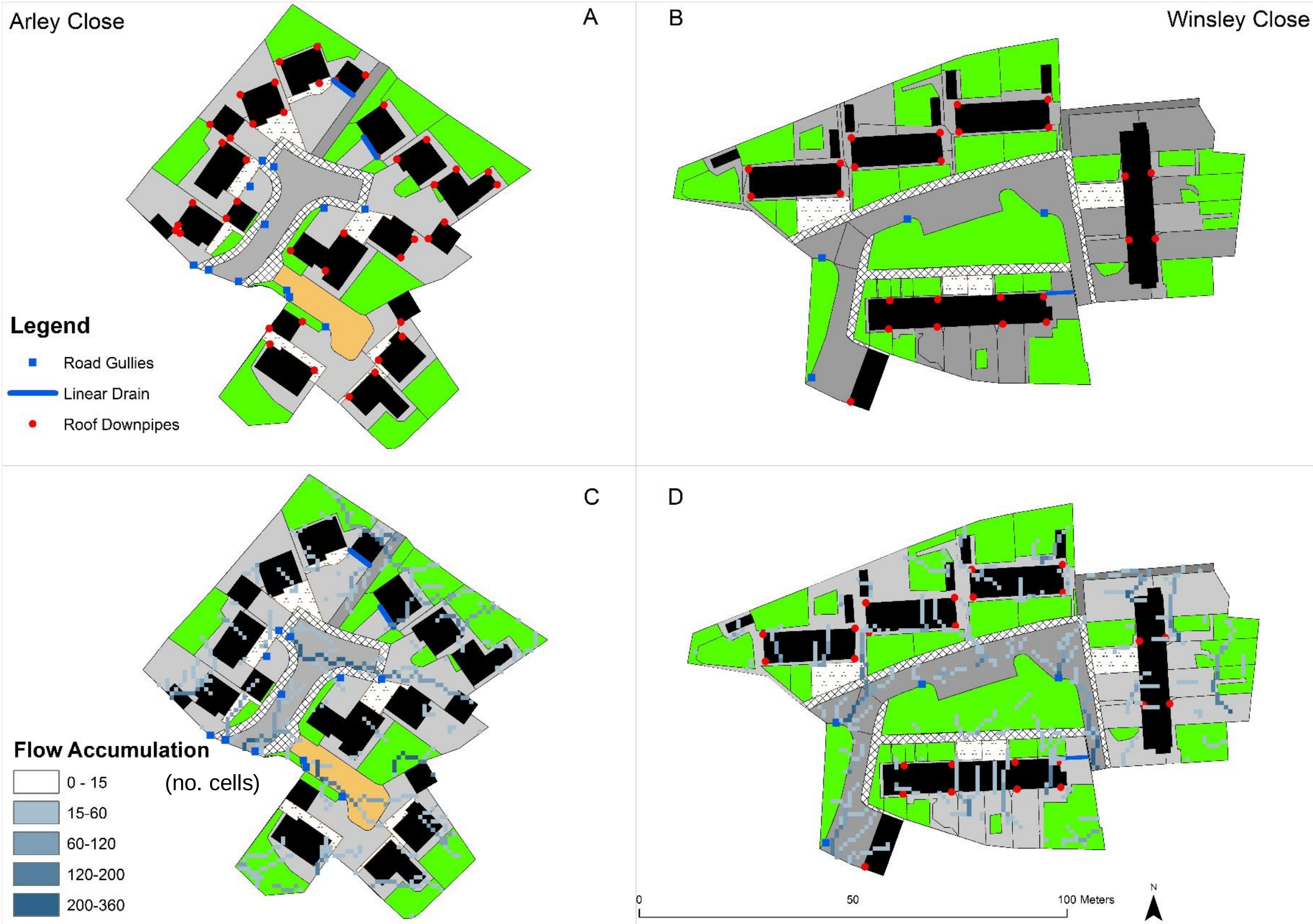

Figure 4.6: (A,B) Drainage gullies, roof downpipe locations and (C,D) flow accumulation pathways for both study sites.

Figure 4.7: Photographic verification (left) of flow accumulation tool output (right) in Arley Close. Camera symbol in (right) shows the location and direction in which photograph is taken. Contains OS data © Crown copyright and database right 2017

Figure 4.8: Gully drainage areas digitised within Arley Close and Winsley Close. Note that the polygon colours are for illustrative purposes only to differentiate between the different gully areas.

Drainage areas and the maximum drainage distances for the gullies within Arley Close and Winsley Close are summarised and compared in Figure 4.9. Winsley Close contains five drainage areas ranging in size from 66m^2 to 377m^2 (mean =218.75m^2, median = 205m^2) , whereas Arley Close has a larger number of drainage areas (13) with eight drainage areas under 100m^2 (range = 27-362m^2, mean 113.85m^2 , median = 60m^2). The maximum drainage distances within Arley Close are greatly reduced (range = 7-32m, mean= 15.7m) in comparison to Winsley Close (range = 9-36m, mean = 27m) (Figure 4.10).

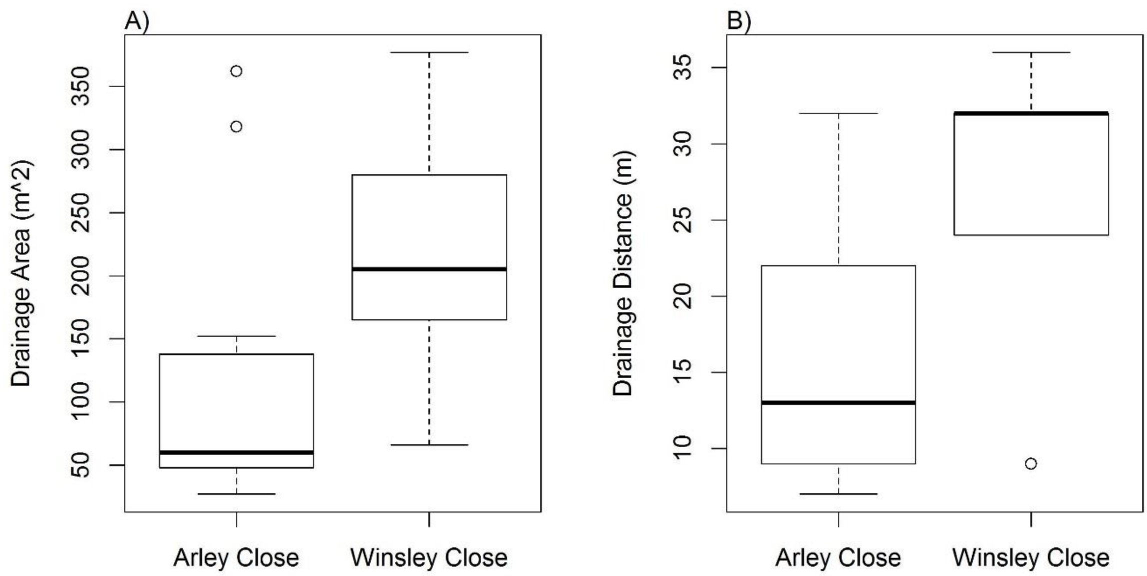

Figure 4.9: Gully drainage areas and maximum drainage distance for gullies in the two study catchments. A: Gully drainage areas, B: Gully area drainage distances.

The combination of an increased number of gullies, draining smaller surface areas with reduced drainage distances creates a greater connection efficiency in Arley Close than Winsley Close, as the analysis of connected area versus distance (described in Section 3.4.2) shows (Figure 4.10). The two curves representing the areas of surfaces connected versus the distance from a gully are similar for both sites at distances above ~10m (Figure 4.10 A). However, Arley Close has a much larger area in the proximity of drainage gullies, under 10m distance.

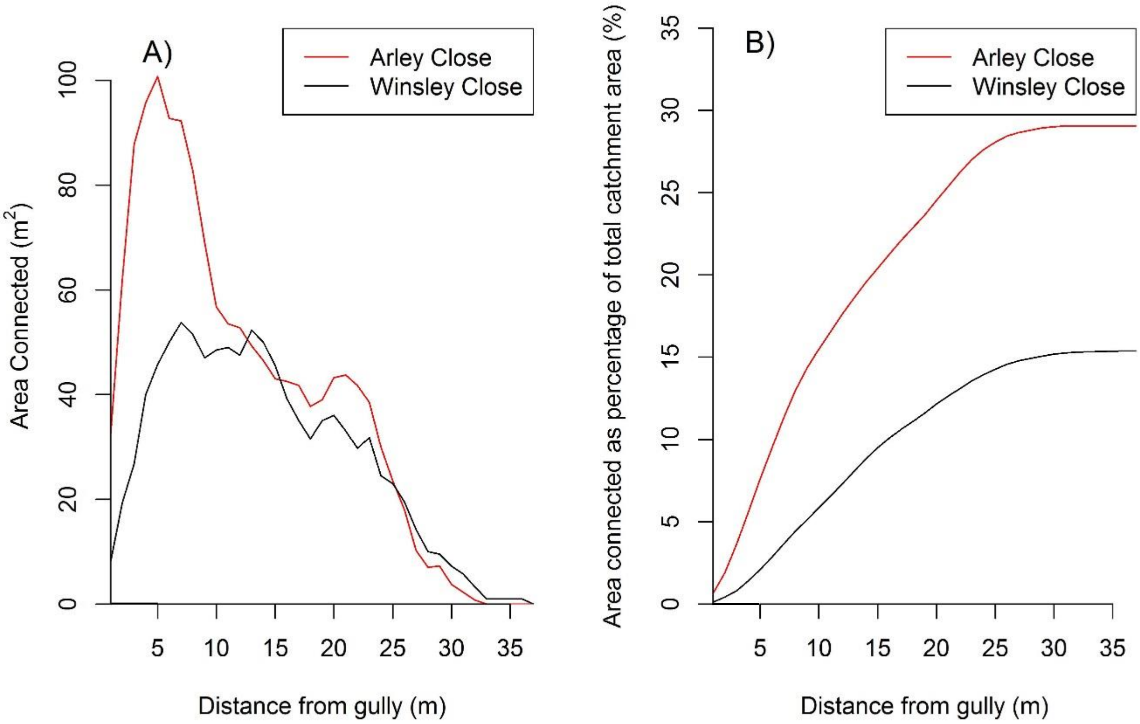

Figure 4.10: A) The area of connected impervious surface plotted against the distance from a drainage gulley. B) The area connected expressed as a percentage of total catchment area plotted against distance from a gully.

When plotted as a percentage of the total catchment area (Figure 4.10B), the difference between the two study areas is notable. A greater proportion of Arley Close is connected impervious land surface with highly efficient connections in comparison to Winsley Close. Surfaces within 10m of a gully account for nearly 15% of the total catchment area in Arley Close, whereas in Winsley Close only 5% of the catchment area is impervious land surface within 10m of a drainage gully. Only 15% of the total catchment area in Winsley Close is connected impervious land surfacing, whilst Arley Close has nearly double the proportion of total catchment area as connected impervious land surfacing (i.e. made up of roads and domestic impervious surfaces to the front of properties).

4.4.2 Directly connected and indirectly connected surfaces

Where surfaces are joined together, over time, infiltration can occur as wearing and weathering processes weaken the join between surfaces (Section 2.5). This is likely to affect the generation and transfer of runoff from surfaces to the surface water drainage system, as runoff is intercepted and stored or infiltrated into joins. Therefore, those surfaces that connect directly with a surface water drainage system (via a hydraulic entry point) are likely to transfer runoff with greater efficiency than those whose runoff must flow across other surfaces, and surface joins to connect with a surface water drainage system. Therefore, each surface in Arley Close and Winsley Close is classified into one of three connectivity categories (described in Section 3.4.3):

(i) Directly Connected Impervious Surfaces: Those surfaces that have a direct connection to a hydraulic entry point to the surface water drainage system (e.g. a road with at least one drainage gully).

(ii) Indirectly Connected Impervious Surface: Surfaces that do not have a direct connection to the surface water drainage system and instead contribute runoff to the surface water drainage system by draining onto a Directly Connected Impervious Surface.

(iii) Non Connected Impervious Surface: Surfaces that do not have a connection (either direct or indirect) to the surface water drainage system, instead draining to nearby permeable surfaces

It is possible to examine what type of surfaces make up the connected impervious surfaces and define those surfaces with direct connections and those with indirect connections. Table 4.6 contains the areas of surface for each catchment with direct and indirect connections to the surface water drainage system. Despite Winsley Close having a larger overall catchment area, Arley Close has a directly connected impervious surface that is more than $500m^2$ larger in area whilst Winsley Close contains a larger area of indirectly connected surfacing. Roofs make up the largest component of directly connected impervious surfacing within both study areas, whilst driveways are the largest land surface with direct connections within Arley Close and roads in Winsley Close. Winsley Close does not contain any directly connected driveways, whilst neither site contains directly connected footpaths.

Table 4.6: Surface types for directly connected and indirectly connected surfacing for Arley Close and Winsley Close.

Arley Close

Surface/Connection Type	Driveway (m^2)	Road (m^2)	Roofs (m^2)	Footpath (m^2)	Total (m^2)
Direct	696	480	1156	0	2332
Indirect	47	228	0	0	235

Winsley Close

Surface/Connection Type	Driveway (m^2)	Road (m^2)	Roofs (m^2)	Footpath (m^2)	Total (m^2)
Direct	66	817	992	0	1875
Indirect	203	327	255	117	902

4.3 DISCUSSION

Arley Close and Winsley Close are both small residential sub-catchments of the wider north Swindon peri-urban area. The cumulative effect of small differences in the design of each domestic land parcel (i.e. whether a garden is vegetated or a tarmac driveway) adds up to make large differences in the surface cover at the larger sub-catchment scale. In particular, differences in the design of residential development in terms of public areas, gardens and drainage system layout have all contributed to differences in the overall surface cover and the efficiency of connections within the study areas. This finding is similar to that reported by Perry and Nawaz (2008) who find that increasing impervious cover in an urban area of the UK is partially driven by changes to garden surface cover (i.e. the paving of gardens into driveways). However unlike Perry and Nawaz (2008) the differences in surface cover reported here are a result of the original design of each catchment and not through incremental changes in urban surface cover over time.

When analysed at the whole study sub-catchment scale, the proportion of urban surface under vegetated cover is greatest in Winsley Close, whilst Arley Close has a greater proportion of surface area under roof cover (Figure 4.4). Estimates of percentage impervious cover (PIMP) of each site are highly sensitive to the assumptions used to define the surface types within the rear gardens of properties. Whilst some visual verification of semi-impervious surface types is possible in certain areas (see Section 3.3.1) this is not universal and so assuming that all non-vegetated surfaces to the rear of properties is semi-impervious would underestimate the total imperviousness of each catchment. The variation in estimated imperviousness is greatest at Winsley Close where there is a larger area of rear garden non-vegetated surfaces. However, Arley Close has a greater impervious cover ranging from 54% to 71% vs 43% to 64% at Winsley Close. This demonstrates the importance and difficulties of defining land cover within domestic parcels with a greater detail than just a simple binary impervious-pervious classification of surfaces based on the interpretation of aerial photography or remote sensing, suggesting that greater research is required on appropriate methods for defining surface types within residential urban areas. The high PIMP values recorded in Arley Close and Winsley Close place both sites within a “heavily urbanised” category of land use as defined by Goldshleger et al. (2009), indicating that the urbanisation process is likely to have had a dramatic impact on the rainfall runoff behaviour of the catchments in comparison to non-urbanised catchments with similar soil and slope characteristics.

Despite its smaller total catchment size, Arley Close has a greater number of hydraulic entry points connecting the urban surface to the surface water drainage system (Table 4.5). The size of areas being drained are smaller and mean maximum drainage distances to each gully are reduced at Arley Close in comparison to Winsley Close. Surface connection efficiency is greatest in Arley Close, with a larger area of connected impervious surface within close proximity (less than 10m) to a hydraulic entry point compared to Winsley Close. In Arley Close, connected surfaces are not only in the public domain (roads) but a large proportion are also contained within private driveway areas. As a result Arley Close contains a larger area of impervious surfacing with direct connections to the surface water drainage system in comparison to Winsley Close, demonstrating that the connectivity of the urban land surface is highly sensitive to the number and location of hydraulic entry points upon urban surfaces. In both sites roofs constitute the largest component of directly connected impervious surfacing (Table 4.6) which contradicts results of similar studies like Lee and Heaney (2003) who report that the largest component of connected surfaces within residential areas in Colorado, USA are transport related (e.g. roads). This demonstrates that there should be careful consideration of connectivity within urban areas, and it is perhaps not appropriate to apply the findings of one study in one area or country to other areas without detailed site verification, as estimates of connectivity could be inaccurate. This variability in surface types and connectivity could help to explain why empirical equations linking imperviousness to connectivity are shown to perform poorly when Lee and Heaney (2003) apply literature derived relationships to areas outside of their original derivation.

A greater research effort is required to not only understand the connection process within urban areas, but crucially to identify and compile useful datasets so that connectivity can be assessed at larger scales. The findings of this study suggest that such data should take the form of the presence and location of hydraulic entry points to the surface water drainage system coupled with an assessment of surface topography (with the analysis of LiDAR data). In the United Kingdom at least, LiDAR data is largely available for urban areas (see Section 3.4.1) whereas data on the locations and types of hydraulic entries to the surface water drainage system are sporadic. Whilst the manual approach to delineating connected surfaces taken in this study may be impractical over large urban areas, there may be scope to advance automated methods that could be applied to larger scales which could be verified by targeted site inspections, e.g. Han and Burian (2009). The technique used here to define connection efficiency could be applied to compare the differences between a number of urban areas to fully understand how surface connectivity varies across large urban areas. Detailed site visits are required to accurately define the surface cover within the study areas as the Ordnance Survey Master Map data lacks surface definitions in domestic areas and road side areas. Additional data may be required to complement the OSMM data for use in hydrological modelling and surface water management planning within urban areas.

The next step of the thesis is to quantify how the rainfall-runoff behaviour of the two study areas differs; in particular how the differences in surface cover and surface connectivity translate into differences in peak flow rate and percentage runoff of rainfall-runoff events. Sensitivity of rainfall-runoff behaviour to variability in rainfall characteristics and antecedent conditions is also compared.

Chapter 5

COMPARING THE RAINFALL-RUNOFF BEHAVIOUR OF ARLEY CLOSE AND WINSLEY CLOSE

This chapter compares the rainfall-runoff behaviour of Arley Close and Winsley Close. Rainfall and runoff data are processed to determine the peak flow rate and percentage runoff values of 34 rainfall-runoff events. Statistical analysis is used to quantify the differences in rainfall-runoff behaviour of the two catchments and to compare the sensitivity of hydrological behaviour to antecedent conditions and rainfall characteristics.

5.1 INTRODUCTION

Understanding the urban rainfall-runoff process is a prerequisite for a number of scientific and practical applications in surface water management, hydrological modelling and urban design. Hydrological scientists require fundamental understanding of how precipitation is converted into runoff within the urban landscape, so that the impacts of urbanisation can be estimated in catchments lacking monitored data (Beven, 2011), new urban development can be assessed (Perry and Nawaz, 2008) and mitigation measures designed and installed into areas of existing and new urban development (Charlesworth et al., 2003).

Hydrological models require physically plausible linkages between different types of urban surface, development patterns and hydrological processes to provide confidence in model outputs (Salvadore et al., 2015). In general, an increased proportion of impervious surfacing within a catchment increases the proportion of rainfall that is converted into runoff (Packman, 1980a; Hollis, 1975). However, the relationship between imperviousness and runoff generation is complex and non-linear (Goldshleger et al., 2009), with variations in materials, condition and connectivity to the surface water drainage system all influencing rainfall-runoff performance at the small surface scale (Redfern et al., 2016). Consequently, the rainfall-runoff response of urban catchments is highly variable, with the proportion of rainfall converted into runoff, peak flow rate and hydrograph shape varying, not just between different catchments, but also between rainfall events within the same catchment (Kidd and Lowing, 1979; Maksimovic and Radojkovíc, 1986). Sources of hydrological variability can include: (i) contributions from soil drainage (related to soil moisture) (Berthier et al., 2004), (ii) variable contributions of runoff from permeable areas (Boyd et al., 1993), and (iii) variable losses of runoff from seemingly impervious surfaces (Hollis and Ovenden, 1988a). The rainfall-runoff properties of urban catchments at the development plot scale are therefore likely to be influenced by physical properties such as the proportion of different types of surfaces within a catchment, construction materials, surface age and surface connectivity.

By studying the rainfall-runoff behaviours of Arley Close and Winsley Close this thesis provides the opportunity to understand how differences in residential urban design at small-scales build to the larger hydrological response at the residential development scale. Chapter 4 establishes that the two study areas are similar in terms of land use (residential) and in the percentage impervious cover (Medium estimates (Table 4.3, 4.4.) Arley Close, 63% versus Winsley Close, 54%). However, the two sites differ in the design of catchment surfaces (private driveways in Arley Close, public open spaces in Winsley Close) and in the efficiency with which the surface water drainage system connects to the urban surface. The aim of this chapter is to compare the rainfall-runoff behaviours of the two study catchments through the analysis of monitored rainfall-runoff data, thus quantifying the impact on hydrological behaviour of differences in urban design between the two study sites. This is achieved by answering two research questions:

(i) Have the differences in urban design of Arley Close and Winsley Close led to differences in rainfall-runoff behaviour?

(ii) Is the rainfall-runoff behaviour of the two study sites sensitive to the same rainfall characteristics and antecedent conditions?

The results of these analyses are discussed in the context of surface water management planning, residential design and hydrological modelling.

5.2 RESULTS

5.2.1 Instrumental series analysis

Measurements of soil moisture, rainfall and runoff within the surface water drainage systems of two residential sub catchment areas of north Swindon (Arley Close and Winsley Close) of contrasting urban design are available for a period of 18 months; between May 2014 and December 2015. The data collected from PR2 soil moisture profile probes (Section 3.5.3), a TDR300 soil moisture probe (Section 3.5.4), Stingray 2.0 Ultrasonic Doppler Flow Monitoring (UDFM) equipment (Section 3.5.1) and Tipping Bucket Rainfall gauges (TBR, Section 3.5.5) are processed to produce data that are as reliable and relevant to Arley Close and Winsley Close as possible.

5.2.2 Analysis of soil moisture data collected from PR2 and TDR300 soil moisture probes

Two PR2 soil moisture profile probes are used to record soil moisture (m^3/m^3) on an hourly basis throughout the monitoring period at locations in close proximity to Arley Close and Winsley Close (Figure 3.9). PR2 profile probes record soil moisture measurements at 100 mm depth. Data is missing on a number of occasions throughout the PR2 soil moisture data as a result of malfunction caused by vandalism and rust (Section 3.6.3). To infill periods of missing data a linear interpolation is used between two known points at either end of the missing data period. On 27th October 2015, the series of soil moisture measurements collected at Arley Close falls within one hour by 14.5 m^3/m^3, caused by vandalism (the probe was lifted from the access tube). To correct this error an uplift of 14.5 m^3/m^3 is applied to data collected post 27th October 2015. After August 2015, the PR2 probe near Winsley Close records soil moisture readings at an increased variability and sensitivity than prior to August 2015. This is a result of probe damage again caused by vandalism. To attempt to correct this error a Double Mass Curve (DMC) between the Arley Close and Winsley Close PR2 probes is established and the slope of the DMC in the period August-December 2014 and August - December 2015 compared (Figure 5.1). The slope of the DMC is examined by fitting a simple linear regression model using the Ordinary Least Squares method described in Section 3.8. The DMC for the whole data period, and linear lines for the two compared periods are plotted in Figure 5.1. The slope of the DMC during the period August-December 2015 is approximately 18% greater than the August-

December 2014 period. Data in the period August-December 2015 are therefore adjusted to bring about an average reduction of DMC slope to match the August-December 2014 period. The raw data and post processed data collected with PR2 probes near Arley Close and Winsley Close is presented in Figure 5.2.

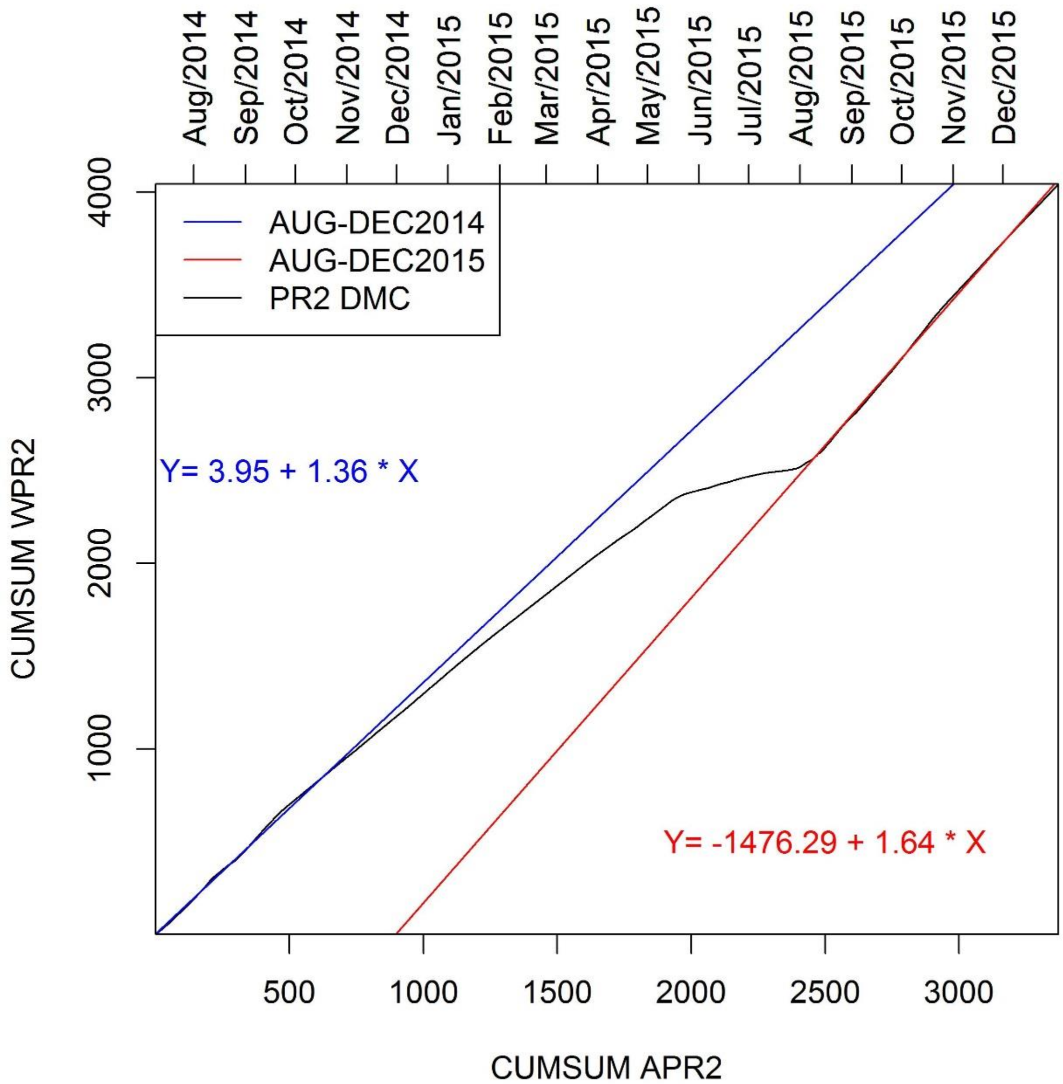

Figure 5.1: Double Mass Curve plotted for the PR2 soil moisture series collected near Arley Close and Winsley Close. The Blue and Red lines show the linear regression models fitted to the periods Aug-Dec 2014 and 2015.

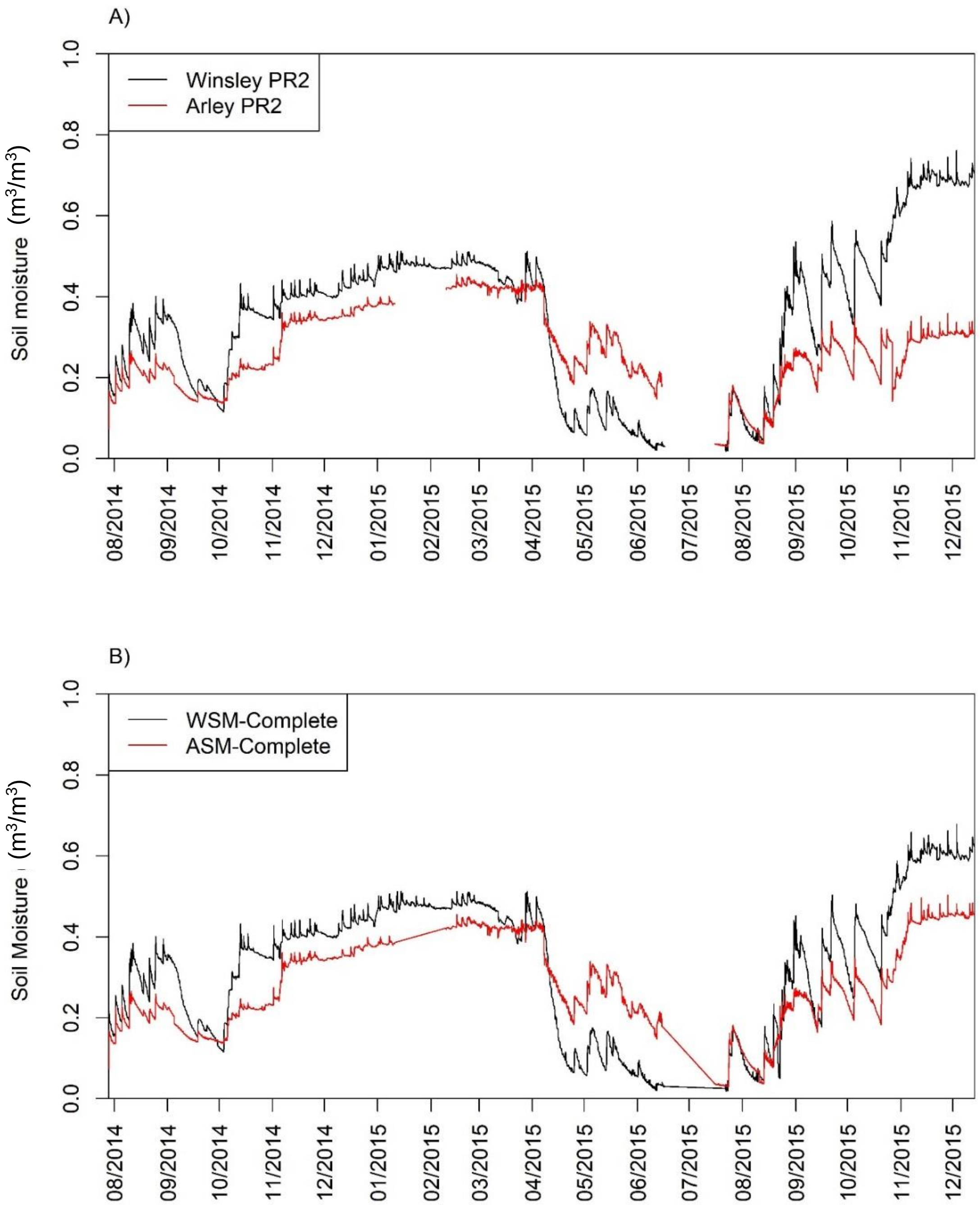

Figure 5.2: A) Raw data collected by PR2 soil moisture probes, B) PR2 data once corrected for malfunction and vandalism (WSM/ASM = Winsley Close/Arley Close Soil Moisture).

During the period April-August 2015 soil moisture measurements deviate for the two PR2 probes, with the PR2 probe at Arley Close exhibiting increased soil moisture readings during the period (Figure 5.2). This is reflected in the DMC for the two series (Figure 5.1), where the slope of the DMC deviates from a straight line. This is because of differences in vegetation management in the two locations where soil moisture is recorded with PR2 probes. The vegetation surrounding the PR2 probe in Arley Close is cut at a later date to that surrounding the probe located near to Winsley Close as a result of differences in land management between the two schools, reflecting the complexity of operating a monitoring network within the urban environment.

To validate the data collected by the PR2 probes to site specific measurements of soil moisture collected with the TDR300 probe, readings of soil moisture collected with the TDR300 probe are calibrated to site specific soil conditions using calibration curves created using the methodologies described in Section 3.5.4 (Figure 5.3 A,B). Once calibrated the TDR300 soil moisture readings are compared over time by means of a series of boxplots (Figure 5.3 C,D). Calibrated TDR300 measurements of soil moisture are highly variable within each monitoring episode and this variation is ascribed to variations in both soil moisture conditions and small-scale variations of soil characteristics (e.g. soil texture, density, dielectric constant). However, there is minimal variation in mean value over time, with TDR300 data lacking the seasonal pattern exhibited by the PR2 soil moisture data (Figure 5.4 A,B).

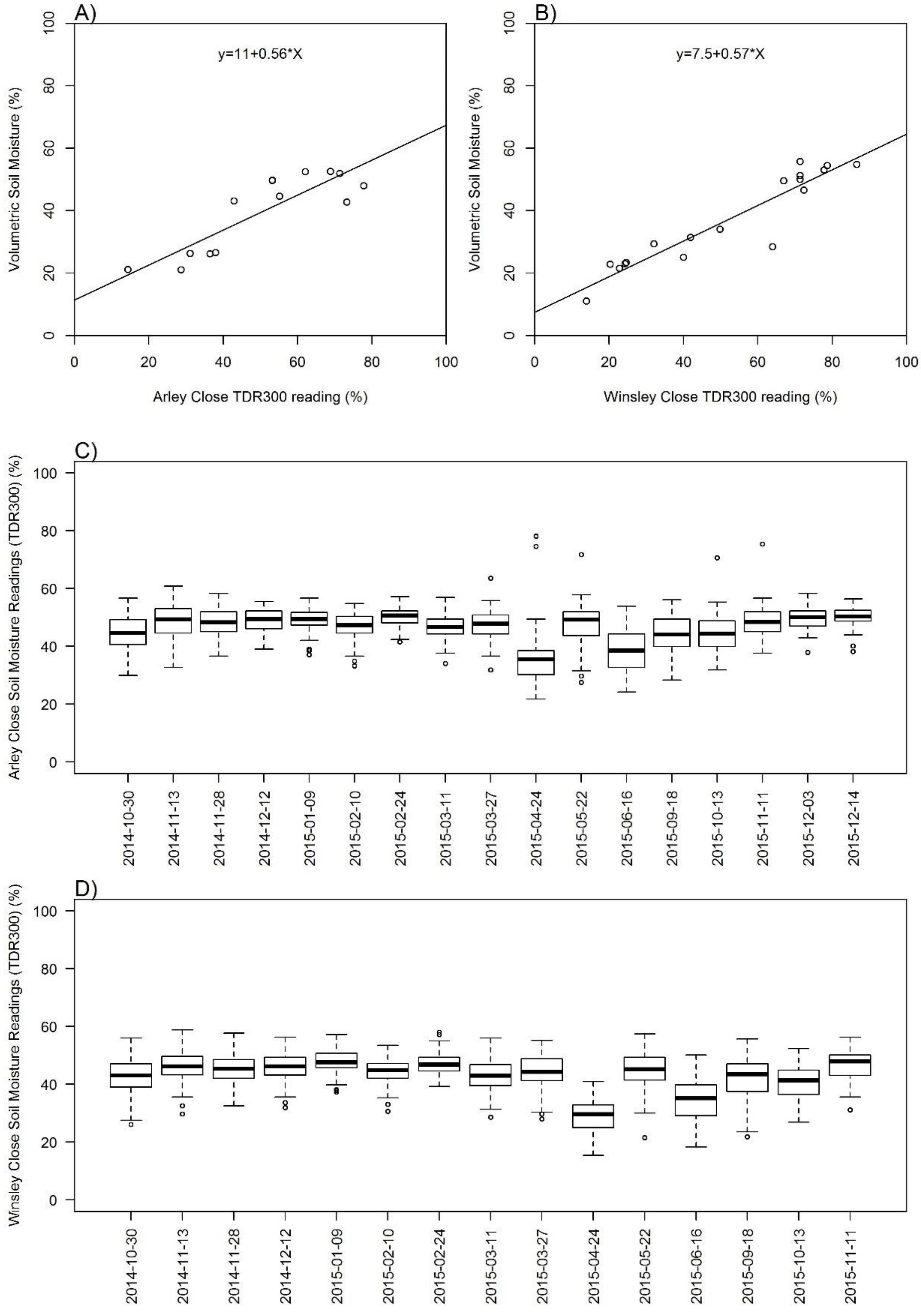

Figure 5.3: A) TDR300 calibration curve for Arley Close, B) TDR300 calibration curve for Winsley Close, C) Timeseries of calibrated TDR300 soil moisture measurements in Arley Close, D) Timeseries of calibrated TDR300 soil moisture measurements in Winsley Close.

To validate the data collected by the PR2 probes for application to Arley Close and Winsley Close, measurements of soil moisture from the calibrated TDR300 probe are compared to measurements by the PR2 probes (Figure 5.4).

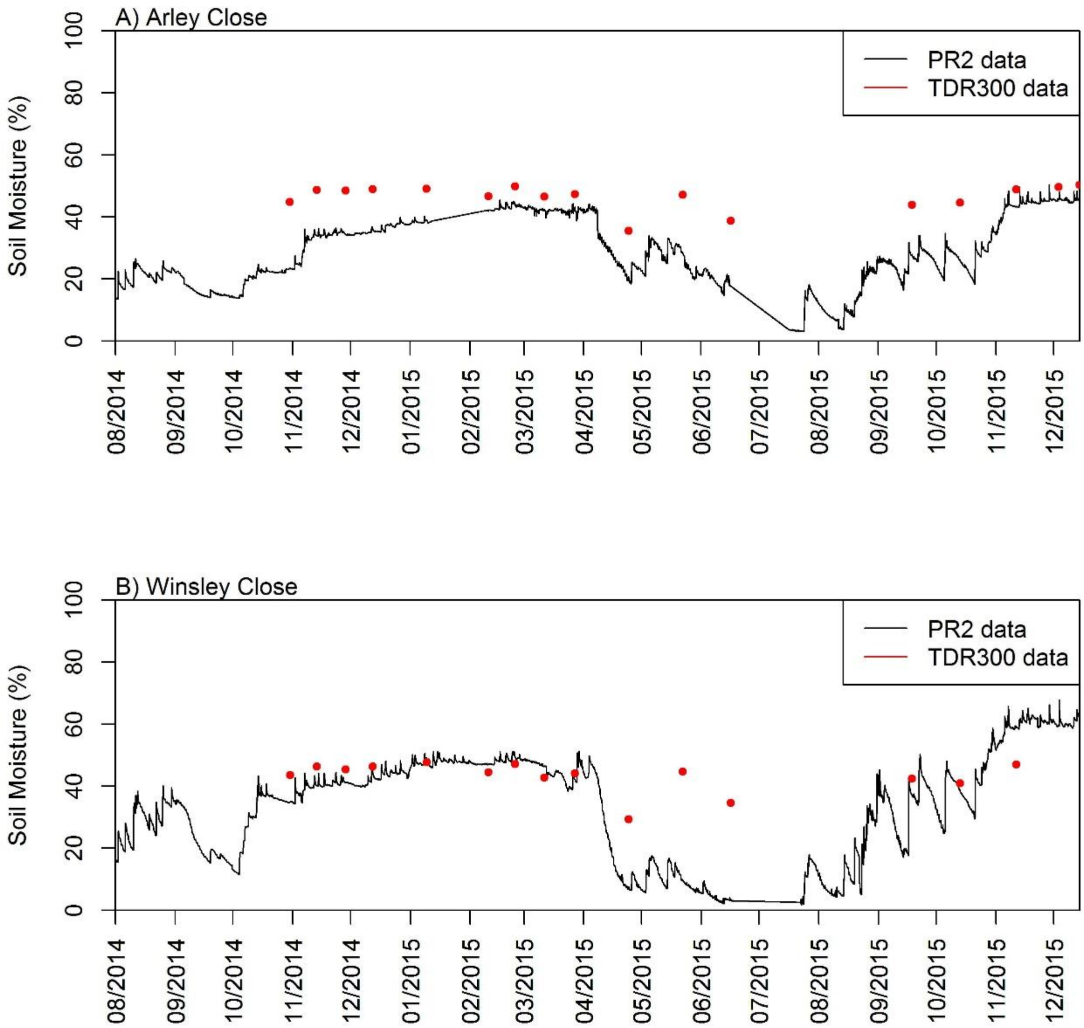

Figure 5.4: Comparison between soil moisture readings collected using TDR300 (average points, Red) and PR2 (Black line), for (A) Arley Close and (B) Winsley Close.

TDR300 data is missing for the periods August - November 2014 and July –September 2015 as a result of data handling errors and equipment malfunction (corrupted microcontroller in TDR300). Despite this it is possible to compare site calibrated TDR300 and PR2 soil moisture readings in both Arley Close and Winsley Close for a large proportion of the study period. Between October 2014 and April 2015 there is a good correspondence between TDR300 and PR2 readings of surface soil moisture in Winsley Close (Figure 5.4. B). In Arley Close, readings of soil moisture recorded by the PR2 increase during the period, whilst TDR300 vary little. During the summer of 2015 (May-September) soil moisture as recorded with the PR2 probes reduces, however soil moisture as recorded by the TDR300 does not reduce as much at either site. Reduced seasonal sensitivity of the TDR300 probe (e.g. not reducing in summer) is ascribed to a high sensitivity of surface soil moisture readings collected with the TDR300 to the moisture conditions of surface vegetation (grass) which contains moisture from morning dew and previous rainfall. This is a result of the reduced depth of the TDR300 readings (76mm vs 100mm with the PR2 probe) and the reliance on entering the TDR300 rods through the soil surface (and therefore vegetation) to record soil moisture. If it were possible to use an increased TDR300 rod length then this error may be reduced. However, this is unfeasible in the current monitoring experiment given the experience from field trials (Section 3.5.4) which demonstrates that rod lengths longer than 76mm deform and render data unreliable. Overall during the study period, measurements of soil moisture by the PR2 and TDR300 probes deviate by a maximum of approximately 20% and an average of 10% (across both Arley Close and Winsley Close). Given the manufacturers stated accuracy of the PR2 probe of +/- 6% or +/- 0.06 m^3/m^3, discrepancies between the two pieces of soil moisture monitoring equipment are within tolerable ranges. Therefore, the data collected by the PR2 probe provides a satisfactorily reliable estimate of surface soil moisture in Arley Close and Winsley Close during the study period.

5.2.3 Rainfall data from the CEH and Environment Agency tipping bucket rain gauges (TBR)

Three Tipping Bucket Rain gauges (TBRs) are placed within the north Swindon area for the monitoring period by CEH (Figure 3.11). In addition, the Environment Agency maintain a TBR to the south of Swindon. As described in Section 3.5.5, the CEH TBRs collect data at an increased temporal resolution in locations of greater proximity to Arley Close and Winsley Close than the EA TBR. However, the EA TBR is in a more secure location with reduced vegetation growth. Therefore, the rainfall data collected by the CEH and EA gauges is processed to produce rainfall data that is as accurate and applicable to Arley Close and Winsley Close as possible.

The accumulated sum of rainfall data for each of the three CEH TBR rain gauges is plotted with the data series recorded at the Environment Agency gauge (referred to as the EA gauge) in Figure 5.5 (A). Of the three rainfall series, Pinehurst is the most comparable to the EA gauge as both the Vygon and the Penhill gauges have periods when no rainfall data is collected, as such they deviate from the EA series, with each terminating prior to the end of the monitoring period. After the 18 month study period the Pinehurst rain gauge has measured a total rainfall depth within 18mm of the total precipitation depth recorded by the EA gauge, equivalent to an average discrepancy each month of 1mm during the study period.

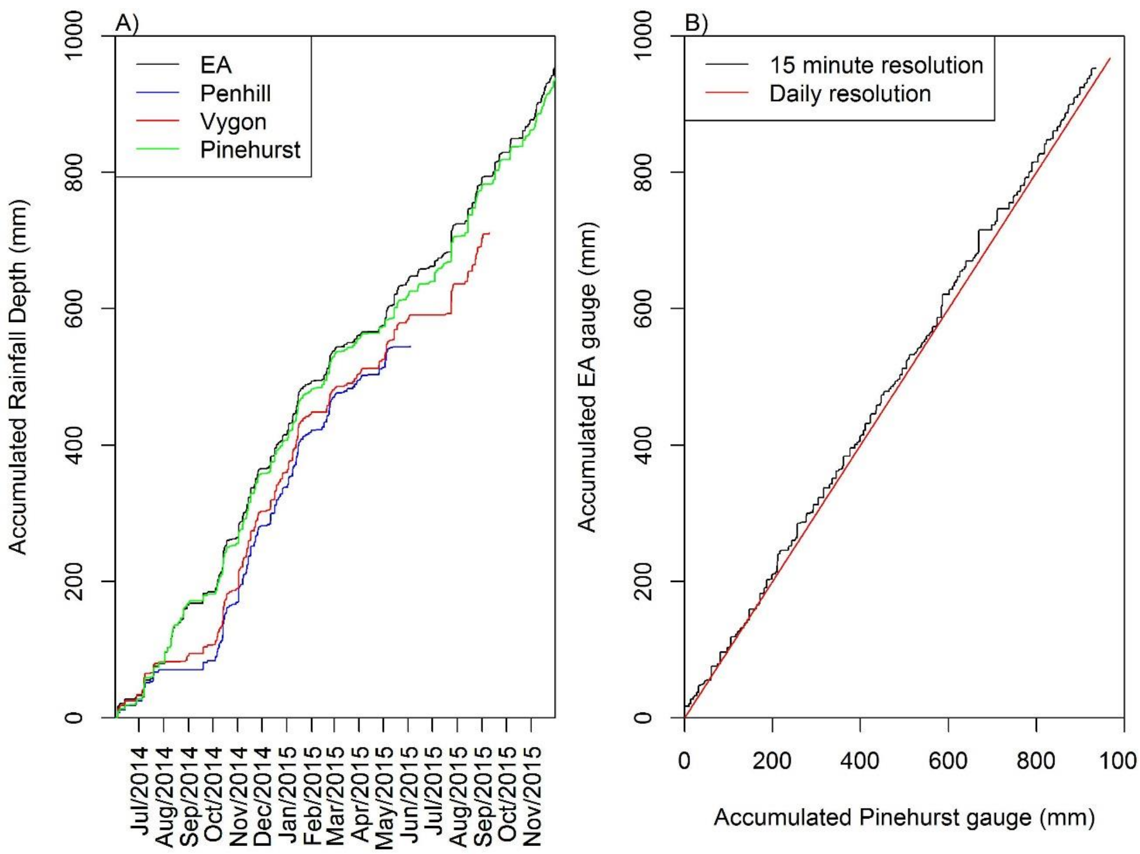

Figure 5.5: A) Accumulated rainfall depths for the CEH gauges in comparison to the EA TBR. B) A Double Mass Curve comparing rainfall data collected by the EA gauge and the Pinehurst TBR.

An analysis of the Pinehurst-EA gauge relationship using a Double Mass Curve (DMC) illustrates that there is a good correspondence between the two TBRs, with no discernible breaks/changes of slope, indicating a consistent relationship (Figure 5.5 B). The stepped nature at 15 minute resolution reflects the temporal mechanisms of precipitation moving across the Swindon area, a lower temporal resolution (Daily totals) is also applied and these stepped features are lost (red line; Figure 5.5 B).

The Pinehurst rain gauge is chosen as the source for rainfall data for Arley Close and Winsley Close as:

(i) there is a complete data set for the entire study period,

(ii) there is good agreement between the Pinehurst and EA gauges,

(iii) the Pinehurst gauge is in a location of closer proximity to Arley Close and Winsley Close than the EA gauge, and;

(iv) the Pinehurst rain gauge collects rainfall data at a greater temporal resolution in comparison to the EA gauge (2 minutes vs 15 minutes).

As rainfall depths, timing and duration may vary within the north Swindon area additional analyses comparing the series collected at Pinehurst and an additional TBR placed next to the PR2 soil moisture probe near Arley Close between Nov 2015 – Dec 2015 is conducted to ascertain any discrepancies between the timing, depth and duration of rainfall in a location of closer proximity to Arley Close. The difference in timing of precipitation events between the Pinehurst and Arley Close gauge is examined with a DMC (Figure 5.6 A). There is a lag in the timing of precipitation events that varies throughout the available data series. This makes any attempt to examine lag between the long precipitation series and the runoff monitoring at Arley Close unfeasible and reflects the lack of a single prevalent storm front direction in the UK, as such precipitation may be recorded before or after runoff in Arley Close. In addition, there is a systematic pattern of increased precipitation recorded at Arley Close. A regression model is fitted to examine the average deviation from the 1:1 relationship between the two gauges and this shows that there is on average an 11% increase in precipitation recorded at Arley Close in comparison to the Pinehurst TBR. Therefore, when rainfall event depth data collected at Pinehurst is applied to Arley Close an uplift of 11% is applied to increase the rainfall event depths recorded at Pinehurst.

The Penhill TBR is in a location of greater proximity to Winsley Close than the Pinehurst TBR (Figure 3.11). To apply the Pinehurst rainfall series to Winsley Close a DMC between the TBR data series collected at Pinehurst and Penhill for a period where data is available at each site (September 2014-May 2015) shows that an additional 11% of precipitation is collected at Penhill, therefore an uplift of 11% is applied to the Pinehurst precipitation series at Winsley Close (Figure 5.6 B). A reliable and quality assured rainfall data series is therefore generated for application to Arley Close and Winsley Close.

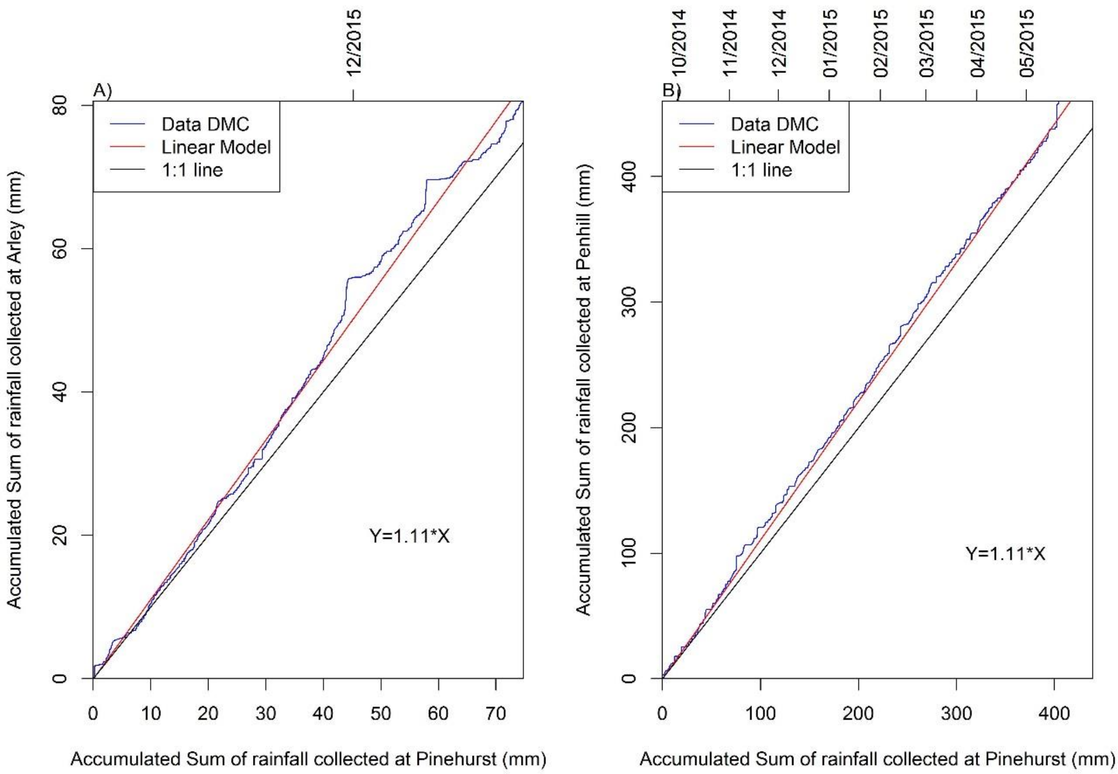

Figure 5.6: Double mass curves comparing rainfall series collected at Pinehurst and A) Arley Close and B) Penhill. Linear regression models are used to estimate the average deviation from a 1:1 relationship.

5.2.4 Velocity-depth corrections: removing, infilling and correcting errors

Runoff within the surface water drainage systems serving Arley Close and Winsley Close is monitored using two Stingray 2.0 Ultrasonic Doppler Flow Monitoring (UDFM) devices (Section 3.5.1). It is possible for a number of errors to occur through the monitoring of runoff with UDFM technology. These errors are outlined in Section 3.6.2, Table 3.1, and a script in the R programming language is written to identify, remove, infill or estimate depth readings where appropriate. Once malfunction errors are removed from the data series, depth estimates are required for where flow depth is under 25mm. Figure 5.7 shows the plotted linear relationship that is used to estimate flow depths when flow depth is below the sensitivity of the Stingray 2.0 UDFM (below 25mm depth) in (A) Arley Close and (B) Winsley Close.

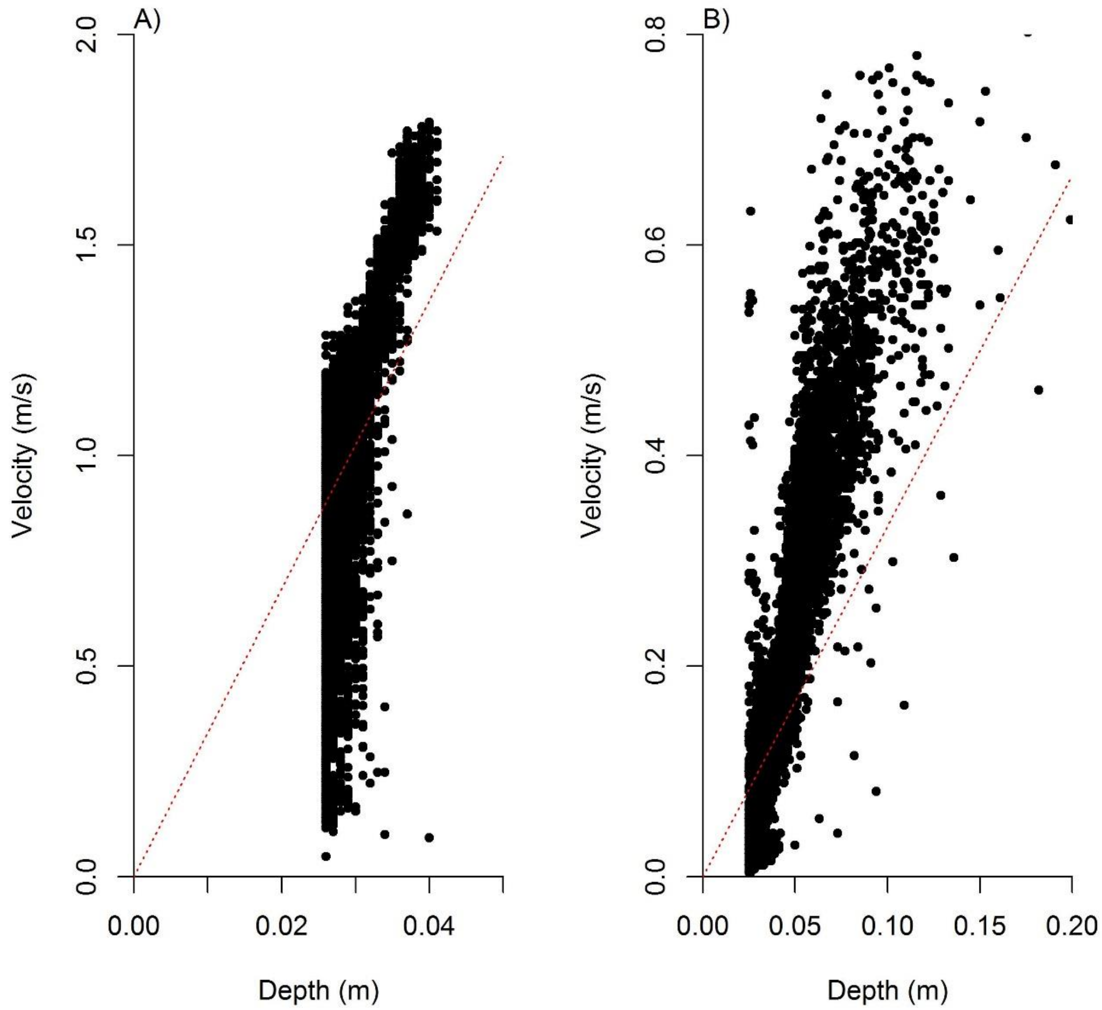

Figure 5.7: Velocity vs depth for flow within (A) Arley Close and (B) Winsley Close showing linear model used to estimate depth readings below 0.025m (Red line).

A better fit between the observed data and the regression line is possible if the regression model is not confined to having the intercept at (0,0). However the regression line needs to pass through (0,0) so that the velocity-depth relationship can be extrapolated to zero depth. Scatter in the velocity-depth data is ascribed to the following possible sources: (i) turbulence in flow conditions, (ii) debris within the pipe network, (iii) the backing up of flow under high flow conditions and potential instrument error (not previously corrected in Section 3.6.2).

To validate the velocity-depth correction methodology, a before and after comparison of an event hydrograph recorded in Arley Close is presented in Figure 5.8. Figure 5.8 (A) is the hydrograph for non-corrected data, whilst Figure 5.8 (B) shows the hydrograph once the data has been corrected. The non-corrected hydrograph has a number of points where flow returns to zero, not present in the corrected hydrograph. This is where the depth of flow is under 25mm and therefore no depth readings are recorded. By infilling an estimate of depth, flow ordinates are infilled and thus the hydrograph is completed. Whilst the peak flow rate is the same for both hydrographs, the overall volume recorded is reduced if data corrections are not made.

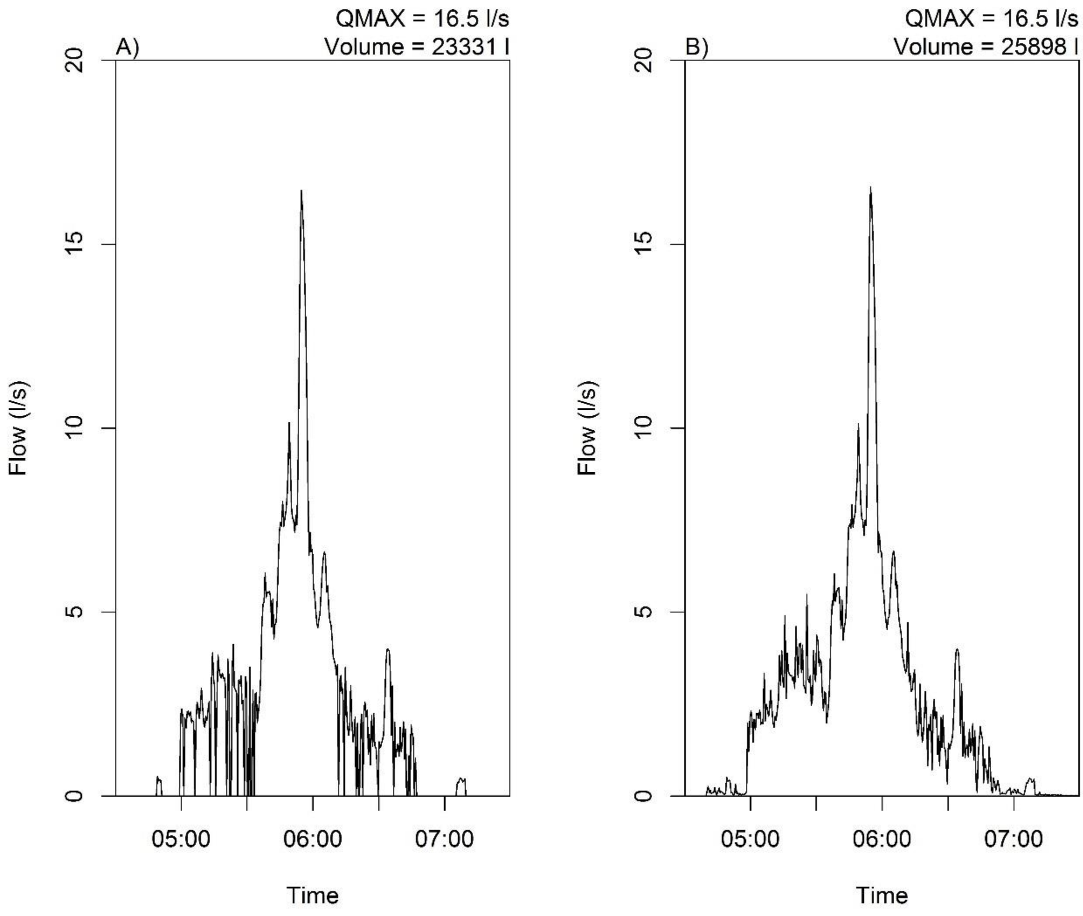

Figure 5.8: An example hydrograph for Arley Close with A) erroneous velocity-depth data and B) with errors corrected.

5.3 RAINFALL-RUNOFF EVENTS

Continuous measurements of rainfall and runoff at Arley Close and Winsley Close are processed to extract individual rainfall-runoff events, based on the methodologies and selection requirements set out in Section 3.7.1. Rainfall-runoff events are then processed to extract event runoff, removing baseflow using a linear interpolation method (Section 3.7.3). In total, 34 rainfall-runoff events meet the selection criteria (outlined in Section 3.7.4) and are available for analysis at both study sites (see Figure 5.9). Of the 34 events, nine occur in winter (Dec, Jan, Feb), seven in spring (Mar, Apr, May), seven in summer (Jun, Aug) and eleven in autumn (Sep, Oct, Nov). A number of additional events that meet the selection criteria of rainfall depth over 1mm and single peaked runoff response are omitted from analyses, as flow does not return to zero (or pre event conditions) before the next rainfall event occurs. A number of events recorded at Arley Close are not recorded at Winsley Close (and vice versa), subsequent checks against field notes attribute this discrepancy to malfunctions with field equipment; therefore these events are omitted from subsequent analysis.

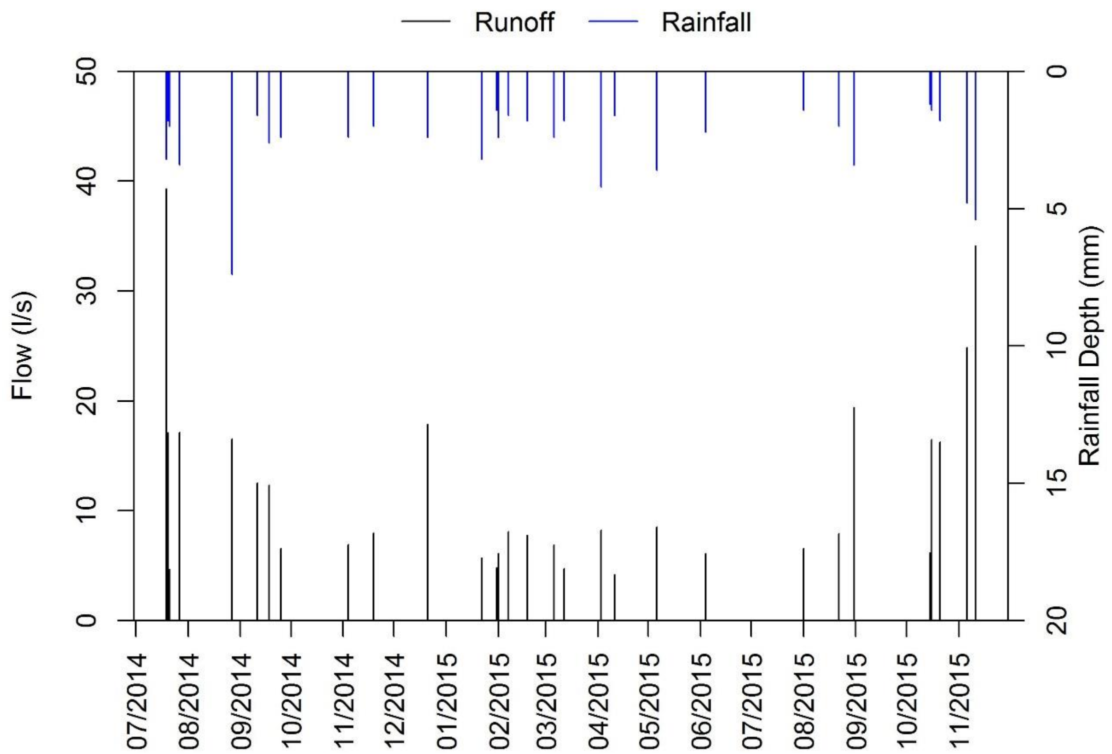

Figure 5.9: Time series of rainfall-runoff events. The runoff series shown is from Arley Close and is for illustrative purposes only. Figure shows all events analysed, not all events monitored.

Total event rainfall depth, maximum 10 minute rainfall intensity and event durations are plotted as a 3d scatterplot in Figure 5.10. This shows that event depth is positively associated with both rainfall intensity and duration. The events selected for analysis are predominantly sampled from relatively low values of depth, duration and intensity resulting in distributions that are skewed towards lower values of depth, duration and intensity (Figure 5.10). Seasonally there is little grouping of events, however there are no spring events over 2.0 mm/10 minute rainfall intensity and only one winter event (event 34). There are five summer and autumn events over 2.0 mm/10 minute rainfall intensity.

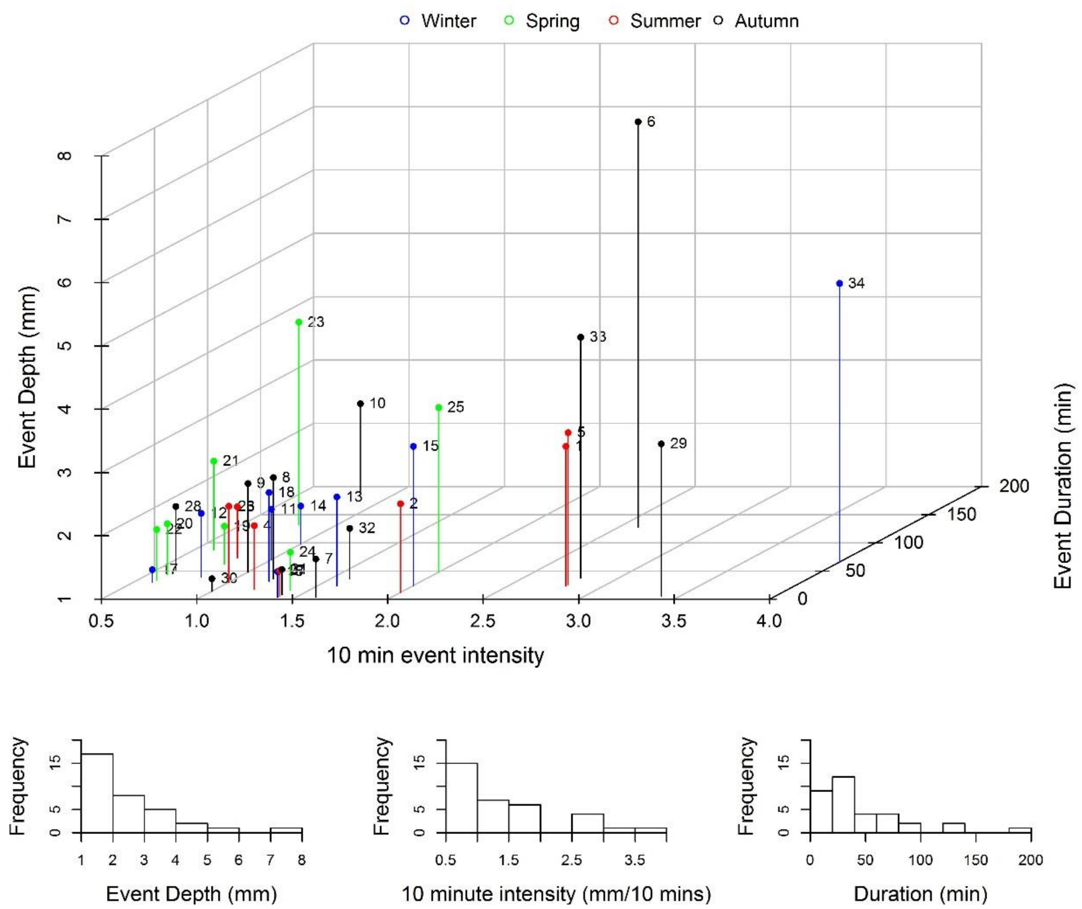

Figure 5.10: Rainfall event characteristics for 34 studied events. Points are coloured by season. Histograms of rainfall characteristics are plotted underneath. Drawn with the R 3dscatterplot package (Ligges and Mackler, 2003).

To assess the return period of each of the 34 selected rainfall events, the rainfall event Depth-Duration-Frequency (DDF) curves described in Section 3.9 are used. Rainfall event durations are entered into the ReFH2 software described in Section 3.9.1 to calculate the 1yr return period event depth that is expected in Arley Close and Winsley Close for the monitored event durations. Figure 5.11 plots the recorded event depths (red points) against the event depths for an event of a 1 year return period (green points). Events 29 and 33 have event depths that exceed the expected 1 year return period rainfall depth, however all other events plot below this threshold, indicating that the analysed events are of a low (under 1 year) return period, which is to be expected given the short monitoring period.

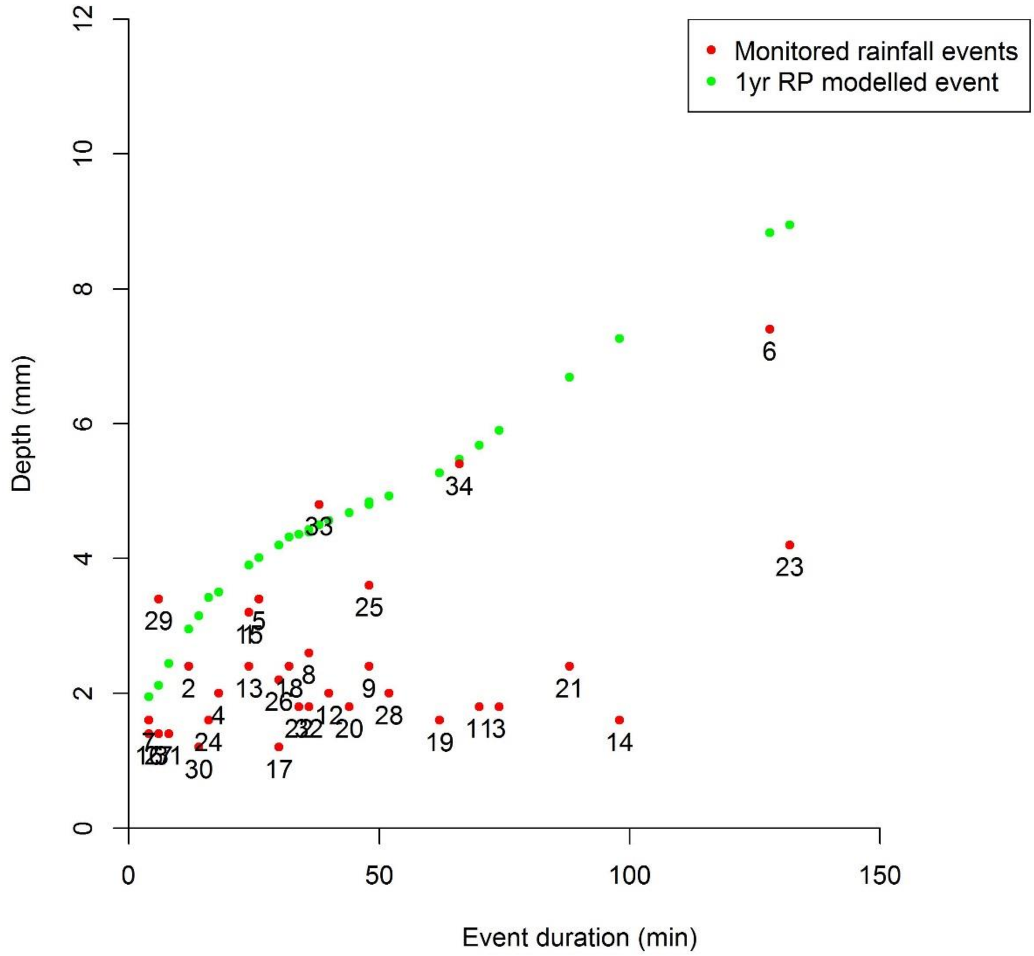

Figure 5.11: Comparison between the selected rainfall events and modelled 1 year return period (RP) events of the same duration. Printed numbers indicate event number.

Hyetographs and hydrographs for each of the 34 events are plotted on separate axes in Figure 5.12. Hydrograph shape is highly variable and sensitive to the shape of rainfall hyetographs. Variability in hydrograph shape is illustrated by comparing Events 1 and 15 (Figure 5.13).

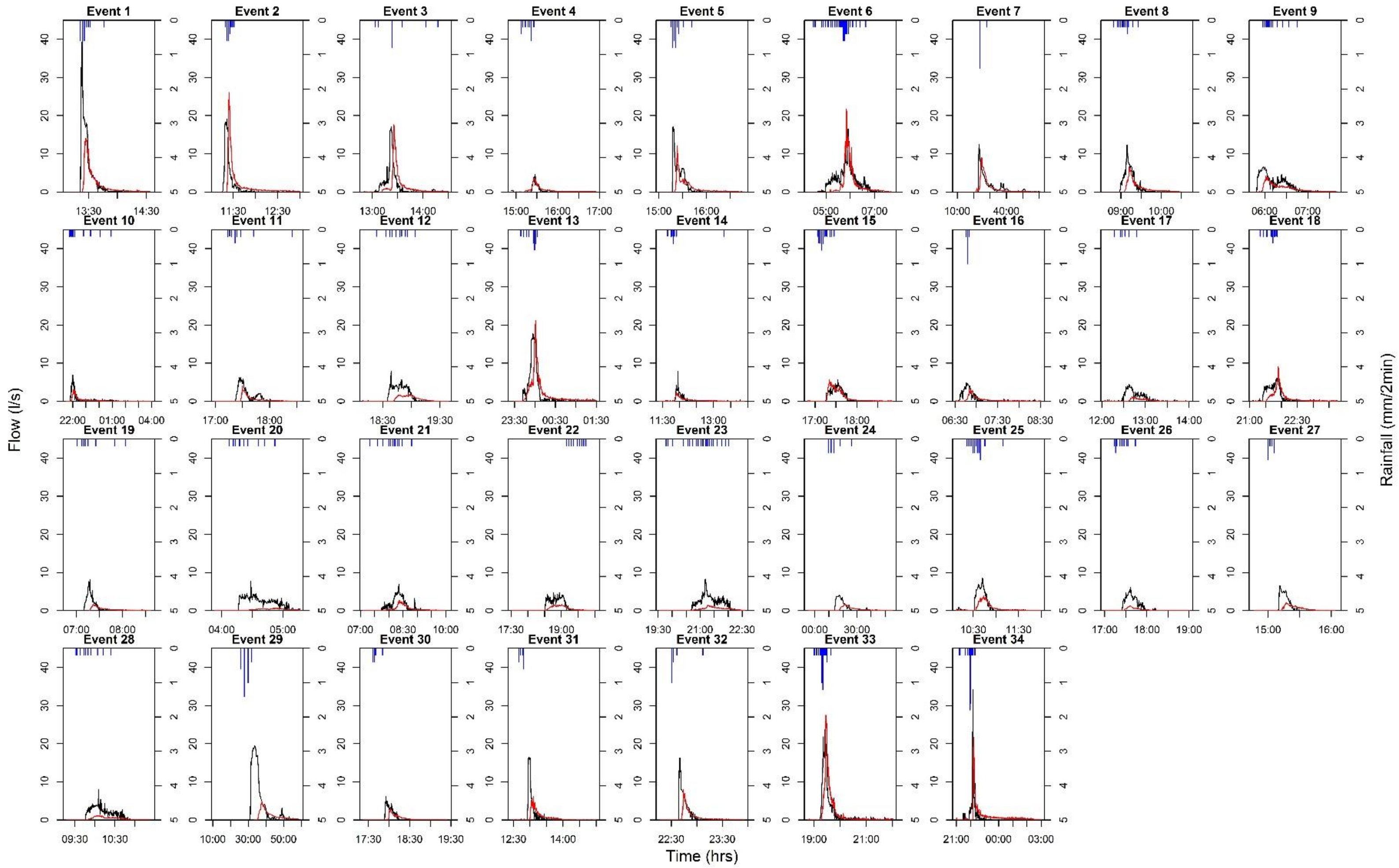

Figure 5.12: 34 rainfall-runoff event hydrographs and hyetographs. Red lines are runoff at Winsley close, black lines Arley Close.

Events 1 and 15 share the same total event depth (3.2 mm) and durations (24 minutes), however the two events differ in terms of maximum 2 minute rainfall intensity, with a maximum value of 1.2mm/2 minutes for Event 1 and 0.6mm/2 minutes for Event 15. The hydrographs for each event are very different. During Event 1, both Arley Close and Winsley Close have peak flows that exceed 10 l/s, whereas for Event 15 peak flows are under 10 l/s at both sites despite the similarity in duration and total precipitation depth. For Event 1 the peak flow at Arley Close is more than double that at Winsley Close, whereas for Event 15 the peak flows are more similar. This suggests that variability in hydrograph shape and therefore runoff characteristics are sensitive to short temporal scale changes in rainfall conditions, and in particular to rainfall intensity.

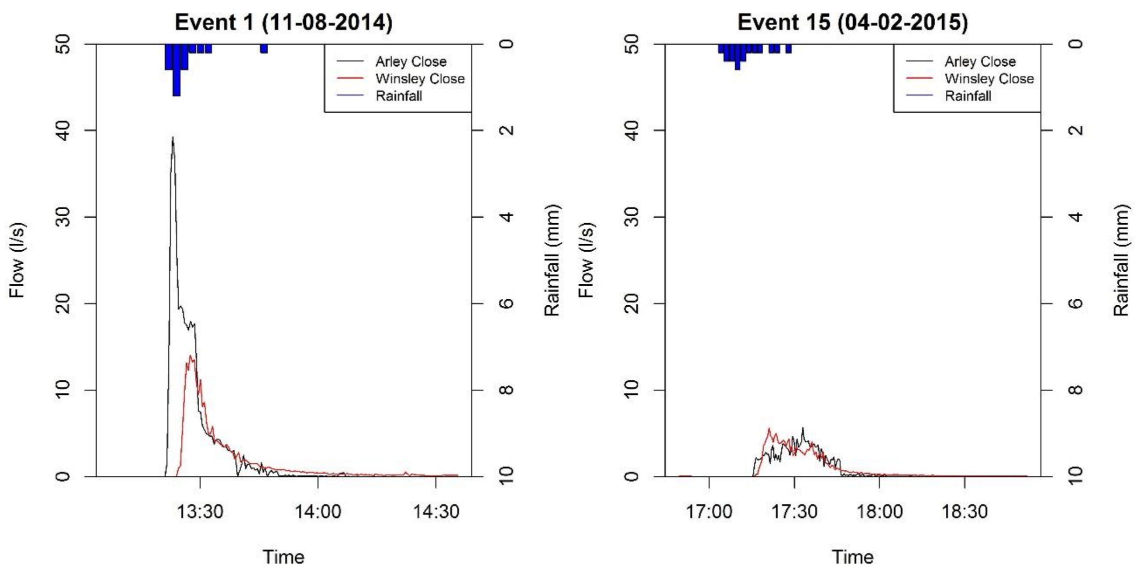

Figure 5.13: Comparison between events 1 and 15. Each event has a total rainfall depth of 3.2 mm and duration of 24 minutes. The two events have different maximum within event intensities (max 2 min intensity, Event 1 = 1.2mm, Event 15 = 0.6mm).

All 34 events are plotted on a single set of axes in Figure 5.14. The x axis is centred to a twenty minute window around the time of peak flow and flow values on the y axis are normalised by catchment area to enable direct comparison of the two catchments. Each of the 34 event hydrographs are plotted in grey, with the average hydrograph plotted in red for each site.

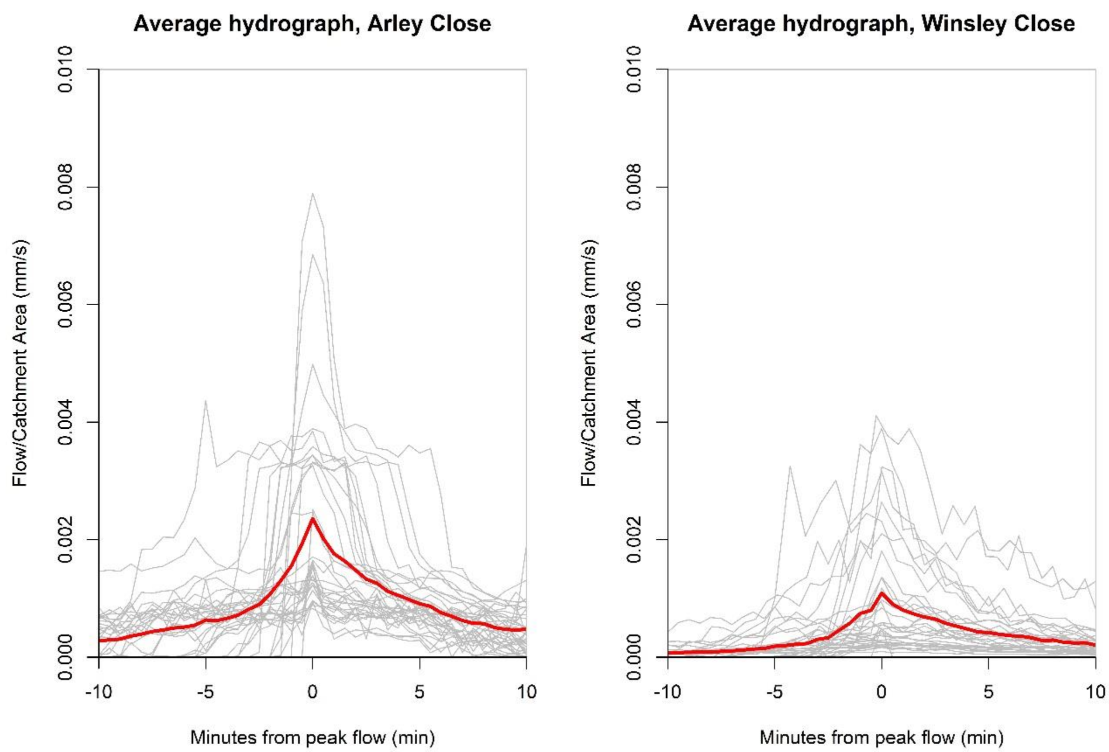

Figure 5.14: 34 Hydrographs plotted on single axis, for Arley Close and Winsley Close. The average hydrograph for each site is plotted in Red. The x axis has been centred to a 20 minute window around the time of peak flow for each event. Flow ordinates are normalised by catchment area to allow for direct comparison between study catchments.

The hydrographs at Arley Close are greater in magnitude than Winsley Close and there are a number of hydrographs that start from zero flow, before quickly reaching peak flow rates, indicating a rapid response to rainfall at Arley Close. The average hydrograph shape is similar for both sites (red lines, Figure 5.14), though the height of the average hydrograph and the steepness of the rising and falling limbs are greatest at Arley Close. There is a considerable amount of variability in hydrograph shape at both sites, with Arley Close having the greatest hydrograph shape variability.

5.3.1 Comparing values of peak flow (QMAX) and percentage Runoff (PR).

Each rainfall-runoff event is processed to determine the peak flow rate (QMAX) and percentage runoff value (PR), Section 3.7.5. Each event value of QMAX and PR recorded at Winsley Close is plotted against the values recorded at Arley Close in Figure 5.15 (A) and 5.14 (B). The 1:1 relationship is plotted on Figure 5.15 (A,B) as a black line, indicating where the events would plot if QMAX or PR are equal at both sites. Any point located to the right of this line indicate that PR or QMAX is greater at Arley Close; conversely any points plotting to the left of this line show that PR or QMAX values are greater at Winsley Close. All but two events plot to the right of the line comparing QMAX values (Figure 5.15 A); with all but one event plotting to the right of the line when comparing PR values (Figure 5.15 B); however, deviation from the 1:1 relationship into the Winsley Close side of the plots is small. Arley Close therefore has a consistently greater rainfall-runoff response in terms of peak flow and percentage runoff across studied rainfall-runoff events. Both the median peak flow value at Arley Close and median percentage runoff values are more than double those at Winsley Close (median normalised AQMAX = 0.0016 mm/s, median normalised WQMAX = 0.0006 mm/s, median APR= 60%, median WPR = 25%; Figure 5.15 C and D). There is little seasonal patterning within the QMAX or PR data, however there is more variation in spring events for Arley Close than Winsley Close, whilst winter, summer and autumn events show similar levels of variability at Winsley Close and Arley Close. The difference in mean normalised QMAX and PR values between the two sites is significantly different at P = 0.05, determined with the Mann Whitney U test (non-parametric test of difference).

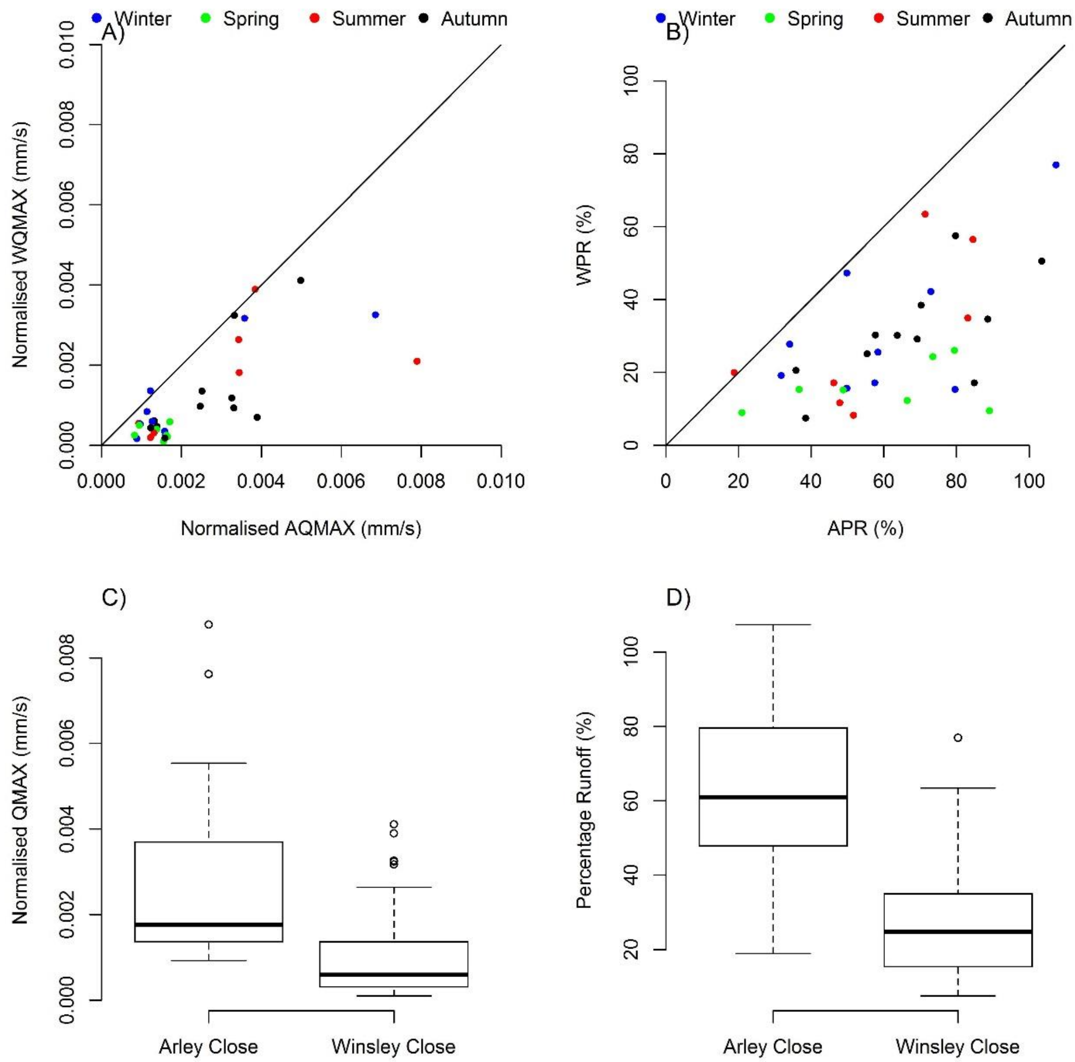

Figure 5.15: A,B) QMAX and PR values at Winsley Close plotted against those at Arley Close. Any points to the right of 1:1 line shows that Arley Close is greater, points to left of 1:1 line, Winsley Close is greater. The axes have been normalised by catchment area to allow for direct comparison between catchments. C,D) Comparison of QMAX and PR values between study catchments.

To investigate further what drives variability in rainfall-runoff behaviour at both sites, the next Section (5.4) examines how sensitive QMAX and PR values are to rainfall characteristics and antecedent conditions using multiple linear regression modelling.

5.4 ASSESSING SENSITIVITY OF RAINFALL-RUNOFF BEHAVIOUR TO RAINFALL CHARACTERISTICS AND ANTECEDENT CONDITIONS

This Section analyses the sensitivity of peak flow rates (QMAX) and percentage runoff (PR) values to rainfall characteristics and antecedent conditions, using multiple linear regression modelling as described in Section 3.8.

5.4.1 Model fitting procedure

The aim of this Section is to compare the sensitivity of rainfall-runoff behaviour (as defined by the metrics of QMAX and PR) to the explanatory variables described in Table 5.1 which are derived from analysis of monitored rainfall and soil moisture data. A regression model containing correlated explanatory variables is sensitive to the order in which variables are passed to the fitting algorithm, and not necessarily the underlying behaviour of the system under study (Section 3.8.5). Whilst correlated variables may be used for interpolation within model limits, interpretation of model parameters to understand the behaviour of the studied system is compromised. It is important therefore to reduce as much as possible the collinearity of explanatory variables within this study's modelling framework.

Table 5.1: Explanatory variables describing rainfall characteristics and antecedent conditions for use in regression modelling (reproduction of Table 3.2).

Variable Name	Definition	Units
Depth	Total event rainfall depth	mm
Duration	Total event duration	Minutes
2MinMaxInt	Maximum 2 minute rainfall intensity	mm/2minutes
10MinMaxInt	Maximum 10 minute rainfall intensity	mm/10minutes
API5	Antecedent (5 day) Precipitation Index (see 3.9.2.1)	mm
SMD	Soil Moisture Deficit (see 3.9.2.1)	mm
UCWI	Urban Catchment Wetness Index (see 3.9.2.1)	mm
Pre1HR	Pre event 1 hour rainfall depth	mm
Pre2HR	Pre event 2 hour rainfall depth	mm
Pre6HR	Pre event 6 hour rainfall depth	mm
ASM/WSM	Soil moisture recorded by PR2 probes, ASM = Arley Close, WSM = Winsley Close.	m^3/m^3

To define the correlation between the explanatory variables, a correlation matrix is used (Figure 5.16). This presents the correlation coefficient (Pearson) for each pair of explanatory variables. Cells within the matrix are coloured to highlight those coefficients above 0.5 (yellow) and under -0.5 (red), indicating medium to strong positive and negative correlations.

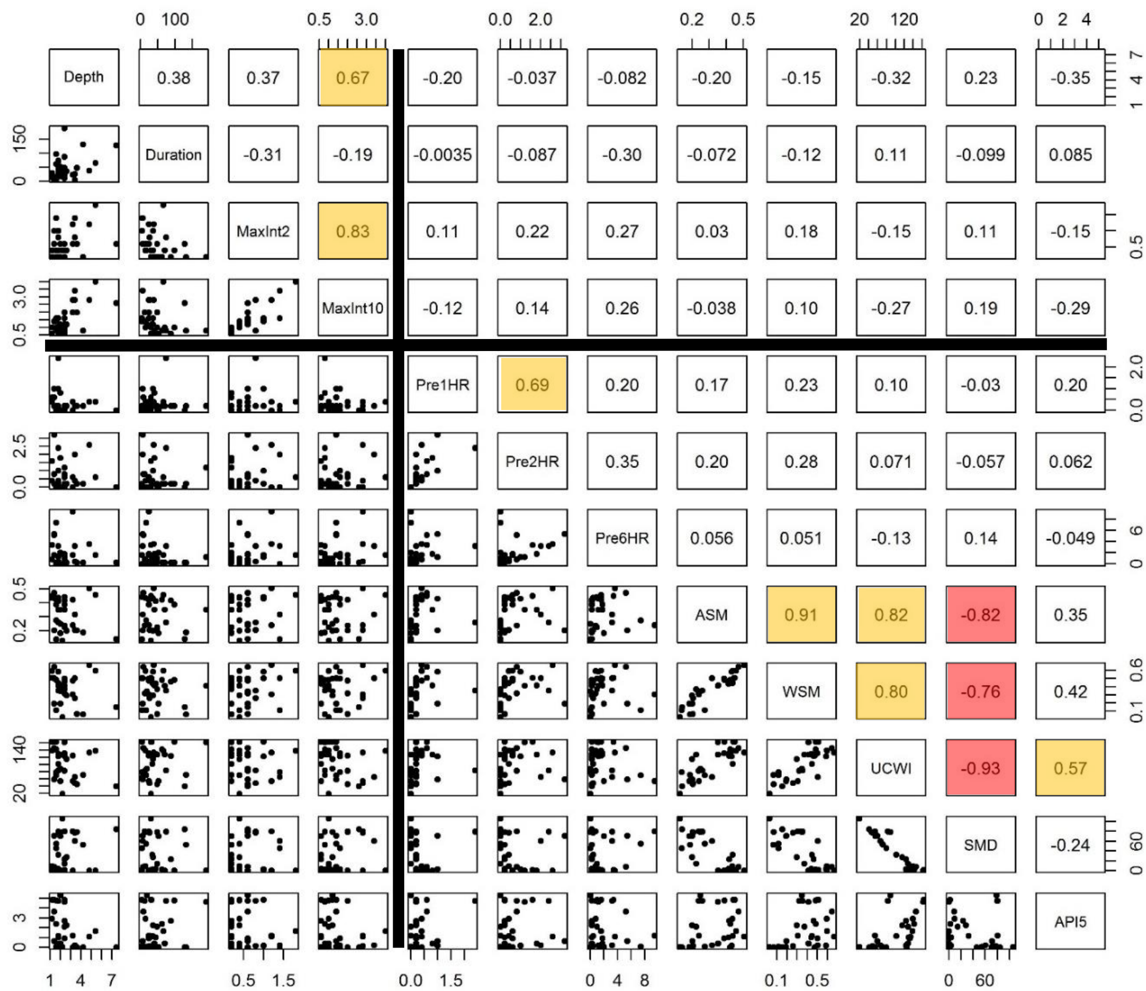

Figure 5.16: Correlation matrix for explanatory variables within the regression modelling.

The correlation matrix is divided into four regions, based on whether explanatory variables are from the rainfall characteristics or antecedent conditions group of variables. The top left region compares the rainfall characteristics, the bottom right antecedent conditions. The correlation matrix illustrates that various metrics of rainfall characteristics and antecedent conditions are correlated. However, there is little correlation between rainfall characteristics and antecedent conditions, which is reasonable as the two sets of metrics represent different aspects of the events. Therefore the following modelling procedure is applied:

(i) Explanatory variables are split into two groups defined as (1) rainfall characteristics and (2) antecedent conditions.

(ii) One variable is selected from the antecedent group, one from the rainfall characteristics group.

(iii) A multiple linear regression model is fitted between either PR or QMAX (dependant variable) and a combination of one antecedence and one rainfall characteristics variables (explanatory variables). The significance (P=0.05) of each regression coefficient is noted along with the adjusted R^2 value of the overall model fit.

(iv) The procedure is repeated for all possible combinations of antecedent and rainfall characteristics variables.

(v) A table of model outputs is used to determine the optimum model for analysis and interpretation.

(vi) The optimum model for analysis and interpretation is defined as where the regression coefficient for both explanatory variables is significant (P =0.05). Where more than one model is highlighted as having two significant explanatory variables in the results table, the model with the greatest adjusted R^2 value is chosen.

(vii) Residual analysis (Section 3.8.4) is completed on optimum models to ensure conformity with the assumptions of linear regression modelling. If a model deviates from the assumptions of linear regression modelling, the modelling procedure is repeated following an appropriate transformation of the dependant or explanatory variables.

Multiple linear regression modelling is completed using the base version of the R programming language.

5.4.2 Regression results

Initial investigations demonstrated that using non-log transformed values of QMAX result in violations of the linear regression assumptions (namely homoscedasticity), the analysis for QMAX therefore progresses with log-transformed QMAX values only (Section 3.8.4). Tables 5.2 and 5.3 contain the results of regression modelling between the explanatory variables and the values of log(QMAX) and PR for both Arley Close and Winsley Close.

Models where both variables are significant at P=0.05 are highlighted in yellow and bold. Optimum models (those with significant variables and the greatest adjusted R^2 value) are highlighted in red and yellow.

Table 5.2: Regression model table for log(QMAX) values. + = variable is significant at 0.05 level. - = not significant. Left hand symbol relates to antecedent condition, right hand symbol is rainfall characteristic variable. A = Arley Close, W = Winsley Close. Numbers are the model adjusted R^2 value. Yellow highlighter with bold is a model with two significant regression coefficients, Red is the optimum model where the model has two significant regression coefficients and the greatest value of the adjusted R^2

logQMAX		**Rainfall Characteristics**			
Site	**Antecedence**	**Depth**	**Duration**	**2MinMaxInt**	**10MinMaxInt**
A	**UCWI**	-/+,0.23	-/-,-0.02	-/+,0.45	-/+,0.50
W		-/+,0.22	-/-,-0.06	-/+,0.37	-/+,0.43
A	**SMD**	-/+,0.23	-/-,-0.04	-/+,0.45	-/+,0.50
W		-/+,0.21	-/-,-0.05	-/+,0.37	-/+,0.41
A	**Pre1Hr**	-/+,0.31	-/-,-0.04	-/+,0.45	**+/+,0.56**
W		-/+,0.29	-/-,-0.03	-/+,0.38	-/+,0.48
A	**Pre2HR**	-/+,0.28	-/-,-0.02	-/+,0.45	-/+,0.51
W		-/+,0.24	-/-,-0.04	-/+,0.37	-/+,0.42
A	**Pre6HR**	**+/+,0.33**	-/-,-0.02	-/+,0.45	**+/+,0.5**
W		-/+,0.23	-/-,-0.05	-/+,0.37	-/+,0.42
A	**ASM**	-/+,0.23	-/-,-0.06	-/+,0.45	-/+,0.45
W	**WSM**	-/+0.29	-/-,-0.01	-/+,0.37	-/+,0.38
A	**API5**	-/+,0.23	-/-,-0.03	-/+,0.44	-/+,0.50
W		-/+,0.28	-/-,0.05	-//+,0.39	**+/+,0.49**

Table 5.3: Regression model table for PR values. + = variable is significant at 0.05 level. - = not significant. Left hand symbol relates to antecedent condition, right hand symbol is rainfall characteristic variable. A = Arley Close, W = Winsley Close. Numbers are the model adjusted R^2 value. Yellow highlighter with bold is a model with two significant regression coefficients, Red is the optimum model where the model has two significant regression coefficients and the greatest value of the adjusted R^2.

PR		**Rainfall Characteristics**			
Site	**Antecedence**	**Depth**	**Duration**	**2MinMaxInt**	**10MinMaxInt**
A	**UCWI**	-/-, -0.04	-/-, -0.04	-/-, -0.01	-/-, .0.03
W		+/-, 0.12	-/-, 0.01	-/-, 0.11	**+/+, 0.13**
A	**SMD**	-/-,-0.04	-/-, -0.04	-/-, -0.02	-/-, -0.02
W		-/-, 0.04	-/-, 0.03	-/-, 0.05	-/-, 0.06
A	**Pre1Hr**	-/-, -0.02	-/-, -0.02	-/-, 0.01	-/-, -0.004
W		-/-, 0.1	-/+, 0.14	-/-, 0.08	-/-, 0.11
A	**Pre2HR**	-/-, -0.05	-/-, -0.05	-/-, -0.2	-/-, -0.03
W		-/-, 0.04	-/-, 0.02	-/-, 0.04	-/-, 0.004
A	**Pre6HR**	-/-, -.0.04	-/-, -0.04	-/-,-0.001	-/-, -0.004
W		-/-, 0.02	-/+, 0.04	-/-, 0.02	-/-, 0.01
A	**ASM**	-/-, 0.03	-/-, -0.03	-/-, -0.003	-/-, -0.001
W	**WSM**	+/-, 0.19	+/-, 0.10	+/-, 0.15	+/-, 0.15
A	**API5**	-/-, -0.06	-/-, -0.06	-/-, -0.04	-/-, -0.04
W		**+/+, 0.18**	-/-, 0.04	+/-, 0.15	**+/+, 0.18**

In general, the results in Tables 5.2 and 5.3 show there is a stronger link between event characteristics and QMAX than PR.

The optimal models for QMAX are:

$$\text{Log(AQMAX)} = 1.36+0.53*\text{MaxInt10}+0.34*\text{Pre1HR} \qquad \text{Model. 5.1}$$

$$\text{Log(WQMAX)} = -0.03+0.87*\text{MaxInt10}+0.14*\text{API5} \qquad \text{Model. 5.2}$$

Where, AQMAX is values of QMAX at Arley Close and WQMAX is values at Winsley Close, MaxInt10 is the maximum ten minute rainfall intensity, Pre1HR is the pre-event one hour rainfall depth and API5 is the Antecedent (5-day) Precipitation Index. Models 5.1 and 5.2 are "log-level" regression models, where the dependant variable (*Y*) has been log-transformed, log(Y), and the explanatory variables ($x_i \ldots x_n$) are not transformed. The coefficient estimates ($\beta_1, \ldots \beta_p$) can be interpreted to understand how changes in values of the explanatory variables affect the response of the dependant variable. The log-level regression coefficients are interpreted as follows: For a unit increase of X_1, the percentage increase in Y is given by:

$$\%\ \text{change in}\ Y = 100.(e^{\beta p} - 1) \qquad \text{Equation 5.1}$$

This rule applies to all explanatory model variables ($x_1, \ldots, x_p$) and their corresponding model coefficient values ($\beta_1, \ldots, \beta_p$), where it is assumed that all other explanatory variables are held constant (Wooldridge, 2009).

The log-level structure of Models 5.1 and 5.2 indicate a non-linear relationship between values of QMAX and the independent variables. Interpreting the regression coefficients contained within Models 5.1 and 5.2 using Equation 5.1, an increase of one unit of 10 minute rainfall intensity leads to a 69% increase of peak flow rate at Arley Close and a 138% increase at Winsley Close. A one unit increase of Pre1HR rainfall total leads to a 40% increase in peak flow at Arley Close, whilst a one unit increase of API5 increase peak flow rates at Winsley Close by 15%. Subsequent analyses tested whether there is any interaction between the explanatory variables, none is found.

The model for AQMAX (Model 5.1) contains the Pre1HR rainfall total as the antecedent condition variable, whereas the model for Winsley Close (Model 5.2) contains API5. This indicates that the peak flow rates at Arley Close are sensitive to short term variability in antecedent conditions, whereas peak flow rates at Winsley Close are more sensitive to antecedent conditions over the preceding five days prior to a rainfall event.

No significant regression coefficient values are found for PR values at Arley Close, i.e. neither rainfall characteristics nor antecedent conditions has a detectable influence (Table 5.3). At Winsley Close two models (Model 5.3 and Model 5.4) contain significant parameters and have the same adjusted R^2 value (Table 5.3):

$$WPR = 7.6 + 4.1*API5 + 5.1*RainDepth \quad \text{(Model. 5.3)}$$

$$WPR = 9.6 + 3.82*API5 + 7.56*MaxInt10 \quad \text{(Model. 5.4)}$$

Models 5.3 and 5.4 differ in terms of whether Rain Depth or 10 minute intensity is included along with API5. In Model 5.3, a per unit increase of RainDepth and API5 produce an increase in percentage runoff values of 4.1 and 5.1 (PR units e.g. %). Model 5.4 however suggests that the per unit increase in PR attributable to rainfall intensity is 7.56%, whilst per unit increases of PR attributed to API5 is 3.82%. Overall, the multiple linear regression modelling methodology applied to Percentage Runoff values for the 34 studied events in Arley Close and Winsley Close is unable to provide a coherent understanding of the sensitivity of PR behaviour. In Arley Close, regression modelling provides no models with greater explanatory power than the mean value alone, whilst at Winsley Close the variable selection methodology is unable to determine which variables PR values are sensitive to. Whilst the regression coefficients in Models 5.3 and 5.4 are statistically significant ($P = 0.05$) the adjusted R^2 values are low, demonstrating that a large proportion of variability in PR values is unexplained by the regression models.

Diagnostic plots testing the robustness of the fit between the modelled data and the assumptions of linear regression modelling are shown in Figure 5.17, a description of how to interpret the diagnostic plots in contained in Section 3.8.4. There is little deviation from the assumptions of linear regression modelling shown for any of the regression models. No systematic patterns are shown in the residuals vs fitted plots (e.g. there is a random scatter of points around zero value) or the Scale-Location plots (e.g. no curves or increasing/decreasing variability). There is a close scatter of points to the 1:1 relationship in the Q-Q plots indicating that the residuals for all four models are normally distributed and in the Residuals vs Leverage plots, the Cook’s distance of all points is under 1.

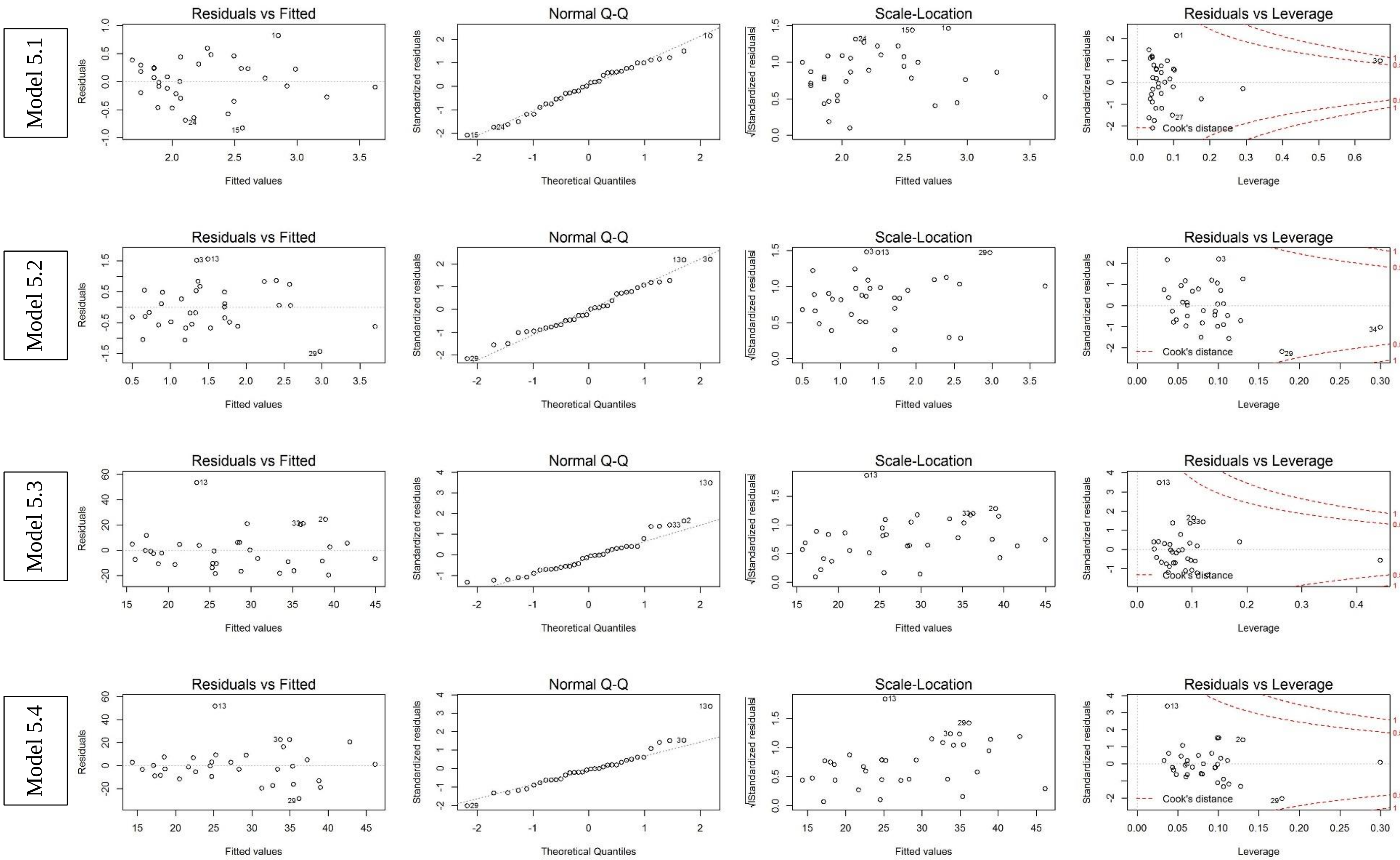

Figure 5.17: Diagnostic plots for the four regression models demonstrating the robust fit between the data and the assumptions of linear regression.

This demonstrates that there is a robust fit between the modelled data and the assumptions of linear regression modelling, validating the use of regression modelling to attempt to assess the sensitivity of rainfall-runoff behaviour in Arley Close and Winsley Close to rainfall characteristics and antecedent conditions.

5.5 DISCUSSION

The results contained within this chapter are the outcome of hydrological analyses of rainfall-runoff data collected from Arley Close and Winsley Close. The monitored data have required careful processing to remove and correct errors that occur as a result of vandalism and instrument malfunction. Further discussion of the monitoring errors and any resultant uncertainty in the stated results is warranted. The soil moisture monitoring equipment deployed in this study (TDR300 and PR2 profile probes) are typically applied within the literature to soils in agricultural or more natural settings (Qi and Helmers, 2010). The presence of stones, urban debris and compacted surface soils in Arley Close and Winsley Close provide soil conditions that make the application of the TDR300 and PR2 probes challenging. Long TDR300 rod lengths deform as the probe rods enter the soil, and as a consequence, only 76 mm rod lengths are applied in this monitoring experiment. The application of short TDR300 rod lengths through surface vegetation to the underlying soils, reduces the sensitivity of the TDR300 to soil moisture (as surface vegetation contributes moisture to the measurement), with the result that there is limited seasonal variation observed in the soil moisture series collected with the TDR300 in both Arley Close and Winsley Close (Figure 5.3). The data series collected by the PR2 profile probes have periods of missing data (as a result of vandalism, Figure 5.2A) and there is an inconsistent slope in the Double Mass Curve comparing the soil moisture series in Arley Close and Winsley Close (Figure 5.1) as a result of differences in the management of vegetation in the monitoring locations, reflecting the complex nature of the urban environment. To overcome these practical complications, comparisons are made between the data collected by the TDR300 probe and the PR2s and whilst there are differences noted in the series collected by these equipment (Figure 5.4), the average difference between the monitored series by each piece of equipment are shown to be within a tolerable error range, validating the application of the data collected by the PR2 probes to Arley Close and Winsley Close.

Velocity and depth data collected using Stingray 2.0 UDFM equipment are processed to remove errors caused possible instrument error. A simple linear regression methodology is used to infill estimates of flow depth when flow conditions are below those of the minimum sensitivity of the monitoring equipment (Figure 5.7). It is not possible to verify the velocity and depth readings during the monitoring period using methods such as spot gaugings (Shaw et al., 2010), as a result of the practical and health and safety restrictions of operating within a surface water drainage system (located within a road). There is a high degree of scatter in the readings of velocity and depth which may be a result of turbulence, backed up flow conditions or additional instrument errors. The fitted linear regression model provides only a partial representation of the velocity-depth relationship recorded in each site; however, the regression line provides an adequate extrapolation to the origin for the purposes of depth infilling.

To increase confidence in the overall analyses of the rainfall-runoff data, rainfall-runoff events are selected for study that meet a number of strict selection criteria (outlined in Section 3.7.4) and the extracted rainfall-runoff events are inspected visually, with events containing either missing or erroneous data omitted from subsequent analyses. Overall, the methodologies applied to process and verify the data with a number of different pieces of equipment, to select rainfall-runoff events with a pre-determined set of selection criteria and the application of a robust statistical modelling methodology reduces uncertainty and provides confidence in the stated results.

Chapter 4 previously examined in detail the differences in surface cover and surface connectivity of the two sites and these differences are summarized below to aid interpretation of rainfall-runoff analyses:

(i) The two study sites have a similar percentage of impervious cover, Winsley Close 43%, Arley Close 54% (under the Medium estimation method outlined in Section 3.3.1, results detailed in Tables 4.3 and 4.4). Impervious surfacing in both sites consists of roofs, roads, other transport related surfaces and domestic surfaces.

(ii) Winsley Close contains two large vegetated public spaces, whilst private gardens are predominantly vegetated. Arley Close contains no large open vegetated spaces, whilst private domestic surfaces to the front of properties are predominantly impervious driveways (Figure 4.5).

(iii) Arley Close has a greater number of hydraulic entry points connecting the urban surface to the surface water drainage system (Table 4.5). This results in small drainage areas, with reduced drainage distances and consequently Arley Close has greater connection efficiency between the urban surface and the surface water drainage system than Winsley Close (Figure 4.10).

The design of Arley Close and Winsley Close strongly influences rainfall-runoff behaviour as shown by the comparison of QMAX and PR values for the 34 studied rainfall-runoff events (Figure 5.15). The median peak flow rate and percentage runoff values at Arley Close are more than double those at Winsley Close and as a result hydrological behaviours differ significantly (P = 0.05, Section 5.3.1). Linking differences in rainfall-runoff behaviour to the precise physical differences in the design of Arley Close and Winsley is uncertain as rainfall-runoff data for each individual surface within the study areas is unavailable. However, the differences in rainfall-runoff behaviour exhibited between Arley Close and Winlsey Close are likely a function of the increased imperviousness of Arley Close and the increased connection efficiency between the surface water drainage system and urban surface. Differences in the design of areas such as private driveways and public spaces increases the overall imperviousness of Arley Close, and the increased number of drainage connection points in private and public areas of Arley Close increases surface connection efficiency. It is likely that these two design differences combine to reduce losses occurring on urban surfaces, as runoff from urban surfaces has a reduced travel distance to the surface water drainage system across the urban surface of Arley Close. Overall, these small-scale differences in physical urban design, accumulate to influence rainfall-runoff behaviour at the larger sub-catchment plot scale.

Peak flow rates at both sites are highly sensitive to the ten minute rainfall intensity, with a one unit increase of intensity increasing peak flows by 138% at Winsley Close and 69% at Arley Close. This finding is similar to that reported by other authors in catchments with increased levels of imperviousness who link peak flow rates to rainfall intensity (Schilling, 1991; Lloyd-Davies et al., 1906). However, the results reported here indicate that the relationship between peak flow rates and rainfall intensity is non-linear following a log-linear response. In addition to rainfall intensity, each site's QMAX values are also sensitive to different indices of antecedent conditions, something that is not included in some commonly applied rainfall-runoff models for engineering design (e.g. The Rational Method, Lloyd-Davies, 1906). At Arley Close QMAX values are sensitive to the depth of rainfall that falls within one hour prior to an event, whilst at Winsley Close, QMAX values are sensitive to the antecedent five day precipitation index (API5). The different physical designs of each catchment are therefore influencing variability of peak flow behaviour in different ways. At Arley Close increased imperviousness, lack of vegetated surfaces and increased connection efficiency of the surface water drainage system has led to a hydrological behaviour that is sensitive to short term changes in antecedent conditions. This suggests that Arley Close has a small storage capacity, and the wetting and drying of impervious surfaces is influencing rainfall-runoff behaviour. At Winsley Close, the large open vegetated surfaces and reduced connection efficiency has created a rainfall-runoff behaviour that is sensitive to longer duration changes in antecedence, thus Winsley Close has greater storage capacity that takes a larger rainfall depth to increase in wetness and contribute to event response. This demonstrates the complex, non-linear rainfall-runoff processes within small-scale urban settings that may not be completely accounted for within current hydrological theory, indicating that improved understanding of the urban rainfall-runoff process should be developed that is adaptive to the particular small-scale characteristics of urban development under study.

In contrast to other studies, e.g. (Kidd and Lowing, 1979), percentage runoff (PR) is difficult to model with multiple linear regression at both sites. At Arley Close, no models with significant ($P = 0.05$) explanatory variables are identified, consequently regression modelling is not able to produce a model with greater descriptive efficacy than the mean value alone. The lack of significant regression coefficients could suggest that the percentage runoff values at Arley Close are static and insensitive to changes in physical conditions. However, this is unlikely, given that there is variability in percentage runoff values at Arley Close (Figure 5.15); instead the lack of significant regression coefficients implies that either the percentage runoff values at Arley Close are insensitive to the tested explanatory variables, or the rigid model structure of linear regression. It is possible that another variable such as temperature (not tested here) could improve regression modelling results. Alternatively, a less rigid model structure applied to the percentage runoff data could improve descriptive and predictive power, however this is undesirable in this study given the difficulties of physical interpretation of low-bias/high-variance model structures e.g. a tree based model (James et al., 2013). At Winsley Close, again modelling percentage runoff values with multiple linear regression is uncertain, given that two models produce significant explanatory variable coefficients and the same values of the adjusted coefficient of determination (R^2), which are low (0.18), indicating that a large proportion of variation in PR values are unexplained by regression Models 5.3 and 5.4. Percentage runoff is an important variable used in a number of different hydrological models and engineering design calculations (Kidd and Lowing, 1979; Woods-Ballard et al., 2007). Given the results reported here, e.g. that it is difficult to model PR values, it is important that the efficacy of rainfall-runoff models for predicting percentage runoff values is assessed against monitored data as the uncertain regression results reported here imply that variability in percentage runoff is difficult to predict with hydrologically derived parameters.

At the whole study catchment scale, Arley Close and Winsley Close are fairly similar in terms of the proportion of surfaces under impervious cover (Chapter 4, Table 4.3, 4.4). Therefore, hydrological models that link total imperviousness to hydrological response would likely estimate that the two sites have similar rainfall-runoff properties (Verbeiren et al., 2013; Dixon and Earls, 2012; Valeo and Moin, 2000), which is inaccurate given the results reported here. Instead, the results reported here suggest that models should be sensitive to how the surface water drainage system connects hydraulically to the urban surface and small-scale variations in surfacing. Assessing the connectivity of surfaces requires detailed data of surface types and hydraulic entry points to the surface water drainage system (i.e. drain gully or down pipe) (Chapter 4, Table 4.5). The lack of relevant data about individual surfaces and urban surface water drainage systems and connectivity at small-scales within urban settings has previously limited the inclusion of such fine scale detail of the urban environment within hydrological models (Han and Burian, 2009). Instead, connectivity is typically estimated or defined as a function of land use or total imperviousness across large urban areas (Lee and Heaney, 2003). However, as demonstrated in Chapter 4 (Section 4.4), the connectivity and surface characteristics of residential areas is highly variable and it is likely that hydrological characterisation based on simple descriptions that group areas based on generalised properties (e.g. land use, imperviousness) would be inaccurate when applied to the study catchments. The data collected and analysed here therefore offer the opportunity to study the performance of the most common approaches to the representation of urban areas within hydrological models, to identify inaccuracies and suggest improvements based on the greater detail of understanding between urban design and rainfall-runoff behaviour generated in this chapter and Chapter 4. There is potentially a discrepancy between the structuring and calibration of urban hydrological models at the development plot scale and the findings of this study. It is important that such a discrepancy is quantified and understood to improve the representation of urban residential areas within hydrological models. This is the topic of the next chapter.

Chapter 6

RUNOFF VOLUME MODELLING FOR SURFACE WATER DRAINAGE DESIGN

This chapter assesses the ability of commonly applied urban rainfall-runoff models to replicate the rainfall-runoff behaviour of Arley Close and Winsley Close. Results are analysed in the context of the consequences of the over sizing or under sizing of surface water drainage assets

6.1 INTRODUCTION

The existing urban environment needs retrofitting with surface water management assets including Sustainable Drainage Systems (SuDS) (Ossa-Moreno et al., 2017). Whether this is to increase capacity in existing surface water drainage networks or to reduce the impacts of historic urban development on the hydrological environment, the need for retrofitted surface water management infrastructure is clearly documented in the scientific and policy literature (Walsh et al., 2005; MacDonald, 2011). However, retro-fitting is hampered by competition for space within urban areas, difficulties of attracting funding for construction and maintenance costs and uncertainty in designing and sizing drainage assets to maximise hydrological benefits (Stovin and Swan, 2007; Backhaus et al., 2012; Marlow et al., 2013).

The design of retro-fitted drainage assets require a number of iterations as designs develop from initial project appraisals to detailed designs for construction (DCLG, 2014). Initial designs are developed to establish targets for runoff volumes and flow rates and thus required storage volumes. These initial designs are used to generate estimates of construction costs to establish the economic viability of a proposed project to attract funding. Given that the UK Treasury only fund flood risk alleviation works with a benefit-cost ratio of at least 8:1 (i.e. a £100k scheme needs to produce £800k of flood protection benefits) (NAO, 2014), accurate modelling of rainfall-runoff behaviour in existing urban areas is vital to produce reliable estimates of construction costs and to confirm the economic viability of retro-fit surface water management schemes.

To estimate the rainfall-runoff behaviour of existing urban development a rainfall-runoff model is chosen and parameterised in an attempt to represent site conditions. There are a number of rainfall-runoff models available and each has its own parameter values that need estimating (Section 3.9.3). Defining surface cover and connectivity within the existing built environment is uncertain and sensitive to the methodological assumptions that are used to infill areas of missing data (Section 4.3.). Selecting appropriate model parameter values to reflect site conditions is difficult given the complexity of the urban surface and the lack of rainfall-runoff data at appropriate scales within urban areas (Kellagher, 2000). The rainfall-runoff modelling process is therefore uncertain and in practice urban rainfall-runoff models are often parameterised using design guidance or assumed values e.g. impervious surface percentage runoff = 80%, (Kellagher, 2013), however there is evidence that these estimated values are inaccurate in some areas e.g. where there is poor surface condition (Section 2.5).

Inaccurate rainfall-runoff modelling based on estimated and assumed parameter values and model structures will lead to initial estimates of drainage design that either over-estimate design requirements, thus unnecessarily increasing estimates of costs, reducing the viability of a project; or underestimate rainfall-runoff behaviour leading to a design that fails to maximise hydrological benefits. Therefore, it is important that hydrologists and engineers understand how the assumptions, methods, decisions and tools that are used to model urban rainfall-runoff behaviour impact on retro-fit drainage design and thus on estimates of construction costs.

This chapter assesses how uncertainty in defining surface cover and choosing parameter values to reflect surface connectivity affects estimates used in drainage design and cost estimates. The average PR value from the monitored rainfall-runoff events described in Chapter 5 is used to estimate the volume of additional runoff that is generated at Arley Close and Winsley Close following urbanisation. It is then assumed that this volume of runoff is to be stored on site using a retro-fitted reinforced concrete storage tank and a figure published by Stovin and Swan (2007) (e.g. £500/m^3)

is used to estimate construction costs. The uncertainty of modelling the rainfall-runoff properties of Arley Close and Winsley Close is then assessed by using a decision tree. This examines how different methods of estimating surface cover, connectivity and choosing a rainfall-runoff model produce a range of possible modelled percentage runoff values. The modelled PR values are used to estimate storage requirements and hence the costs of constructing an appropriate storage tank, which are compared to estimates of costs derived from monitored rainfall-runoff data to quantify any additional costs resulting from inaccurate rainfall-runoff modelling. A sensitivity analysis of the UK Variable Runoff Model is used to examine how model parameterisation to reflect surface connectivity affects drainage design and cost estimates. Different methods of defining the Effective Impervious Factor (IF) (Section 3.9.5) are used and inaccuracies in PR values are converted into drainage design costs overspend, or volume under-design.

6.2 RESULTS

6.2.1 Additional runoff volume from Arley Close and Winsley Close following urbanisation

This Section uses Equation 3.10 described in Section (3.9) to estimate the additional volume of runoff that is generated at Arley Close and Winsley Close following urbanisation.

$$Vol_{xs} = RD\,.A.(PR_{URB} - PR_{GF}) \qquad \text{Equation 3.10}$$

To estimate the greenfield percentage runoff (PR_{GF}) of Arley Close and Winsley Close the plot scale methods of ReFH2 are used (defined in Section 3.9.1). To apply the ReFH2 model a file of point characteristics is downloaded from the FEHweb service which is then loaded into the ReFH2 software. The urban extent is set to 0, and the model executes as though the plot is under greenfield conditions. The 100-year 6-hour design rainfall event is generated and the greenfield percentage runoff values for the direct runoff is calculated (PR_{GF}). The average PR values for Arley Close and Winsley Close derived from the monitored rainfall-runoff events analysed in Chapter 5 represent the conditions of the actual urbanised developed site (PR_{URB} parameter in equation 3.10, Table 6.1).

Table 6.1: Comparison between greenfield and developed percentage runoff values for Arley Close and Winsley Close for the 100 year 6 hour event. Greenfield values are estimated using the ReFH2 site based methods. Developed values are derived from the mean PR value of monitored events described in Chapter 5.

	Arley Close	**Winsley Close**	**Method**
Condition	**PR (%)**	**PR (%)**	
Greenfield (PR_{GF})	22	12	ReFH2
Developed (PR_{URB})	60	28	Observed
Urbanisation change	38	16	

The percentage runoff has more than doubled at both sites, indicating that urban development has had a dramatic impact on percentage runoff values.

Equation 3.10 is used to determine the additional volume of runoff generated at Arley Close and Winsley Close following urbanisation. This is the volume of runoff that would need to be stored or managed on site, were Arley Close and Winsley Close to be retro-fitted with new drainage assets to meet the current drainage design criteria of not increasing runoff volumes downstream following development (Woods-Ballard et al., 2015). Winsley Close requires a runoff storage volume per hectare of development that is approximately half of that required in Arley Close (Table 6.2). The estimated cost of constructing a storage tank large enough to store the runoff volume is £95,000/ha at Arley Close and £40,000/ha at Winsley Close.

Table 6.2: Additional volume of runoff following urbanisation created at Arley Close and Winsley Close for the 100 year 6 hour event and the volume per ha of

development. Costs are estimated based on the retro-fitting of a reinforced concrete storage tank at a unit cost of £500 /m^3 (Stovin and Swan, 2007).

Site	Area (ha)	Rainfall Depth (mm)	PR_{URB}-PR_{GF} (%)	Vol (m^3)	Vol (m^3/ha)	Estimated Cost (£/ha)
Arley Close	0.4982	50.24	38	95	191	£95,000
Winsley Close	0.669	50.24	16	54	80	£40,000

Table 6.2 contains the best estimate of the additional volume of runoff that is generated at Arley Close and Winsley Close due to the urbanisation process. This will provide a baseline estimate against which estimates derived from urban rainfall-runoff modelling can be compared and an assessment of whether modelled estimates of PR_{URB} would lead to the under or over design of runoff storage and estimated construction costs.

6.2.2 Examining uncertainty in urban runoff volume modelling

There are a number of sources of uncertainty in modelling the urban rainfall-runoff process outlined in Section 3.9.4:

(i) Defining Surface cover and connectivity,

(ii) choosing an appropriate urban rainfall-runoff model, and;

(iii) choosing model parameters to reflect site conditions.

Hydrologists and engineers use a number of assumptions and methodologies to infill areas of missing data (Section 3.3.1), estimate the connectivity of surfaces to the surface water drainage system (Section 3.9.5) and describe the rainfall-runoff properties of urban surfaces within hydrological models.

A decision tree is constructed to examine how a range of modelling outcomes are possible, depending on the methodological choices and assumptions that are applied in the rainfall-runoff modelling process (Figure 6.1). In total 72 model outcomes are possible in the decision tree configuration presented in Figure 6.1. To interpret the decision tree start at the first node of the left hand side of the Figure. Here a decision is made about what method should be applied for PIMP estimation (see Section 3.3.1

for details of the possible methods), there are three possible choices which lead to a HIGH, MEDIUM or LOW estimate of PIMP (Table 4.3, 4.4). At the next node a decision/assumption is made about the connectivity of rear garden impervious surfaces (e.g. are non-vegetated rear garden surfaces connected to the surface water drainage system?, Section 3.4.3); there are two options here; connected and disconnected. The next decision node relates to how surface connectivity should be defined for surfaces in public and front garden areas. There are three possible choices here;

(i) 100% connected (i.e. those surfaces with a direct and indirect connection are defined as connected),

(ii) Some method of combining those surfaces with direct and indirect connections to the surface water drainage system in a weighted sum approach (this is just a theoretical approach used in this example to account for the fact that there are a number of different approaches to defining connectivity within the two extremes of (i) and (iii)), and;

(iii) An assumption that only those surfaces with a direct connection to the surface water drainage system should be included.

The final decision node asks what urban rainfall-runoff model should be used to estimate the percentage runoff of Arley Close and Winsley Close. The options are the SuDS method (Section 3.9.2.4), the Fixed UK Runoff Model (Section 3.9.2.1), the Variable UK Runoff Model (Section 3.9.2.2) or the ReFH2 urban extension (Section 3.9.2.3).

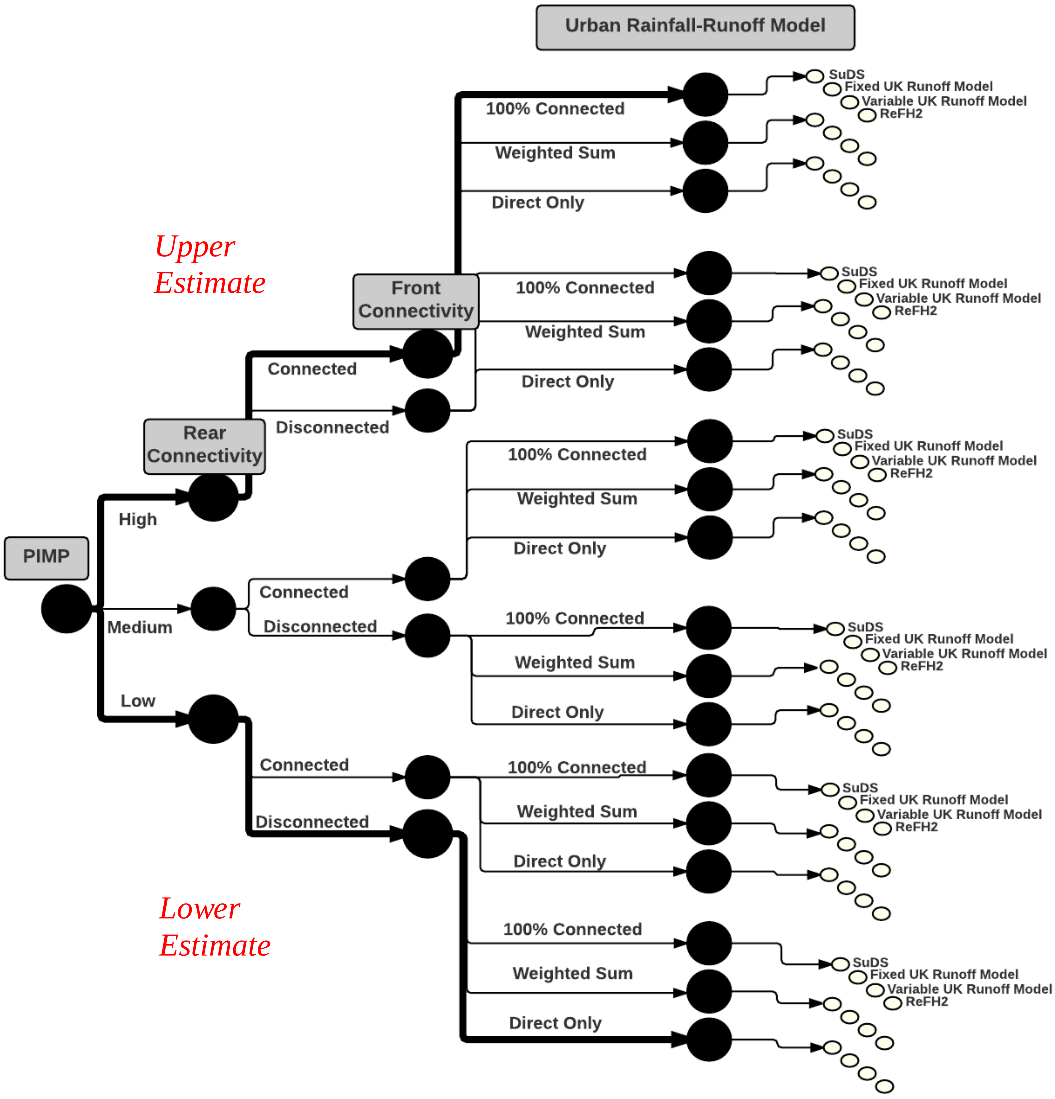

Figure 6.1: Decision tree examining 72 possible outcomes for rainfall-runoff modelling. The darker lines indicate the two scenarios that are examined to quantify the upper and lower bounds of modelled PR_{URB}, storage volume and cost estimates.

To determine the upper and lower bounds of possible modelling estimates, two scenarios are applied (as highlighted by bold lines and labelled in red italics on Figure 6.1). These two scenarios define the maximum and minimum storage volume that are possible to estimate at Arley Close and Winsley Close. Modelled runoff volumes are compared to that calculated using the mean PR value for the monitored rainfall-runoff data at Arley Close and Winsley Close (Section 6.2.1). The results are stated as either the under sizing volume of runoff (m^3/ha), or the cost of additional storage for the over-modelling of PR_{URB} (£/ha). The two modelling outcomes have different units given the different interpretations of the PR_{URB} modelling result (e.g. under design storage m^3/ha vs overdesign cost £/ha).

PIMP values in Table 6.3 are the values derived from implementing the HIGH and LOW methodologies for estimating impervious surfaces (Section 3.3.1). An Effective Impervious Factor (IF, Section 3.9.3) value of 1 means that all impervious surfaces are assumed to connect to the surface water drainage system, the values 0.87 (for Arley Close) and 0.65 (for Winsley Close) are the IF values derived from assuming that only those surfaces with a direct connection to the surface water drainage system contribute runoff. The PR_{mod} column is the PR_{URB} value that the urban model listed in the Model column produces given the PIMP and IF values. The PR_{mon} column details the value of average PR for the events analysed in Chapter 5. The Vol_{mod} and Vol_{mon} columns calculate the additional volume of runoff that is generated through urbanisation for the PR_{URB} values that are modelled and monitored.

Table 6.3: Definition of upper and lower estimates of runoff storage volume required at Arley Close and Winsley Close. The results are compared against the volume estimated from monitored PR values and the overdesign or under-design is defined in terms of costs of over-design or under-design volume per hectare of development (results rounded to nearest £1000 or m^3).

SITE	**High/Low**	**Model**	**PIMP**	**IF**	**PR_{mod} (%)**	**PR_{mon} (%)**	**Vol(mod) (m^3)**	**Vol(mon) (m^3)**	**Error**	**Overspend (£/ha)**	**Under design (m^3/ha)**
ARLEY	High	SuDS	71	1	62	60	100	95	5	£5, 000	0
ARLEY	High	Fixed PR	71	NA	55	60	82	95	-13	0	26
ARLEY	High	Variable PR	71	1	77	60	138	95	43	£43,000	0
ARLEY	High	REFH2	71	1	71	60	120	95	25	£25,000	0
ARLEY	Low	SuDS	54	0.87	38	60	40	95	-55	£0	110
ARLEY	Low	Fixed PR	54	NA	41	60	47	95	-48	£0	96
ARLEY	Low	Variable PR	54	0.87	58	60	90	95	-5	£0	10
ARLEY	Low	REFH2	54	0.87	47	60	63	95	-32	£0	64

SITE	**High/Low**	**Model**	**PIMP**	**IF**	**PR_{mod} (%)**	**PR_{mon} (%)**	**Vol(mod) (m^3)**	**Vol(mon) (m^3)**	**Error**	**Overspend (£/ha)**	**Under design (m^3/ha)**
WINSLEY	High	SuDS	64	1	56	28	148	54	94	£70,000	0
WINSLEY	High	Fixed PR	64	NA	49	28	124	54	70	£52,000	0
WINSLEY	High	Variable PR	64	1	71	28	198	54	144	£108,000	0
WINSLEY	High	REFH2	64	1	64	28	175	54	121	£91,000	0
WINSLEY	Low	SuDS	43	0.65	22	28	34	54	-20	£0	30
WINSLEY	Low	Fixed PR	43	NA	32	28	67	54	13	£10,000	0
WINSLEY	Low	Variable PR	43	0.65	42	28	101	54	47	£35,000	0
WINSLEY	Low	REFH2	43	0.65	28	28	54	54	0	£0	0

The Error column is the difference between the required storage volume estimated through modelling and that through the analysis of monitored rainfall-runoff data. The errors are converted into either an estimated overspend of £/ha, or runoff volume under-design defined as m^3 of runoff per ha. Table 6.3 demonstrates that at Arley Close the two scenarios tested both over and underestimate the volume of runoff generated following urbanisation and this leads to a range of modelling outcomes from a possible over spend of £43, 000/ha to a potential under sizing of surface runoff storage of $110m^3$/ha. At Winsley Close the two scenarios tested over estimate runoff volume and thus construction costs by up to £108,000/ha and under design volume by up to $30m^3$/ha. At both sites the highest overdesign scenario occurs when PR_{URB} is modelled with the UK Variable Runoff Model, a HIGH PIMP estimation methodology and an IF value of 1.

In Winsley Close, it is possible to estimate the excess runoff volume arising from urbanisation accurately, using the REFH2 model, under the LOW methodological assumption for estimating PIMP and an IF value of 0.65. However, under the same methodological assumptions in Arley Close this scenario estimates an under design of storage of 64 m^3/ha. This demonstrates that Arley Close and Winlsey Close require separate methods for estimating surface cover and connectivity to accurately estimate rainfall-runoff behaviours within the same model, indicating that model choice and calibration should be site specific and sensitive to the characteristics of urban development under study. To further explore the parameterisation of rainfall-runoff models within Arley Close and Winsley Close the next section (Section 6.2.3) conducts a sensitivity analysis of the UK Variable Runoff Model.

6.2.3 Sensitivity analysis for UK Variable Runoff Model

To improve the modelling of PR_{URB} values and to reduce the uncertainty of representing surface connectivity within urban rainfall-runoff models, a sensitivity analysis of the UK Variable Runoff Model is conducted. The aim is to determine the sensitivity of modelled PR_{URB} values to PIMP and IF, accordingly values of NAPI and PF are set to 17 and 200 respectively, based on the average values of those recommended by Woods-Ballard et al.

(2015) and a one at a time methodology is used to adjust values of PIMP and IF to calculate PR_{URB} (Section 3.9.4). The results are presented in Figure 6.2.

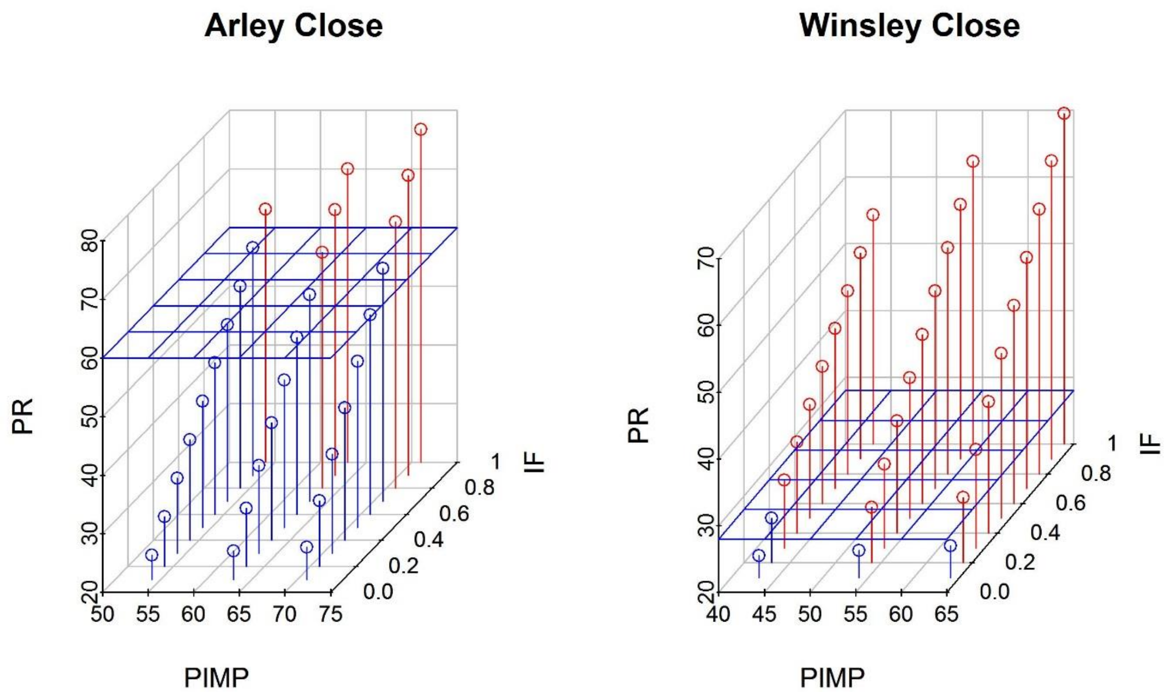

Figure 6.2: Values of PIMP, IF and PR for the UK Variable Runoff Model. Red points indicate that PR is overestimated in comparison to the average monitored value of PR, whilst blue points show underestimates. The 3d hyperplane shows the average monitored PR values

Figure 6.2 shows the values of PR_{URB} calculated for each combination of PIMP and IF value. The points are coloured to show if a modelled estimate of PR_{URB} is above or below the average PR value from the monitored dataset (as shown by the 3d hyperplane on each plot). The three values of PIMP used in each plot are the values derived from the HIGH, MEDIUM and LOW methodologies for estimating impervious surfaces (Section 3.3.1, Table 4.3, 4.4). Modelled estimates of PR_{URB} are highly sensitive to both PIMP and IF with some interaction between PIMP and IF (i.e. at high IF values PR increases at a greater rate with increasing PIMP values). The majority of points at Winsley Close plot above the average PR value derived from the analysis of monitored events (indicating an over estimate of PR_{URB} value) whilst at Arley Close the majority of points plot below PR estimated from monitored data (indicating an underestimate of PR_{URB} value).

To investigate how different methods of estimating IF affect estimates of modelled PR_{URB} the MEDIUM methodology for PIMP estimation is applied and three different methods are used to estimate IF values (outlined in Section 3.9.5):

(i) The first approach for estimating IF uses standard values provided within design guidance for surfaces of various conditions: good, IF=0.75, ok, IF=0.6, poor, IF=0.4, (Woods-Ballard et al., 2015).

(ii) The second approach estimates IF based on an assessment of the geospatial data contained in Chapter 4. Here connectivity is defined in three possible ways: (i) Only those surfaces with a direct connection are connected, (ii) Surfaces with a direct connection are assumed 100% connected, whilst those with an indirect connection are assumed 50% connected. (iii) Both directly and indirectly connected surfaces are considered 100% connected (Table 4.6).

(iii) The third approach estimates the required value of IF needed to derive accurate estimates of PR_{URB} and this value is compared to those derived above.

The results are presented in Table 6.4.

Table 6.4: Summary of IF, PR and the volume of estimated runoff storage at Arley Close and Winsley Close with estimates of overspend or under design in comparison to storage estimates derived from monitored rainfall-runoff data (results rounded to nearest £1000 or m^3).

SITE	**IF Estimation Method**	**PIMP (%)**	**IF**	**PR_{mod} (%)**	**PR_{mon} (%)**	**Vol_{mod} (m^3)**	**Vol_{mon} (m^3)**	**Error**	**Overspend (£/ha)**	**Underdesign (m^3/ha)**
ARLEY	(i) Poor	63	0.45	43	60	53	95	-42	0	84
	(i) Fair	63	0.60	50	60	70	95	-25	0	50
	(i) Good	63	0.75	58	60	90	95	-5	0	10
	(ii) Direct Only	63	0.75	58	60	90	95	-5	0	10
	(ii) Direct + 50% indirect +50% Rear Garden	63	0.85	63	60	105	95	10	£10,000	0
	(ii) Direct + Indirect + Rear Garden	63	1.00	70	60	120	95	25	£25,000	0
SITE	**IF Estimation Method**	**PIMP (%)**	**IF**	**PR_{mod} (%)**	**PR_{mon} (%)**	**Vol_{mod} (m^3)**	**Vol_{mon} (m^3)**	**Error**	**Overspend (£/ha)**	**Underdesign (m^3/ha)**
WINSLEY	(i) Poor	54	0.45	39	28	91	54	37	£28,000	0
	(i) Fair	54	0.60	46	28	114	54	60	£45,000	0
	(i) Good	54	0.75	52	28	134	54	80	£60,000	0
	(ii) Direct Only	54	0.52	42	28	101	54	47	£35,000	0
	(ii) Direct + 50% indirect +50% Rear Garden	54	0.75	52	28	134	54	80	£60,000	0
	(ii) Direct + Indirect + Rear Garden	54	1.00	63	28	171	54	117	£87,000	0

When compared, the modelled and observed estimates of PR_{URB} are closest at Arley Close in comparison to Winsley Close. An IF value of 0.8 is required to generate a PR value that matches the average monitored value at Arley Close. This is close to the IF values that would be used under Method 1:Good (e.g. assuming urban surfaces are in good condition, IF=0.75) and the directly connected only assumption under Method (ii) of defining surface connectivity (IF = 0.75). At Winsley Close PR values are overestimated for all the methods that have been tested for estimating IF. An IF value of 0.19 is required to generate the monitored PR value of 28%. The IF value of 0.19 is considerably lower than that used under the assumption that impervious surfaces are in poor condition (IF = 0.45) and the IF values derived from the analysis of spatial data [Method (ii)]. This implies that current methods for estimating IF, and the underlying assumptions describing urban rainfall-runoff processes in the Variable UK Runoff Model are insensitive to the specific conditions and processes controlling runoff generation in Winsley Close. At Arley Close there are a range of volume estimates between an under design of 84m^3/ha to an over spend of £25,000/ha. At Winsley Close the over spend arising from inaccurate rainfall-runoff modelling is up to £87,000 /ha, with all methods of estimating IF generating an over prediction of required runoff volume and thus construction costs.

6.3 DISCUSSION

Due to a paucity of rainfall-runoff data within the urban environment and a lack of generalised understanding of how patterns of imperviousness impact rainfall-runoff behaviour, the parameterisation of hydrological models is often based on estimates and assumptions. Methodological assumptions are applied to infill areas of missing data (e.g. defining surface cover in domestic rear gardens, Section 3.3.1), to estimate the connectivity of surfaces e.g. 70% of impervious surfaces are connected to the surface water drainage system (Packman, 1980a), and to describe the rainfall-runoff properties of impervious surfaces e.g. 100% of rainfall is converted into runoff, Wiles and Sharp (2008). In a review of urban hydrology Redfern et al., (2016, Chapter 2) demonstrates that the rainfall-runoff properties of extant impervious surfaces are more complex than current urban hydrological theory allows for, meaning the current representation of seemingly impervious surfaces in hydrological models is likely to be inadequate or even flawed in some areas. This could mean that runoff from urban areas is over-predicted and thus potential mitigation options are over designed, restricting the ability of retro-fitted surface water management schemes to attract funding due to an inflated estimate of construction costs. This chapter has therefore examined how sensitive cost estimates of retro-fitting surface water drainage assets are to the methodologies and assumptions that are used to represent urban areas within hydrological models.

When estimated using the average PR value derived from monitored rainfall-runoff events to define PR_{URB} in equation 3.10, Arley Close requires a storage volume that is more than double that of Winsley Close (191 m^3/ha vs 80 m^3/ha, Table 6.2). This shows that the increased imperviousness and increased connection efficiency of Arley Close leads to a rainfall-runoff behaviour that requires a much greater intervention to return to greenfield conditions.

Modelled values of urbanised percentage runoff (PR_{URB}) are sensitive to the uncertainty of choosing appropriate rainfall-runoff models, defining surface cover, connectivity and the choice of model parameter values. A decision tree (Figure 6.1) demonstrates that there are 72 possible modelling outcomes given the need to make decisions about the methodological approach to defining surface cover, connectivity and rainfall-runoff model. Whilst this number could be increased or decreased depending on the number of options displayed at each decision, the exercise demonstrates the sensitivity of model outputs to methodological uncertainty caused by incomplete data describing the urban environment and limited understanding of the urban rainfall runoff process at small-scales within urban areas. This leads to a range of modelling outputs that result in either the under design or overdesign of storage estimates at Arley Close, and the over design of storage at Winsley Close. The significance of this is that at Winsley Close, current modelling tools could over predict the PR_{URB} value, runoff volumes and thus construction costs by upto £108, 000/ha. This could limit the ability of a surface water drainage scheme to attract funding at Winsley Close given the costs-benefit ratio that is needed to meet UK Treasury rules. At Arley Close costs are over estimated by upto £43, 000/ha, or the runoff volume is under-estimated by upto 110 m^3/ha (Table 6.3). It is hard to assess what impact under designing storage assets would have on the efficacy of surface water drainage design given that Arley Close and Winsley Close have been considered in isolation to their surroundings. However a direct link is established between the assumptions used in rainfall-runoff modelling and estimated costs of retrofitting surface water drainage systems and this demonstrates that additional research is required to choose appropriate modelling tools, and to describe and parameterise surface types and connectivity within urban areas to reduce modelling uncertainty.

A sensitivity analysis is used to examine how the choice of method to estimate surface connectivity influences surface water drainage design, when applied within a commonly used rainfall-runoff model; the UK Variable Runoff Model. Two techniques are tested to estimate values of IF, (i) based on design guidance, and (ii) based on analyses of surface information. This shows that at Arley Close methods (i) and (ii) can approximately reproduce the average monitored PR_{URB} value and thus achieve a relatively accurate value of required runoff storage. At Winsley Close however, all of the tested methods over predict PR values and this leads to an estimated over design cost of between £28, 000/ha and £87,000 £/ha. This is likely a result of the underlying assumption of the UK Variable Runoff model which is that 100% of rainfall on connected impervious surfaces is converted into runoff. Given the evidence reviewed in Chapter 2 (Redfern et al., 2016), the increased surface age and reduced connection efficiency of Winsley Close, it is unlikely that this assumption holds for Winsley Close, thus demonstrating that greater research is required to fully understand the urban rainfall-runoff process for representation in hydrological models and the consequences of relying on assumed or guidance values of model parameters.

Given the high sensitivity of PR modelling to methodological assumptions used to define surface cover and connectivity, and the choice of rainfall-runoff model, it is important that new methods and datasets are derived to accurately define surface cover and connectivity within urban areas, thus reducing reliance on assumptions. In particular the surface types present within domestic gardens need defining as these surfaces are missing in the current surface datasets of the UK (e.g. Ordnance Survey Master Map, Section 4.3). Relying on simple methods to estimate imperviousness and to describe the urban rainfall-runoff process, may over predict runoff from urban areas with a more complex mix of aged pervious and impervious surfaces (such as Winsley Close) and this may limit the ability of engineers and economists to recommended retro-fitted surface water drainage systems based on inflated estimates of costs caused by inaccurate rainfall-runoff modelling. For example, if the assumptions used by Warhurst et al. (2014) that 100% of rainfall falling onto impervious surfaces is converted into runoff within a surface water drainage system (an IF of 1 in the Variable UK Runoff model), were applied to Arley Close and Winsley Close, this would lead to an overestimate of PR_{URB}, storage volume and construction costs. This is pertinent given that the underlying assumptions of Warhurst (2014) is based on recommendations for the initial sizing of surface water drainage storage (Kellagher, 2012). Overall, these results demonstrate that understanding of, and the methods used to represent urban areas within hydrological models should be sensitive to the specific small-scale physical characteristics of the studied urban development. Applying assumptions and methods across urban areas that exhibit variations in surface cover, age and connectivity will lead to inaccuracies in rainfall-runoff modelling and thus the surface water management planning and drainage design process.

This research has only focussed on pre-development and post-development runoff volumes and not flow rates or flow rate attenuation. Therefore this should be seen as a first step to understanding the linkages between uncertainty in rainfall-runoff modelling and retro-fit drainage design. Future research, utilising more advanced modelling tools that can represent the hydraulic routing of runoff generation could help to fully quantify how uncertainty leads to modelling and cost inaccuracies and the impact of these inaccuracies on surface water management planning.

Chapter 7

DISCUSSION

This chapter discusses the findings of the thesis drawing from the analyses presented in the preceding chapters. The results are discussed in the context of existing urban hydrology theory, hydrological modelling and surface water management planning.

7.1 INTRODUCTION

Surface water management planning and hydrological modelling should be underpinned by hydrological theory that accurately reflects how rainfall is converted into runoff within urban settings. This thesis has examined two fundamental theories of urban hydrology:

(i) that urban surfaces are impervious to the infiltration of precipitation, and,

(ii) that surface connectivity is a binary, connected or disconnected process.

A review of field measurements reported within the scientific and engineering literature of hydrological processes on urban surfaces and the comparison of the physical characteristics and hydrological behaviours of Arley Close and Winsley Close provides evidence to reject these commonly applied assumptions, offering an improved understanding of how variability in urban surface cover, surface condition and surface connectivity influences urban rainfall-runoff behaviour. This chapter discusses the key findings of the thesis, including discussions of residential surface cover, surface condition, and surface connectivity; as well as the suitability of current soil characteristics data in urban hydrology. The implications of these key findings are highlighted for hydrological modelling, residential design and the planning of retro-fitted surface water drainage assets. The methodologies used in the thesis are then reviewed, with recommendations for improved hydrological monitoring in future research highlighted.

7.1.1 Residential surface cover

Arley Close (constructed in the 1990s) and Winsley Close (constructed in the 1950s) contain different proportions of different types of surface cover within domestic and public areas, demonstrating that changing societal and economic factors over the twentieth century have influenced housing design and planning policy, responding to variable market and political pressures (Cullingworth and Nadin, 2002). The areas of rear garden in both developments are twice that of front gardens (Section 4.3) and this 1:2 ratio of front to rear garden area has been recorded in other parts of the United Kingdom reflecting common designs of U.K residential parcels (Loram et al., 2007). Front gardens predominantly contain impervious surfaces in Arley Close, whilst in Winsley Close front gardens are predominantly vegetated lawns (Section 4.3). Increased car ownership between the 1950s and 1990s (Dargay and Hanly, 2007) is likely to be responsible for the dominance of private parking spaces within front gardens of Arley Close whilst the detached and semi-detached housing of Arley Close reflects trends in housing design in private residential areas over the latter half of the twentieth century (Cullingworth and Nadin, 2002). Public spaces differ in terms of the proportion of surface cover under vegetated surfaces, with two large areas of vegetated surfaces present in Winsley Close (Section 4.3). Increased vegetated cover within public areas of Winsley Close reflects the design philosophy underpinning the layout of Winsley Close (the American Radburn Principle) where housing is grouped together around areas of central shared open space (Section 3.1.1). This layout philosophy influences residential design in the post war era, in a number of areas in the U.K (Alexander, 2009), meaning that the design of Winsley Close is fairly typical of public housing constructed during the 1950-1960s era.

There are limited datasets available that define and characterise the types and materials of surfaces within the existing urban environment, meaning current hydrological modelling and surface water management planning is often based on the analysis of aerial photographs or remote sensing (Akbari et al., 2003). In this thesis Ordnance Survey Master Map (OSMM) data, aerial photography and Individual Parcel Assessments (IPA) are combined to characterise surface cover within Arley Close and

Winsley Close (Section 4.3). OSMM data is chosen as it is available for urban areas throughout the United Kingdom and contains data on the location and size of surfaces such as roads and roofs. However, this thesis demonstrates that surface cover within domestic curtilages and road verges are not accurately represented within OSMM (Section 4.3). This is a similar finding to that reported by Perry and Nawaz (2008) who ascribe this missing data to a historic lack of direct planning control for domestic surfaces. In recent years however, planning policy has changed in the UK to include the development management of domestic surfaces, with impervious surfaces over $5m^2$ no longer included within permitted development rights (Warhurst et al., 2014). Therefore, there is now a need for new datasets defining surface cover within domestic parcels, for use in planning policy enforcement, hydrological modelling and surface water management planning.

Defining surface cover within domestic areas based on the interpretation, classification and digitisation of aerial photography is inherently uncertain, given that the complex three dimensional shape of the urban environment obscures ground surfaces within aerial photographs and satellite remote sensing (Section 3.3.1). In this thesis, areas of missing data defining surface cover within domestic gardens are infilled by applying assumptions taken from relevant literature e.g. non vegetated garden surfaces are impervious, Lee and Heaney (2003), or that garden patios are considered impervious, Perry and Nawaz (2008). Estimates of total imperviousness are shown to be sensitive to the methodological assumptions used and the significance of estimating imperviousness for hydrological modelling and surface water management is demonstrated in the results reported within Chapter 6 (Section 6.2.2) supporting other studies that have highlighted the sensitivity of modelling to estimates of imperviousness (Arnold and Gibbons, 1996; Sanzana et al., 2017). Methods of overcoming the uncertainty of analysing aerial photography and remote sensing at small-scales and defining the hydrological properties of urban surfaces within urban areas are therefore required to improve the definition, monitoring and representation of urban surface cover within hydrological models (Myint et al., 2011).

7.1.2 Surface condition

Chapter 2 establishes that the condition of urban surfaces greatly affects rainfall-runoff properties (Redfern et al., 2016). Surface features such as cracks, joins and kerbing facilitate the interception, storage and infiltration of runoff and this impedes the generation of surface runoff across extant surfaces, in comparison to small samples of surface materials tested under laboratory conditions (Section 2.5). The hydrological properties of roads and roofs are different, as roads degrade in condition through exposure to weathering and wearing processes, increasing losses and reducing runoff. This means that over different timescales the hydrological properties of urban surfaces can change, with surface characteristics (e.g. condition) affecting rainfall runoff properties and connectivity of surfaces to the surface water drainage system. Whilst it is recognised that surface condition can affect rainfall-runoff properties within surface water management planning guidance (Kellagher, 2000) it is difficult to link degraded condition with rainfall-runoff properties without detailed experimental data which is often lacking (Wiles and Sharp, 2008).

It is currently not possible to accurately determine the condition of urban surfaces through the analysis of aerial photography and satellite remote sensing (Jengo et al., 2005), therefore in this thesis, site visits are used to assess surface condition in Arley Close and Winsley Close. Whilst there is little surface degradation observed in either study area, visual inspection of surfaces alone may not be sufficient to determine hydrologically relevant condition, given the insensitivity of runoff losses to surface defect size reported by Wiles and Sharp (2008). Instead determining surface age may be an approach that is more sensitive to rainfall-runoff properties, as poor surface condition is likely to be a function of increased surface age (and thus increased exposure to wearing and weathering processes, Section 2.5). However, there is currently little data available examining how surface age affects rainfall-runoff properties at the development plot or catchment scale. The results within this thesis suggest that surface age, in combination with layout and drainage connection efficiency influence sub-catchment rainfall-runoff behaviour illustrated by the fact that Winsley Close (developed in the 1950s) has an average percentage runoff and peak flow rate value that is less than half that of Arley Close (constructed in the 1990s, Section 5.3.1).

The hydrological monitoring conducted in this study reflects the common approach of collecting rainfall-runoff data at the whole catchment scale within hydrology (Davie, 2008). Thus, it is not possible to examine the rainfall-runoff performances of individual surfaces within Arley Close and Winsley Close, to quantify how surface age affects rainfall-runoff properties in isolation to other potential variables (e.g. connectivity). To improve understanding of the linkages between surface age, condition and connectivity with rainfall-runoff behaviour future research could link catchment scale rainfall-runoff monitoring with techniques that build on the work of Hollis and Ovenden (1988a) or Wiles and Sharp (2008), whereby the hydrological properties of in-situ urban surfaces are determined through experimentation. An irrigation experiment that examines the losses on extant urban surfaces as a function of drainage distance, condition and connection type (direct or indirect connection) would be particularly useful for quantifying how surface condition influences urban rainfall-runoff behaviour in existing urban areas. If conducted across a number of different development types, of different ages, understanding of urban rainfall-runoff behaviour could then be developed that is sensitive to the age of construction, something that it is possible to map with current GIS and remote sensing techniques e.g. the historic land use mapping used by Miller et al. (2014).

7.1.3 Surface connectivity

The connectivity of urban surfaces to surface water drainage systems is an important factor affecting the rainfall-runoff properties of urban areas (Roy and Shuster, 2009; Sanzana et al., 2017). Connectivity is currently regarded as a binary process within urban hydrology, i.e. a surface is considered either connected to or disconnected from the surface water drainage system (Shaw et al., 2010; Shuster and Rhea, 2013). This thesis has examined the connectivity of surfaces within Arley Close and Winsley Close and expanded this simplistic definition of connectivity to include connection efficiency (Section 4.4.1), additionally defining those surfaces with a direct and indirect connection to the surface water drainage system (Section 4.4.2). This provides a novel methodology comparing how the layout of surfaces, local topography and the distribution of hydraulic connection points affects the connection between the urban surface and surface water drainage system. The methodology is based upon pre-existing tools in a commonly applied GIS software (ArcGIS) and readily available open data (LiDAR data from the Environment Agency). Therefore it would be possible to apply this methodology to other areas of the United Kingdom and internationally where LiDAR data is available to examine how connectivity varies across different urban land uses, constructed in different time periods to improve understanding of urban surface connectivity.

Connectivity is controlled by the presence, location and type of hydraulic entry points between the urban surface and surface water drainage system (Lee and Heaney, 2003). In Arley Close and Winsley Close connection points are identified through detailed site study, and are either road gullies, roof downpipes or linear drainage features reflecting commonly occurring hydraulic connections in residential areas (Alley and Veenhuis, 1983) - Section 4.4. At both sites roofs constitute the largest area of impervious surface with a direct connection to the surface water drainage system (Section 4.4.2), contradicting studies that have mapped connectivity within domestic areas within the United States that show that roads constitute the largest connected surface, though roofs are also highly connected in these studies (Lee and Heaney, 2003; Roy and Shuster, 2009). This could reflect increased research and management effort in the United States to disconnect domestic roofs from surface water drainage systems to improve rainfall-runoff characteristics, either through planning policies or post construction incentive schemes (Walsh et al., 2005; Thurston et al., 2010; Sohn et al., 2017) and demonstrates how the connectivity of urban surfaces varies across different urban areas both locally and internationally. Overall, Arley Close has an increased connection efficiency between the surface water drainage system and the urban surface (the area connected within 10m of a drainage gully is greater, Section 4.4.1) demonstrating that surface connectivity is sensitive to development age and the characteristics of urban design (Roy and Shuster, 2009). The addition of road gullies to private impervious surfaces increases the efficiency of connections to the surface water drainage system in Arley Close and increases the area of directly connected impervious surface. Therefore controlling, and reducing private surface connectivity may reduce the overall connection of surfaces within residential development.

Intensive study is required to map the positions of hydraulic entry points (road gullies, roof downpipes) within Arley Close and Winsley Close as it is not possible to determine their locations from aerial photographs or satellite remote sensing and no publically available data exists describing their distribution (Section 3.4). Similar methods of mapping the connectivity of surfaces have been used within the literature e.g. Roy and Shuster (2009), though this is one of the first studies to define in detail the connectivity of domestic surfaces within the United Kingdom through site inspections; Miller et al. (2014) and Kjeldsen (2009) estimate UK surface connectivity as 70% of total imperviousness based on estimates used by Packman (1980a), whilst Perry and Nawaz (2008) and Warhurst et al. (2014) assume all urban impervious surfaces are connected to drainage systems. Arley Close and Winsley Close both contain roads and roofs that are connected to the surface water drainage system. However, it would be inaccurate to define these surfaces as having the same connection characteristics, given the increased number of connection points in Arley Close which create small drainage areas, with small drainage distances, with increased connection efficiency. Thus generalising the connectivity characteristics of residential areas, extrapolating from one area to another, is likely to provide inaccurate estimates of connectivity as connectivity varies across urban areas. Where relationships between imperviousness and connectivity have been derived e.g. Alley and Veenhuis (1983), they show poor performance when applied to areas outside their original derivation (Lee and Heaney, 2003). More research is therefore required to improve the measurement and definition of surface connectivity to address this challenge. Techniques that apply generalised estimates of connectivity should be avoided to facilitate the improved representation of urban surfaces within hydrological modelling and surface water management planning.

7.1.4 Urban soil properties and rainfall-runoff behaviour

There is currently limited data available for characterising soils within the urban environment, and thus existing datasets, not originally intended for use in urban settings are commonly applied within urban hydrology (Law et al., 2009). Two current soil datasets are used for initial comparisons of soils in Arley Close and Winsley Close (the WRAP and HOST classification systems, Section 3.2). Each of these datasets is used extensively for hydrological purposes in the United Kingdom, including in urban hydrology (Kidd and Lowing, 1979; Woods-Ballard et al., 2007). The WRAP classification defines soils as being type 4 in both Arley Close and Winlsey Close (Section 4.2.1), which suggests restricted drainage characteristics. The HOST classification defines soils in Arley Close as type 25 and in Winsley Close as both types 2 and 25 (due to Winsley Close being located at the boundary between two 1km^2 HOST grid cells, Figure 4.1). HOST classes 2 and 25 have different hydrological characteristics (Table 4.1) and thus soil samples collected from Arley Close and Winsley Close are studied to determine and compare the soil characteristics of vegetated surfaces. The mineral grain size distribution and bulk density are similar whilst organic content is greater in Winsley Close. This difference in soil organic content is ascribed to two possible differences between the vegetated surfaces of Arley Close and Winsley Close. Firstly, Winsley Close is an older development and thus vegetated surfaces within Winsley Close have had a greater time period over which to accrue organic matter (De Kimpe and Morel, 2000) and secondly, Winsley Close contains mature trees, which contribute organic matter to urban residential soils through leaf fall and wood debris (Woltemade, 2010). The analysis of soil samples in this thesis therefore confirms the variability of soil characteristics in urban areas and their sensitivity to local conditions.

Defining urban soil properties at small development plot scales using large scale datasets is difficult and uncertain as urban soils and vegetated areas are exposed to a range of environmental conditions and management practices, resulting in urban soils that have a range of physical properties that develop in a highly variable, complex spatio-temporal pattern (Pouyat et al., 2010; Huot et al., 2017). Understanding how representative and relevant current soil maps, commonly applied in urban hydrology, are to urban soil characteristics and variability is uncertain since there are a number of challenges of applying current soil characteristics maps within the urban environment at the small development plot scale. The urban surface is organised into parcels of irregular shape and size that do not easily match either the gridded format of HOST or large-scale representation of WRAP. Given that no significant regression coefficients link soil moisture to rainfall-runoff behaviour in either development (Section 5.4.2), it is unclear what hydrological processes link vegetated surfaces within urban areas to larger plot scale rainfall-runoff behaviour of urban developments (Boyd, 1994) and thus it is uncertain what physical soil properties influence urban rainfall-runoff behaviour. HOST is based upon soil properties that affect the generation of runoff within large fluvial catchments (Boorman et al., 1995). What relevance these processes have to the generation of runoff within surface water drainage systems at the small urban residential plot scale is unclear. Therefore, it is plausible that HOST is not a useful dataset for comparing soils within the urban environment despite its wide use in some hydrological modelling and surface water management applications (Woods-Ballard et al., 2007). WRAP is sensitive to soil properties that affect runoff generation during events, and therefore may be more appropriate for describing small-scale, event based rainfall-runoff processes. However, at only 1:625000 scale it is difficult to be certain how representative WRAP is of small-scale conditions within urban environments. Arley Close and Winsley Close both contain surface soils that are defined as Light Silts/Loams, occupying similar areas on the UK Soils Texture ternary diagram (Section 4.2.1). Whether this similarity of soil grain size distribution is a consequence of historic geological and soil generating processes, or the fact that soils of similar characteristics are often imported into green spaces in urban areas during construction is unclear (Pouyat et al., 2007). In addition, it is currently uncertain how the impacts of urbanisation on soil properties affects rainfall-runoff properties at the plot scale, and how this can be estimated from existing soils data (Law et al., 2009). Overall, additional research is required to examine how urban soil characteristics vary from those suggested by large-scale soil maps to develop methods of relating urban development patterns with soil and hydrological properties.

7.1.5 Rainfall-runoff behaviour of Arley Close and Winsley Close

Analysis of monitored rainfall-runoff data collected in Arley Close and Winsley Close shows that the combined differences in design and ages of development result in average peak flow rates and percentage runoff values at Arley Close that are more than double those at Winsley Close, a statistically significant result (Section 5.3.1). Statistical modelling (multiple linear regression) highlights that peak flow rates at both sites are sensitive to the ten-minute rainfall intensity supporting the theoretical unpinning of the Rational Method (Lloyd-Davies et al., 1906; Shuster et al., 2005). However, the regression results indicate a non-linear response between peak flow rates and rainfall intensity in combination with measures of antecedent conditions (Section 5.4.2). The implications of this result for understanding the urban rainfall-runoff process is uncertain but potentially significant. Small changes in rainfall intensity at higher rainfall intensities may produce increases in peak flow rate in a manner that is unaccounted for within current theory (e.g. that the relationship between rainfall intensity and peak flows is linear). Additional research is therefore required to examine the implications of non-linear associations between peak flow rates and rainfall intensity, especially under altered rainfall patterns as a result of climate change (Trenberth et al., 2003).

Percentage Runoff values are variable at both sites, yet at Arley Close PR values are insensitive to the tested rainfall characteristics and the measures of antecedence (Section 5.4.2). At Winsley Close, describing the sensitivity of percentage runoff is uncertain, given that two possible models containing different parameters are shown to be statistically significant, with the same adjusted coefficient of determination. This contradicts the work of Kidd and Lowing (1979) who demonstrate that multiple linear regression can be used to predict the percentage runoff of events within small urban catchments. However, Kidd and Lowing (1979) is based on analyses of rainfall-runoff data collected from 17 catchments across the UK and thus focusses on linking percentage runoff to variables that describe land cover (percentage imperviousness) and soil types (WRAP classification) similar to the work of Goldshleger et al. (2009). Here, the regression modelling is examining rainfall-runoff behaviour within each catchment, attempting to link variability in percentage runoff values to rainfall characteristics and antecedent conditions, something that is shown to be difficult in previous research given the large number of hydrological processes acting across even small urban catchments (Ramier et al., 2011).

7.2 IMPLICATIONS OF RESULTS FOR URBAN HYDROLOGICAL MODELLING

There are a number of sources of uncertainty in modelling the rainfall-runoff properties of urban development, including:

(i) Defining surface cover in urban areas,
(ii) choosing a rainfall-runoff model,
(iii) choosing parameter values.

A decision tree in Chapter 6 (Section 6.2.2) examines this uncertainty, defining a range of potential model outputs based upon the methodological choices and assumptions that are made by a hydrological modeller. This shows that there is a range of potential model outcomes, highlighting the sensitivity of model outputs to data input e.g. urban surface definition (Shields and Tague, 2012), model parameter choice (Yu and Coulthard, 2015) and the definition of surface connectivity. Previous research has confirmed the sensitivity of hydrological modelling to these inputs and suggested that modelling results should be presented as a probability (to account for uncertainty), rather than a deterministic single value (Salvadore et al., 2015), though this may be difficult in engineering design applications.

This thesis provides evidence to question the use of simplistic, binary approaches for defining surface hydrological properties in urban areas e.g. impervious vs pervious and connected vs disconnected, which are fundamental hydrological assumptions underpinning much contemporary urban rainfall-runoff modelling and surface water management planning (Wiles and Sharp, 2008; Warhurst et al., 2014). The hydrological properties of urban surfaces are complex and sensitive to a number of different hydrological, wearing and weathering processes that respond to variations in the materials of construction, slope, age, condition and connectivity to the surface water drainage system (Redfern et al., 2016). The hydrological properties of green spaces within urban areas are affected by the process of urbanisation (e.g. compaction, importation of foreign materials) whilst the ongoing environmental conditions of urban areas also affect the hydrological properties of urban soils e.g. the deposition of hydrophobic pollutants (Pouyat et al., 2010). Representing such complexity within hydrological models and surface water management planning is potentially unnecessary, given that not all hydrological processes at all scales need accounting for within hydrological models or surface water management planning (Beven, 2011). However, where deficiencies in understanding cause inaccurate rainfall-runoff modelling (as demonstrated in Chapter 6), this limits evidence based surface water management planning, thus reducing the efficacy of hydrological management (Borowski and Hare, 2007). Understanding what level of detail is required to accurately represent the urban surface within hydrological theory, and at what scale certain physical features and processes produce significant effects on hydrological behaviour is therefore a research priority (Blöschl and Sivapalan, 1995; Leandro et al., 2016; Ichiba et al., 2017).

The analyses contained within Chapter 6 demonstrate the importance of hydrological models that are sensitive to site specific physical conditions, and thus, improved hydrological models, and parameter estimation methods that can be tuned to reflect surface condition, material type and connectivity are required. Urban surfaces, that would typically be defined as impervious within urban hydrology (e.g. road, footpath etc.) should not be assumed to be 100% impervious to the infiltration of precipitation or assumed to convert 100% of rainfall into runoff in all urban settings. This contradicts much of the parameterisation used within hydrological modelling (Warhurst et al., 2014) and surface water management planning, the implications of which could be significant. If a model is developed to examine the impacts of urbanisation on groundwater (Bhaskar et al., 2016; Schütte and Schulze, 2017), then assuming there is no infiltration on impervious surfaces will likely over predict these impacts. Similarly, estimating runoff volumes based on 100% percentage runoff values on urban surfaces (even where there is a direct connection to the surface water drainage system) over predicts runoff volumes (as demonstrated in Chapter 6, Tables 6.3, 6.4) and thus potentially overestimates the impacts of urbanisation on downstream areas. The models that are applied in Chapter 6 are those recommended for use in surface water management planning in the United Kingdom. They were originally developed for uses within new urban developments, and as such their underlying assumptions (e.g. 100% of rainfall is converted into runoff on connected urban surfaces) may be appropriate in this application. However, their use within existing aged urban areas for the purposes of planning retro-fit drainage systems is shown to be inconsistent. Therefore a separate set of model parameters and guidance for use within existing urban areas that accounts for variations in development age and thus condition and connectivity characteristics should be developed.

7.3 URBAN HYDROLOGY IN RESIDENTIAL DEVELOPMENT DESIGN

The rainfall-runoff behaviour of Arley Close and Winsley Close is influenced by their design, supporting other research that has examined how residential layout and drainage density influences rainfall-runoff behaviour (Hatt et al., 2004; Meierdiercks et al., 2010). To improve residential design for reducing runoff generation understanding of how the number and locations of hydraulic connection features affects the connectivity of urban surfaces and thus rainfall-runoff behaviour is a priority. In particular, untangling the relationships between urban imperviousness, surface water flood risk, the design of surface connectivity and runoff generation to downstream areas is needed as reducing surface connectivity may reduce the generation of runoff to downstream areas (Walsh et al., 2005), however this could potentially increase risks of local surface water ponding and thus flooding (Maksimović et al., 2009). Limiting gully positions to only public surfaces may reduce direct surface connections whilst ensuring that important transport infrastructure remains clear of surface water (Fryd et al., 2013). Private land would therefore need landscaping to accommodate runoff generated on private impervious surfaces. This is possible, given that no flooding incidents are reported in Winsley Close during the study period, despite its reduced number of hydraulic connection points in comparison to Arley Close (Section 4.4). In addition, urban vegetated strips could be designed to accommodate surface runoff from private impervious surfaces (Blanco-Canqui et al., 2004).

Gardens constitute a large, potentially green urban space whose hydrological characteristics are recognised as being important for the future application of surface water management technologies e.g. rainwater gardens (Asleson et al., 2009). Within hydrological modelling and surface water management planning, gardens (and other urban green spaces) are often considered pervious surfaces with either similar rainfall-runoff properties to natural surfaces, or else as surfaces with no runoff generation capability (Law et al., 2009). However, Chapter 2 (Section 2.6) describes how urban gardens and other vegetated surfaces may be affected by the process of urbanisation and the ongoing environmental conditions present in urban areas, reducing urban soils' ability to hold or absorb water. Designing new urban gardens to include trees may improve hydrological properties, given the ability of tree roots to reduce soil compaction (Bartens et al., 2008) and the addition of organic content from leaf litter which may improve soil infiltration and water holding capacity (Edmondson et al., 2014).

Whilst Sustainable Drainage Systems (SuDS) can be applied within new residential developments (Woods-Ballard et al., 2007) their uptake is restricted by variations in planning, adoption, funding and maintenance policies as a result of a lack of nationally applied policy (e.g. Implementation of Schedule 3 of the Flood and Water

Management Act 2010)(O'Donnell et al., 2017). For example, South Oxfordshire District Council and Durham County Council will adopt and maintain certain SuDS structures if built in a new development (Council, 2016a; Council, 2016b) , whilst in other regions of the UK more complex models of adoption and maintenance agreements are present (WEP, 2015). If developers were encouraged to consider how the design of new developments affects rainfall-runoff behaviour this may limit the need for certain SuDS structures and may reduce the economic costs of applying SuDS techniques in new residential developments, whilst reducing the need for the large-scale adoption of physical structures by reluctant authorities. This would require a large research effort to effectively link different surface design options to reductions in rainfall-runoff behaviour, however the research detailed in this thesis suggests that the choice of surface materials, the design of car parking, reducing surface connectivity and limiting the direct drainage of private areas could all help to reduce runoff volumes and peak flow rates. For example, if private car parking spaces within the domestic parcels of Arley Close were constructed out of an alternative material (e.g. gravels) rather than tarmac, this would likely provide surfaces whose drainage properties more closely mimic natural surface types (like a SuDS component), whilst the maintenance of the surface could be managed by a homeowner rather than requiring adoption by a larger body (i.e. water company, Lead Local Flood Authority etc.). In addition, if domestic impervious surfaces were constructed to drain to adjacent pervious surfaces (for example a grassed lawn), rather than to drainage gullies as in Arley Close, this could also aid in reducing runoff volumes (Mueller and Thompson, 2009). Small-scale changes in residential design could help to reduce the overall rainfall-runoff properties of development and thus potentially achieve similar design outcomes to Sustainable Drainage Systems.

7.4 IMPLICATIONS FOR RETRO-FIT SURFACE WATER DRAINAGE SYSTEMS

The existing urban environment in many areas needs retrofitting with surface water drainage assets, including Sustainable Drainage Systems (SuDS) (Macdonald and Jones, 2006; Stovin and Swan, 2007). Retrofitting the urban environment with new drainage systems is restricted by a number of technical, bureaucratic and economic factors given the costs of construction, competition for space and needs for long term maintenance (Grant et al., 2017). Surface water management planning decisions and drainage design needs to be based upon sound evidence and understanding of urban rainfall-runoff processes to maximise the hydrological benefits of retro-fitted drainage systems (Lamond et al., 2015). However, there are limited monitored datasets describing the rainfall-runoff performance of existing urban catchments worldwide meaning engineers and hydrologists make decisions based upon the outputs of hydrological models (Beck et al., 2017; Fletcher et al., 2013).

Rainfall-runoff modelling tools commonly applied in UK surface water management planning do not reproduce the rainfall-runoff characteristics of the two study catchments consistently (Chapter 6). In Winsley Close, if standard modelling tools, literature assumptions and methods of defining parameter values are applied then the required storage volume and thus construction costs are over estimated by up to £108,000/ha (Table 6.3). In Arley Close it is possible to reduce this error, however, there are a variety of possible modelling outcomes that lead to cost overestimates that are up to £43,000 /ha and estimates of storage volume up to 110m^3/ha undersized (Table 6.3). Chapter 6 therefore illustrates that limitations of understanding of hydrological processes in urban areas and parameter uncertainty, has a direct impact on potential modelling outcomes and thus the surface water management design process, demonstrating the importance of improving knowledge of hydrological processes in extant urban areas for surface water management planning.

Chapter 6 examines a reinforced concrete tank as the storage design option. Other technologies (e.g. plastic crates) and a more distributed, source control based design (favouring the retro-fitting of permeable surfaces or other storage options) may reduce cost estimates (Stovin and Swan, 2007). However, more distributed designs have a higher requirement for working on private as well as public land (Moore et al., 2012) and so may face other non-cost based challenges (e.g. adoption for maintenance purposes). The cost estimates used here (£500/m^3), for a reinforced concrete storage tank, do not include costs associated with land purchase or professional fees. The analyses presented within Chapter 6 therefore are a first attempt to link the uncertainty in the rainfall-runoff modelling process with the surface water management planning decision making and design process using available data and costs estimates. In Winsley Close model estimates of the required runoff storage volume are over-estimated, and thus costs are over-estimated by up to £108,000 /ha. This figure ignores the additional forty percent that is added in UK surface water management planning to take into account future changes in urban runoff generation as a result of climate change (DCLG, 2017). This would mean that initial design calculations based upon the rainfall-runoff models tested in Chapter 6 would actually overestimate the required costs of a storage tank by up to £151, 000/ha in Winsley Close. The significance of this overestimate of construction costs is further demonstrated when the funding criteria of the UK Treasury are examined. To qualify for UK Flood Defence Grant in Aid, the main form of UK government funding for surface water flood risk alleviation works (Priestley, 2017), projects need to demonstrate a benefit to cost ratio of at least 8:1 e.g. £8 of flood risk reduction benefits for every £1 spent on a project (Section 6.1). This would mean that any potential retro-fit drainage scheme would require an additional £1.2m /ha of flood risk alleviation benefits in comparison to design estimates based on accurate rainfall-runoff modelling in Winsley Close and it would be difficult to demonstrate such benefits, thus potentially restricting the ability of small-scale retrofit drainage schemes to attract funding, thus reducing the ability of hydrologists and engineers to manage the urban hydrological system.

7.5 REVIEW OF MONITORING METHODOLOGIES

Only a small number of studies have explored high resolution plot scale urban hydrology directly reporting rainfall-runoff behaviour (Section 2.2), reflecting the challenges of measuring and recording hydrological data within the urban environment. These challenges are explored in greater detail in the next sections with recommendations for improved hydrological monitoring in urban areas proposed.

7.5.1 Data collection, processing and analysis

This thesis contributes to the international literature, where there is a general lack of high resolution plot scale studies in urban hydrology (Section 7.5.). This Section examines the practical difficulties of measuring rainfall-runoff data within the urban environment, recommending steps that could be taken to improve rainfall-runoff monitoring for future research.

7.5.1.1 Runoff monitoring

Runoff within the studied surface water drainage systems is intermittent (Section 3.5), being typical of small urbanised catchments (Maharjan et al., 2016). Flow depths vary and in the case of the Stingray 2.0 (Ultrasonic Doppler Flow Monitor, UDFM) used within this study, depths reduce to a level below the sensitivity of the sensor (25mm, Section 3.6). In this thesis a generalised linear relationship between velocity readings and depth is used to infill missing estimates of depth when flow depth is below sensor range using a standard hydrometric industry method (Hydro-Logic, 2014). Infilling missing values of depths is shown to be important for estimating runoff volumes (Section 5.2.4) and it is therefore important to understand how the physical properties of a monitoring location and monitoring equipment may affect data collection and thus available data analyses. On reflection, to avoid this, a small weir could have been constructed (with requisite permissions) to maintain a constant minimum head of water above the Stingray 2.0 sensor during the study period (Hamill, 2011). Designing such a structure that would meet the requirements of the water undertaker, whilst providing the hydraulic conditions required for effective flow monitoring may be a challenge, especially the need to remove any build-up of sediments behind a weir. As the difficulties of affixing monitoring technologies within surface water drainage pipes have restricted the monitoring of some urban catchments (Maheepala et al., 2001) future research should aim to design a system of affixing Ultrasonic Doppler Flow Monitoring (UDFM) sensors within pipes that exhibit intermittent flow conditions to facilitate improved runoff monitoring.

7.5.1.2 Soil moisture monitoring

It is not possible to place soil moisture PR2 profile probes within green spaces in Arley Close and Winsley Close as there are no secure locations available (Section 3.5.1). Therefore to monitor soil moisture, PR2 probes are placed in what was thought to be secure locations within the grounds of local schools in close proximity to each study site (within 500m), a method that has been applied in previous research monitoring soil moisture within urban settings (Liu et al., 2011; Wiesner et al., 2016). The PR2 probes record soil moisture at 1hr resolution whilst a TDR300 mobile soil moisture probe is deployed on a two-four weekly basis, to collect surface soil moisture readings which are calibrated to site soil conditions following the estimation of volumetric soil moisture content of soil samples (Section 3.5.4). The aim of this methodology is to combine surface PR2 soil moisture readings (100mm depth) with the TDR300 readings (76mm depth) to calibrate and validate the soil moisture readings collected over time by the PR2 probe. However, a number of problems occur with the soil moisture monitoring:

(i) The PR2 soil moisture probes both suffer from vandalism and degradation during the monitoring period impacting on the quality of the data collected.

(ii) The TDR300 probe deforms as rod lengths over 76mm enter the soil (as determined through field trials, Section 3.5.4). Therefore a rod length of 76mm is used. However, this short rod length is highly sensitive to surface vegetation and data collected is not sensitive to seasonal changes in surface soil moisture (Section 5.2.2) a similar finding to Penna et al. (2009).

(iii) Differences in site management and vegetation growth manifests as differences in soil moisture readings collected at Arley Close and Winsley Close during the summer of 2015 with the PR2 profile probes, demonstrating how small-scale changes in site management affect soil moisture and thus data collection. There is an inconsistency in the slope of the DMC comparing soil moisture readings collected by the two PR2 probes because of this (Section 5.2.2).

In this thesis two approaches are used to rectify problems with the soil moisture monitoring data, (i) linear interpolation is used to infill missing data, and (ii) double mass curves are used for Winsley Close following August 2015 (to assess and adjust data collected following vandalism at Winsley Close). To address these challenges in future research the following should be taken into consideration in urban soil moisture monitoring:

(i) Soil moisture monitoring equipment should be tested within urban soils to determine if equipment is of sufficiently robust construction for applications in urban soils prior to purchase and use.

(ii) Access should be negotiated to maintain site vegetation at consistent levels across urban monitoring locations.

(iii) Redundancies should be incorporated into monitoring network design to ensure there is back up data should equipment be vandalised during a monitoring period.

Whilst the risks of vandalism cannot be completely removed from operating in the urban environment, by taking the above into account in future research the risk can be somewhat mitigated.

7.5.2 Practical health and safety considerations

Studying the rainfall-runoff behaviour of residential developments at the small plot scale is difficult, given the practical health and safety restrictions of siting, installing and maintaining flow monitoring equipment within surface water drainage systems (below ground hazards), taking into account additional above ground hazards (e.g. road traffic). Several site visits to the north Swindon area are required to identify locations that provide suitable safe conditions for installing monitoring equipment and the study site selection process is sensitive to practical requirements as well as scientific (Section 3.1.2). To facilitate working within confined spaces and the road network a number of activities are undertaken during this research:

(i) A training course in identifying and managing working within confined spaces is completed (copy of certification, Appendix 1).

(ii) Appropriate health and safety equipment (winch, safety harness etc.) are used to undertake works within surface water drainage systems, with a clear secure working area enabling safe access to surface water drainage system via manholes (Section 3.1.2).

Therefore, to conduct this research, and future urban hydrological research, skills, resources and understanding of the health and safety requirements of operating a monitoring project within the urban environment are required.

7.5.3 Timescales of analysis and data availability

The research contained within this thesis is completed over a period of approximately four years (October 2013 to summer 2017), a typical duration of a PhD project undertaken within the United Kingdom. During the first six months of the project, high precipitation levels led to increased flows within surface water drainage systems of north Swindon. This means that flow monitoring equipment is not installed until the late spring/early summer of 2014. A number of flow measurement equipment malfunctions occur during the initial monitoring period, and the installation of equipment within surface water drainage systems is adjusted whilst replacement parts are supplied by equipment manufacturers. Once the flow monitoring equipment are installed, the PR2 soil moisture probes are installed within school grounds (in July-August 2014). Monitoring continues until mid December 2015, when project practicalities (expiration of health and safety certification) dictate that monitoring ceases. Consequently, there is approximately eighteen months of monitoring data available for analyses in this thesis. This is a typical period over which urban hydrological behaviour has been monitored and studied within the literature. For example, Hollis and Ovenden (1988a) and Gilbert and Clausen (2006) analyse data collected over a twelve month period, Ragab et al. (2003a) a fourteen month period, whilst Legg et al. (1996) only analyse data collected over a two month period.

The prevalence of short term urban hydrological monitoring within the scientific literature reflects the practical difficulties of monitoring hydrological processes within the urban environment whilst also reflecting the high occurrence of projects (and therefore literature) conducted as part of PhD studies. This places urban hydrology in contrast to larger-scale catchment hydrology where long-term hydrological monitoring datasets are available e.g. The National River Flow Archive. This potentially limits urban hydrology, and the type of analyses and therefore research questions that can be asked. This thesis describes how the rainfall-runoff properties of urban surfaces can change over seasonal and longer timescales as materials degrade in condition and surfaces respond to temporally changing physical drivers e.g. temperature and/or wetness (Chapter 2). Monitoring urban rainfall-runoff behaviour over short time periods is unlikely to provide data that fully reflects potential changes in surface hydrological behaviour, and this may stifle hydrology’s ability to establish an accurate parameterisation of how the rainfall-runoff properties of urban surfaces change over different timescales. Similarly a difficulty of conducting hydrological research in the urban environment is the limited availability of data. For example, hydrologists can readily access data on river flow (at least in the United Kingdom and United States), however such data are not available for small-scale urban studies despite previous research that has recorded such data. If a depository of research data were established then urban hydrology researchers could upload data and allow access to a range of researchers, thus facilitating the comparison of a wider range of catchments, nationally and internationally. To this end, the monitoring data generated as part of this thesis will be published online as part of the Environmental Information Data Centre (EIDC), with its own Digital Object Identifier (DOI).

7.6 LIMITATIONS AND FURTHER WORK

Key limitations of the work presented in this thesis include;

(i) This study focusses on the rainfall-runoff properties of two small residential catchments in north Swindon built in the latter half of the twentieth century. It is uncertain how applicable the results reported here are to areas outside the two study locations or to catchments of a larger surface area. Both developments are fairly typical residential developments for suburban areas of the United Kingdom. Both sites exhibit features reported in other areas of the UK (e.g. 1:2 front to back garden area ratios). However, the fact that current urban rainfall-runoff models, largely developed with data collected from urban, residential catchments in the south of the United Kingdom (Kidd and Lowing, 1979), perform poorly when applied to Arley Close and Winsley Close demonstrates that there is variation in the design and thus rainfall-runoff properties of urban areas.

(ii) Only low return period events are analysed in the thesis. Whilst this is to be expected due to the short monitoring period employed, this does limit the ability to fully generalise the findings for a range of hydrological conditions. The two study catchments show dissimilarities in the sensitivity of rainfall-runoff behaviour to antecedent conditions and rainfall characteristics. Whether this difference is present under more extreme event conditions is uncertain.

(iii) Only rainfall-runoff events characterised by a single rainfall input and single runoff output are analysed in this study. This is to simplify the analyses and reduce uncertainty in determining which rainfall input produces subsequent runoff output. However, rainfall does not follow such a strict consistent pattern and instead more complex event profiles (multi-peak events) are possible. Analyses of these events may show more complex interactions between peak flow rates, percentage runoff values and rainfall characteristics and antecedent conditions not present in the regression modelling reported here. Untangling rainfall-runoff relationships for complex multi peak events is complicated and not possible in this thesis given the positioning of rain gauges outside of study catchments (which affects the timing between rainfall and runoff events). In addition, understanding more complex rainfall-runoff events would have required the application of a rainfall-runoff model, which itself would be sensitive to assumptions and uncertainty in parameterisation (Chapter 6). Future research could examine the relationship between rainfall and runoff in multi peak events at the plot scale, where precipitation data collection is possible at more local scales. It could be that during a longer duration event than those examined here Arley Close and Winsley Close exhibit a more similar rainfall-runoff behaviour.

(iv) It is possible that the surface water drainage systems serving Arley Close and Winsley Close contain misconnections from foul water sources (such as washing machines or dishwashers) that may contribute water that does not arise from rainfall, thus potentially overestimating percentage runoff values (Chandler and Lerner, 2015). However, no evidence of this (odour or foul substances) within manholes is observed during the monitoring period.

This thesis has revealed a number of aspects that could be addressed through further research. These are briefly outlined below.

(i) Further research is required to develop methods for describing hydrological features of urban surfaces at small-scales within urban areas, with particular focus on surface types within domestic areas, defining surface condition, surface connectivity and urban soil properties.

(ii) Further research is required to determine the relationship between urban imperviousness, surface connectivity, managing surface water flood risk and the generation of runoff. In particular, determining methods to reduce the generation of runoff by reducing surface connectivity whilst controlling surface water flood risk are required.

(iii) Extant urban surfaces, typically considered as impervious within current hydrological theory should not always be assumed to be 100% impermeable to precipitation, and it should not be assumed that 100% of rainfall falling onto connected impervious surfaces is converted into runoff within surface water drainage systems. Instead, a more detailed understanding of urban rainfall-runoff properties should be developed including the influence of long term changes in condition, different ways in which surfaces connect to the surface water drainage system and differences in surface materials.

(iv) Future research should examine urban soils at a range of depths and where possible expose different soil horizons to identify soil disturbances as a result of urbanisation. Greater research efforts into how urban vegetated surfaces contribute runoff to the surface water drainage system identifying what soil properties affect this process is required.

(v) Rainfall-runoff monitoring within the urban environment should be sensitive to the particular restrictions of operation within the urban environment, including the risk of vandalism and the fact that some equipment may not be originally developed for urban applications. Testing equipment and developing improved monitoring technologies and techniques will help to improve the collection of rainfall-runoff data within the urban environment. Building redundancy into urban rainfall-runoff monitoring network design will help to reduce the likelihood of vandalism impacting on research.

(vi) Surface connectivity should be regarded as more complicated than a simple binary definition where surfaces with direct and indirect connections are determined. Gully and roof down pipe density and overall surface connection efficiency should be examined and linkages to rainfall-runoff behaviour could be expanded by repeating the research conducted here across a greater number of study catchment areas.

(vii) Methodologies for applying rainfall-runoff models and determining model parameters that are sensitive to the specific features of urban development should be developed. Model parameterisation should be sensitive to surface types, conditions, age, and connectivity. This could be through experimental monitoring research using irrigation experiments that examine losses on surfaces of different ages with different condition, materials and connectivity properties.

(viii) Methods of designing residential development to reduce runoff production should be researched, including how the choice of materials, topography and reducing private surface connectivity to surface water drainage systems may reduce rainfall-runoff behaviour. This could then be used in combination with SuDS techniques to reduce the overall runoff production of urban development, whilst reducing the costs and requirements for maintenance of surface water management technologies.

7.7 SUMMARY

Overall, this thesis demonstrates that assumptions often used in the structuring and parameterisation of rainfall-runoff models in small-scale urban areas, do not accurately reflect the complex rainfall-runoff properties of extant urban surfaces within existing aged urban areas. The implications of this are that the outputs of hydrological models may not accurately reflect the true rainfall-runoff performance of urban catchments, potentially reducing the efficacy of surface water management planning. To rectify this, additional research is required to improve understanding of, and the representation of urban surfaces within hydrological theory, focussing on how sensitive urban rainfall-runoff behaviour is to surface cover, surface materials, age, condition and connectivity to the surface water drainage system.

Chapter 8

CONCLUSIONS

This chapter details how the thesis aim and objectives are met before closing the thesis with a final summary.

8.1 FULFILLING THE THESIS AIM AND OBJECTIVES

The aim of this thesis is to:

"determine how the rainfall-runoff behaviour of residential development is influenced by variations in surface cover, hydraulic form and development age, assessing the implications of such differences for rainfall-runoff modelling for use in the planning of retro-fitted surface water drainage infrastructure."

This is achieved by fulfilling the requirements of six research objectives. Below each of the individual objectives are reviewed and details provided of how these are achieved within the thesis.

(i) *Undertake a review of empirical measurements of hydrological processes on common surface types in urban environments, reported within the scientific and engineering literature.*

Empirical measurements of hydrological processes acting on roofs (Section 2.4), roads and domestic surfaces (Section 2.5) and vegetated surfaces (including urban soils, Section 2.6) are examined in Chapter 2 (a paper published within Progress in Physical Geography). The hydrological properties of urban surfaces are shown to be complex and sensitive to a number of different hydrological, wearing and weathering processes that respond to variations in the materials of construction, slope, age, condition and connectivity to the surface water drainage system. Assumptions of surface impermeability applied in hydrological modelling and surface water management planning are inaccurate, demonstrating that current urban hydrological understanding is lacking.

(ii) *Establish a monitoring network (rainfall, runoff, and soil moisture) across two contrasting residential areas that exhibit differences in surface cover and surface connectivity.*

A hydrological monitoring network (rainfall, runoff, and soil moisture) is established in two contrasting residential sub-catchments of north Swindon, constructed during different time-periods; one immediately post- WWII (Winsley Close) and one built during the 1990s (Arley Close). Monitoring equipment is installed and maintained for a period of approximately eighteen months, whilst data are stored and processed to ensure quality (Described in Chapter 3, Sections 3.1, 3.5 and 3.6).

(iii) *Characterise surface cover and connectivity within the two study sub-catchments examining how variation in drainage and surface layout affects the connection between urban surface and surface water drainage system.*

Surface types, surface materials and connection features within the two study sub-catchment areas are mapped, defining surface cover (Section 4.3) and the connection between urban surfaces and the surface water drainage system (Section 4.5). This demonstrates that surface cover and surface connectivity varies across the two study areas, and that surface connectivity is sensitive to local topography and the number and layout of hydraulic entry points (roof downpipes and road gullies). Visual inspections of surface condition are made showing that there are limited visible signs of wearing of surfaces in Arley Close and Winsley Close. Definitions of surface connectivity are expanded from a simplistic binary connected and disconnected approach commonly applied within the literature, to include the overall efficiency of surface connectivity (Section 4.4.1), and surfaces with direct and indirect connections (Section 4.4.2). This demonstrates that despite having roads and roofs that are connected to the surface water drainage system, Arley Close and Winsley Close actually have very different connection properties. Overall, Arley Close has a greater proportion of surface cover under impervious cover, with increased connection efficiency and an increased directly connected surface area (Chapter 4). The implications of this are that surfaces with direct connections to the surface water drainage system are likely to convert a greater proportion of rainfall into runoff, given the reduced opportunity for losses to occur in surface features such as joins, kerbing and defects (features highlighted to allow infiltration, storage and evaporation in Chapter 2).

(iv) Quantify differences in the hydrological behaviour of the instrumented study sub-catchments, focussing on sensitivity of rainfall-runoff behaviour to rainfall characteristics and antecedent conditions.

Individual rainfall-runoff events are extracted from monitored rainfall-runoff data using a Minimum Inter-event Time (MIT) of 30 minutes (Section 3.7.2), with 34 rainfall-runoff events selected for analysis, based upon a number of selection criteria outlined in Section 3.7.3. Baseflow is removed and descriptive metrics describing the magnitude of runoff response are derived (Peak flow rate (QMAX) and Percentage Runoff (PR), Section 3.7.5) and statistical techniques (test of difference and multiple regression modelling) are used to compare rainfall-runoff behaviour across the two sub-catchments in Chapter 5 (Section 5.4.2). Arley Close has peak flow rates and percentage runoff values that are more than double those recorded in Winsley Close (a statistically significant result, P = 0.05, Section 5.3.1), demonstrating that the differences in design and layout of the two areas (defined in Chapter 4) significantly impact the magnitude of event based rainfall-runoff response. The sensitivity of rainfall-runoff behaviour to rainfall characteristics and antecedent conditions are examined through multiple linear regression (Section 5.4.2). Peak flow rates are sensitive to the 10 minute rainfall intensity at each site, with sensitivity to different measures of antecedent conditions exhibited (Section 5.4.2), illustrating how differences in physical design translate into differences in sensitivity of peak flow rates. Percentage runoff values vary at each site: at Arley Close PR values are insensitive to the rainfall characteristics and antecedent conditions tested, while in Winsley Close, describing the sensitivity of PR values is uncertain, given that two regression models, with significant regression coefficients, with the same low value of the adjusted coefficient of determination are found (Section 5.4.2). Describing the sensitivity of percentage runoff values is therefore uncertain across the study sites, demonstrating that the rainfall-runoff behaviour at the small urban catchment scale is perhaps more complex than previously reported. Overall, the hydrological behaviours of Arley and Winsley Close are influenced by their physical design as increased imperviousness, increased connection efficiency and increased directly connected surface area in Arley Close leads to a mean QMAX and PR values double those in Winsley Close.

(v) *Evaluate the ability of common hydrological modelling techniques used in surface water management planning to predict the rainfall-runoff characteristics of the study sub-catchments by examining the sensitivity of estimated runoff volumes to estimates of surface cover, model choice and model parameter value selection.*

Hydrological models used in UK surface water management planning are applied to Arley Close and Winsley Close in Chapter 6. Model results are highly sensitive to hydrological model choice, methods of defining surface cover and connectivity, and methods of defining parameter values (Section 6.2.2 and 6.2.3). Modelled values of PR do not consistently match values recorded through hydrological monitoring, with modelling errors of up to 43% found in Winsley Close (PRmod = 71%, PRmon = 28%, Table 6.3). To improve modelling performance, model parameterisation needs to be based on improved methods of defining surface cover, surface connectivity and choosing parameter values to reflect local conditions (Section 6.3). In particular model parameterisation should be based on improved understanding of the losses that occur on urban surfaces, and how the materials of construction, age, condition and connectivity affect these losses. The assumption that 100% of rainfall falling onto connected urban surfaces results in runoff is shown to over predict percentage runoff values in aged urban areas (Section 6.2.3).

(vi) Assess the implications of different rainfall-runoff modelling outcomes in a retro-fit surface water drainage system context .

The implications of inaccurate rainfall-runoff modelling is assessed by examining increased cost estimates of a retro-fit storage tank to store the additional volume of runoff that is generated at Arley Close and Winsley Close following urbanisation. Costs of storage tank construction are overestimated in Winsley Close by up to £108,000/ha, whilst in Arley Close storage estimates are underestimated by up to 110m^3/ha whilst costs are overestimated by up to £43,000 /ha, depending on what method is used to estimate urban surface cover, model choice and parameter values

(Table 6.3, Table 6.4). Therefore, the implications of inaccurate rainfall-runoff modelling in urban settings is a reduced likelihood of retro-fit storage tanks being an economically viable surface water management option in some areas, arising from inflated estimates of costs.

Therefore, the thesis successfully meets each of the research objectives stated in Section 1.4. Combined, these allow the aim to be addressed as understanding of how the physical features of urban residential development, of different ages and development histories, influences rainfall-runoff behaviour is produced.

8.2 FINAL SUMMARY

To improve understanding of urban rainfall-runoff behaviour, for use in rainfall-runoff modelling (and thus surface water management planning), this thesis provides a number of contributions to the field of urban hydrology including:

(i) A detailed assessment of rainfall-runoff processes acting on extant urban surfaces, which provides an evidence base to reject hydrological assumptions commonly applied in urban rainfall-runoff modelling and surface water management planning.

(ii) A hydrological monitoring data set of rainfall, runoff and soil moisture for two small urban residential catchments in north Swindon, whose design and layout is typical of residential areas within the United Kingdom.

(iii) An improved understanding of surface connectivity; providing a methodology to define the overall connection efficiency of an urban development and define surfaces with direct and indirect connections.

(iv) An understanding of how urban design influences rainfall-runoff behaviour, with particular reference to how the choice of surface materials, local topography and the layout of surface water drainage connection points affects rainfall-runoff behaviour.

(v) An assessment of hydrological model sensitivity to methods used in surface water management planning to define surface cover, surface connectivity and parameter values.

(vi) Definition of the cost implications of inaccurate rainfall-runoff modelling in a retro-fit surface water drainage system context.

Overall, the thesis provides recommendations for improved urban hydrological monitoring, modelling and understanding. Thus this thesis makes a novel and valuable contribution to urban hydrology and associated engineering and scientific fields.

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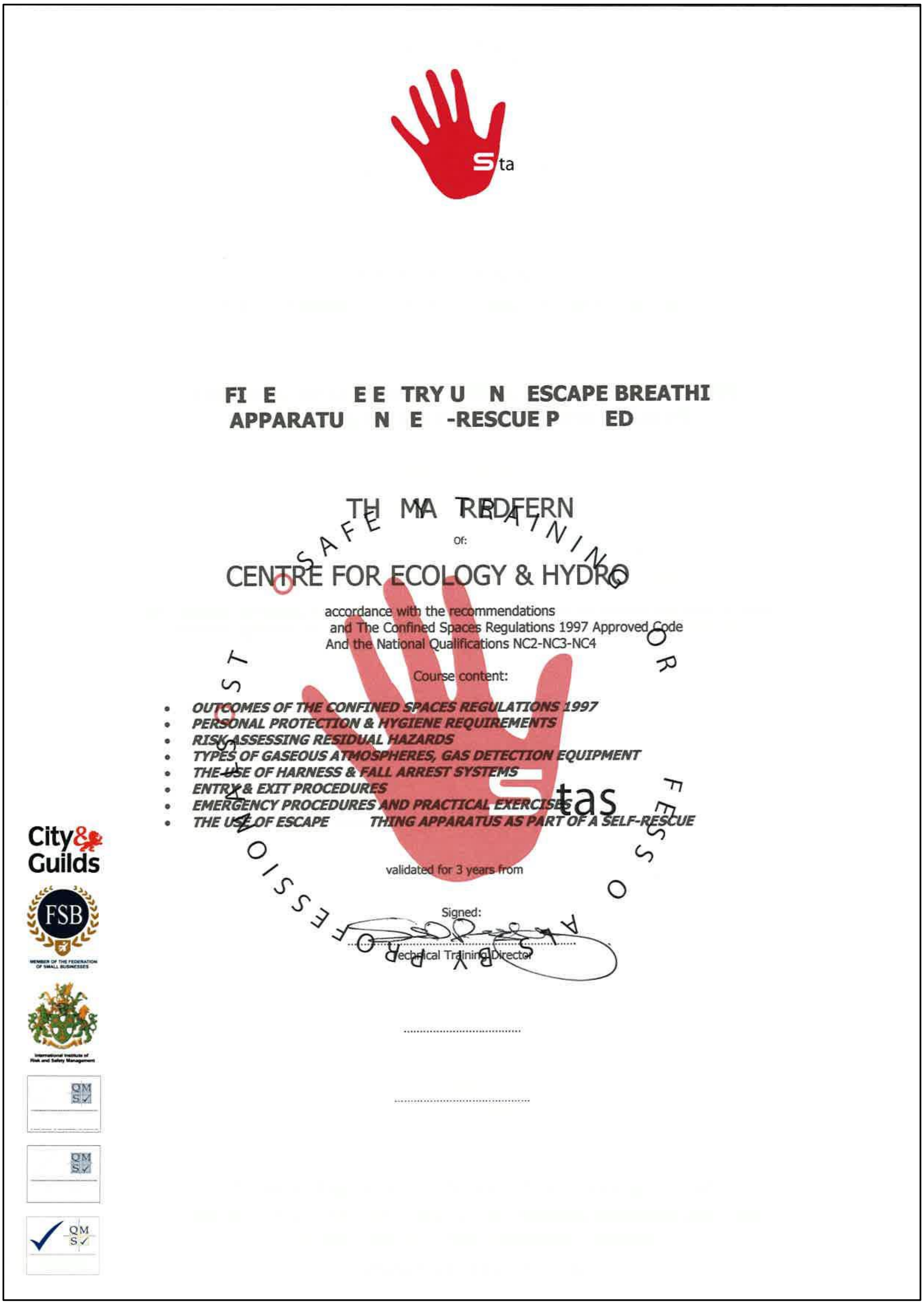
Appendix 1



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Appendix 2

This Appendix explains the programming approach taken to extract and analyse rainfall-runoff events, with some example code written specifically by T.W. Redfern (R code is in italics, R output is centre aligned, #s mark code comments). The aim is not to provide all of the code written, but to demonstrate the structured approach to extract rainfall-runoff events that are then analysed within the thesis.

The following packages are used to access, process and visualise data:

RODBC: Connects R to MS Access databases.

XTS: Used for handling time series data.

Dygraph: A package for creating interactive plots for visual inspection of data.

DataTable: An extension to R data.frames (a standard format for storing data within R) for the fast processing of large datasets in RAM (greater than 100mb).

scatterplot3d: Used for plotting 3d scatter plots.

Once velocity depth corrections are made (Section 3.6.2) and flow rates estimated using equations 3.3 and 3.4, a data.frame object is created that combines the rainfall data collected at the Pinehurst TBR and the flow measurements made in Arley Close and Winsley Close, with the following structure (the data frame object is assigned the name RAINFALLRUNOFF):

head(RAINFALLRUNOFF,3) # where 3 is the number of rows to display

DateTime	Rain	AFLOW	WFLOW
2014-05-23 13:03:43	NA	NA	0.1
2014-05-23 13:03:53	0.2	NA	NA
2014-05-23 13:04:03	NA	0.1	NA

DateTime is the timestamp, Rain is the rain depth, AFLOW and WFLOW are the flow rates measured at Arley Close and Winsley Close respectively. The data contain a number of NA values as the timestamps are sensitive to the precise timing at which equipment logging begins (at second resolution) and this does not match across monitoring equipment.

Event extraction and analysis code is written to extract individual rainfall-runoff events based on a Minimum Inter-event Time (MIT) of 30 minutes (Section 3. 7.1). A number of MIT values were tested, and the resulting rainfall-runoff events produced plotted and visually examined. An MIT value of 30 minutes is chosen as this maximises the extraction of events whilst producing event data that retain a high resolution of the rainfall characteristics of an event.

```
RainData<- data.frame(DateTime=RAINFALLRUNOFF$DateTime,
Vol=RAINFALLRUNOFF$Rain) # to only apply code to rain data

colnames(RainData)<- c('DateTime', 'Vol') # re-name columns

RainData$Vol[is.na(RainData$Vol)] <- 0 # remove NAs from data

Rain_Over_0<- RainData[RainData[,2]!=0,] # Select Data where Rain = >0

MIT<- 30 # user can choose values of MIT

Rainindex<-c(0,cumsum(diff(Rain_Over_0[,1])>MIT)) # Create vector increasing
by 1 as Diff=>MIT (MIT – set by user)

# Split RainData into list of events

RainEvents<-split(Rain_Over_0, Rainindex)
```

The output of this code (*RainEvents*) is a list object containing individual rainfall events with MIT values of at least 30 minutes.

The apply group of functions are then used to apply a function across all of the individual events contained within *RainEvents*, as follows (this returns vectors of the event characteristics):

```
EventVol<-sapply(RainEvents,function(x) sum(x$Vol)) # to calculate the total event rainfall depth

StartT<- sapply(RainEvents,function(x) head(x$DateTime,1)) # to extract the start timestamp of an event

EndT<- sapply(RainEvents,function(x) tail(x$DateTime, 1)) # to extract the end timestamp of an event

MaxInt<- sapply(RainEvents, function(x) max(x$Vol)) # to calculate the maximum 2 minute rainfall intensity of an event

Duration<- EndT-StartT # to calculate the duration of an event (in seconds)

DurationMIN<- Duration/60 # to calculate the duration of an event (in minutes)
```

The output vectors are combined into a data.frame (called RainDATA) and the first selection criteria of the event based rainfall-runoff analysis is used to extract rainfall-runoff events of at least 1mm rainfall depth (Section 3.7.4)

```
# Collate data into single dataframe

RainDATA<- data.frame(StartT, EndT, EventVol, DurationMIN, AvIntensity, MaxInt)

# Events over threshold (1mm total rainfall depth)

Rain1mm<- RainDATA[RainDATA$EventVol>1,]
```

Rain1mm therefore contains rainfall events where the total depth exceeds 1mm. The next step of the analysis is to extract runoff data from for the events contained within Rain1mm. This is achieved by utilising the timeseries manipulation tools of the XTS package. An XTS object is created of the rainfall and runoff series collected at Arley Close and Winsley Close.

RainXTS,- xts(x=RAINFALLRUNOFF$Rain, order.by=RAINFALLRUNOFF$DateTIME)

AFLOWXTS<- xts(x= RAINFALLRUNOFF$AFLOW, order.by = RAINFALLRUNOFF$DateTime)

WFLOWXTS<- xts(x= RAINFALLRUNOFF$WFLOW, order.by = RAINFALLRUNOFF$DateTime)

RRXTS<- cbind(RainXTS, AFLOWXTS, WFLOWXTS) # combines the three XTS objects into one.

Data can be extracted from an XTS object by placing the required date-time range within square brackets and thus rainfall and runoff data are extracted for each event, as follows:

Rain1mm$WINDOW<- paste(Rain1mm$StartT, Rain1mm$EndT, sep="/")

Events<- list() # creates an empty list

for(i in 1:nrow(Rain1mm)){

EventName <- paste('Event',i, sep='')

Events[[EventName]] <- RRXTS[Rain1mm$WINDOW[i]]

}

The output of this code is a list object, where each item in the list is an XTS object for each event contained within the Rain1mm data frame of events. As the Pinehurst TBR is not located within either Arley Close or Winsley Close, the time difference between rainfall and runoff varies at each site during the study period (Section 3.5.5). Therefore the events extracted are plotted to ensure that rainfall lines up with runoff. If a discrepancy is noted, the time window used to extract rainfall-runoff data is modified to ensure the window used to extract data includes relevant rainfall and runoff data at each site.

This provides a data and code structure that allows for the visualisation (plotting) and analysis of rainfall-runoff events extracted from data series collected in Arley Close and Winsley Close. By combining the apply group of R functions, for loops and plotting functions, baseflow is removed from events (Section 3.7.3), events are selected for study (Section 3.7.4) and peak flow rates and percentage runoff values determined (Section 3.7.5). Descriptive metrics for each event are defined (Section 3.7.6) and these data are collated into a data frame that is used for multiple linear regression modelling using the *lm()* R functions. Soil moisture data as collected with the PR2 and TDR300 probes are analysed and processed with similar methods. The soil moisture at the beginning of each rainfall-runoff event is estimated by matching the timestamps of the start of each event against the soil moisture data collected with the PR2 probe.

Appendix 3

This appendix includes photographs of Arley Close and Winsley Close.

Figure A3.1: Arley Close (Image Credit: Google Street View).

Figure A3.2: Winsley Close (Image Credit: Google Street View).

Appendix 4

The aim of this appendix is to compare the average slope characteristics of Arley Close and Winsley Close, to demonstrate that they are similar and thus the average slope of the two catchments is not likely to provide any explanatory power in comparing rainfall-runoff behaviour. Across the urban surface, physical features such as kerbing and walls direct runoff to small-scale hydraulic features (such as drainage gullies). The differences in these small-scale slope characteristics are examined in detail in section 3.4. Here, the average overall slope characteristics of the two catchments are compared by calculating the s1085 slope characteristic. S1085 is a standard hydrological parameter used to describe catchment slope (Shaw et al., 2010). The S1085 slope is calculated by finding the maximum drainage path through a catchment, and then comparing the elevation change between 10% and 85% of stream distance. The s1085 characteristic is calculated as follows:

$$s1085 = \frac{e_{85} - e_{10}}{\Delta x} \qquad \text{Equation A3.1}$$

Where s1085 = the s1085 slope, e_{85} and e_{10} are the elevations at 10 and 85% of drainage length (mAOD (Above Ordnance Datum)), and Δx is the drainage path distance between e_{85} and e_{10} (m).

To compute and compare the s1085 slope characteristics of Arley Close and Winsley Close, the LiDAR data described in Section 3.4 is analysed. Figure A4.1 shows the DTMs for Arley Close and Winsley Close, the maximum elevation in Arley Close is 92.56 mAOD, minimum elevation is 90.57 mAOD. In Winsley Close the maximum elevation is 124.26 mAOD and the minimum elevation is 122.24 mAOD.

To extract the elevation profiles across the potential maximum drainage pathways in each catchment, the profile graph tool of the 3D Analyst ArcGIS Toolbar is used. A line is drawn tracing from the area of highest elevation in each catchment, to the drainage outlet location in each catchment (blue lines, Figure A4.1). Raster values from the digital terrain model are extracted by the ArcGIS tool, and elevation vs drainage distance plots are presented in Figure A4.2. There are local variations in slope as a result of local topographic features, however both profile graphs show a consistent decline in elevation along the drainage profile.

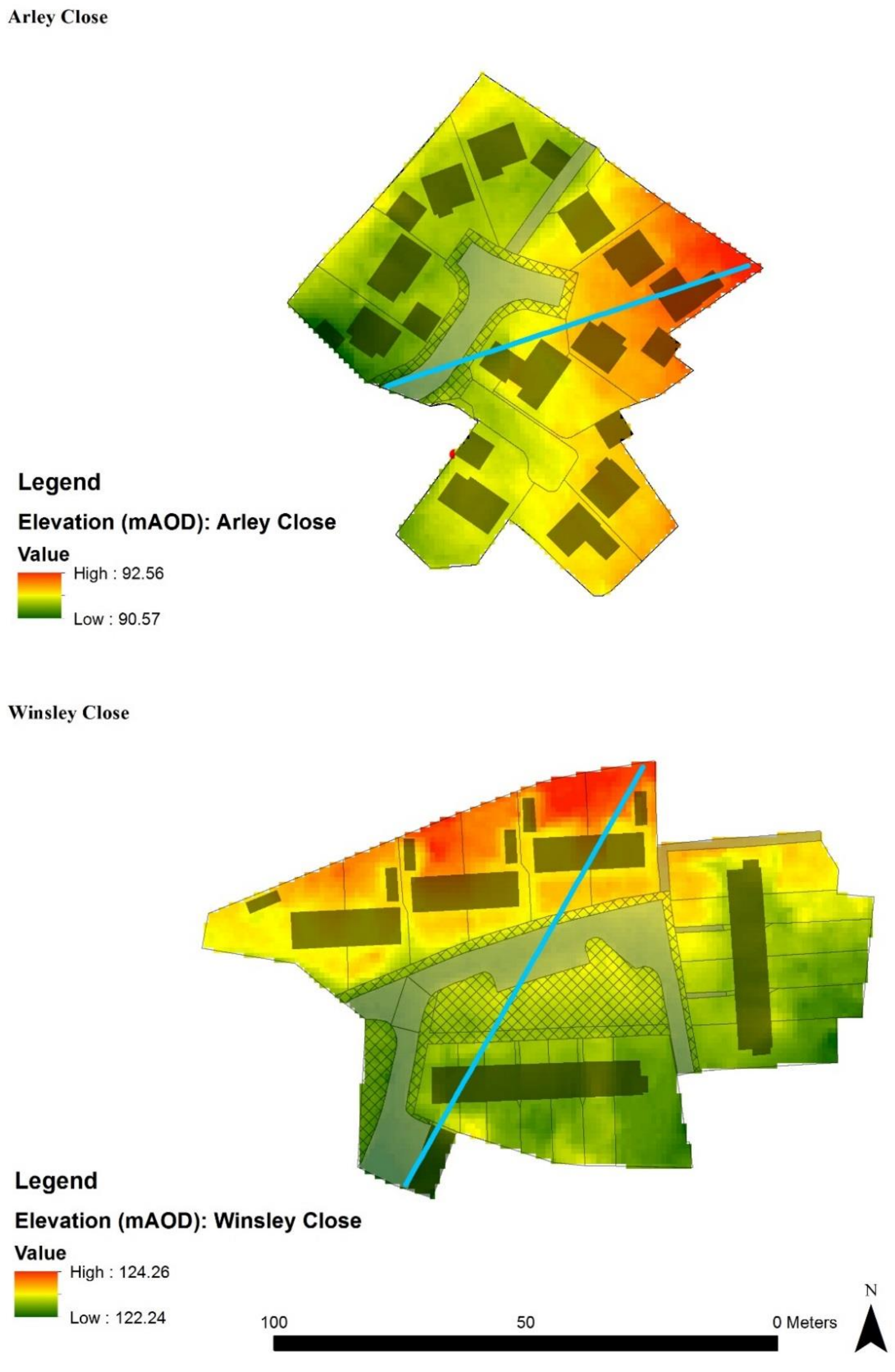

Figure A4.1: Elevation profiles and extracted drainage pathways in Arley Close and Winsley Close.

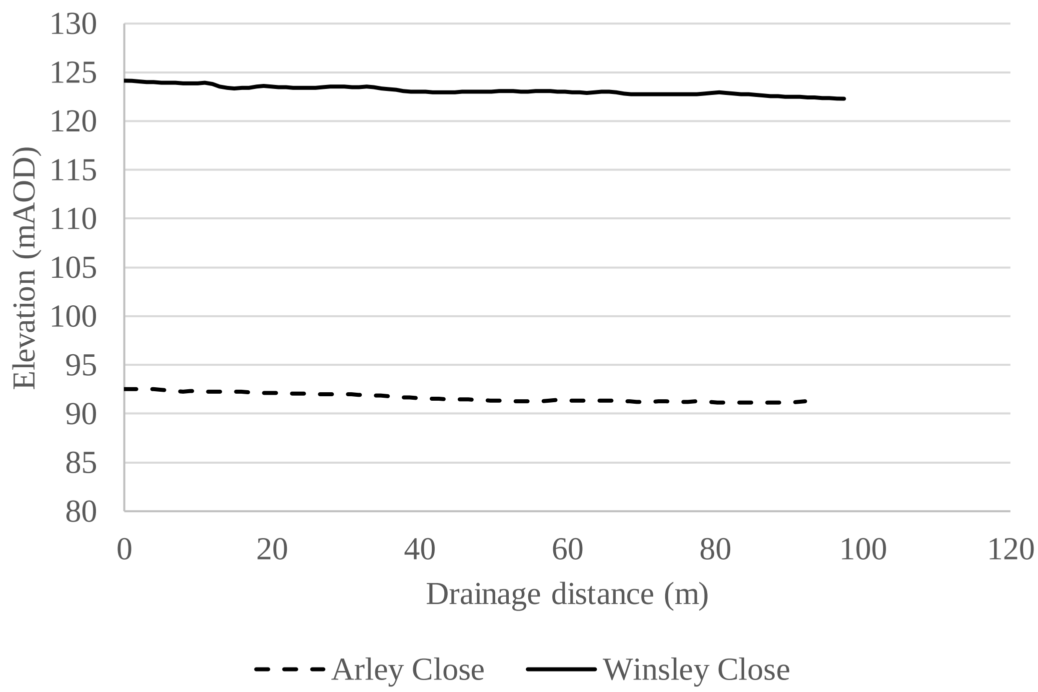

Figure A4.2: Elevation (mAOD) is plotted against drainage distance (m) to compare the slope characteristics of Arley Close and Winsley Close.

Table A4.1 shows the calculations to estimate the s1085 slope characteristic of each catchment. Arley Close has an s1085 slope of 1.54% whilst Winsley Close has an s1085 slope of 1.45%, demonstrating that the average slope characteristics of Arley Close and Winsley Close are similar, as stated in Section 3.1.1.

Table A4.1: s1085 calculations in Arley Close and Winsley Close.

	Arley Close	Winsley Close
e_{85}	92.31	123.89
e_{10}	91.26	122.84
Δx	68.15	73.10
s1085	1.54%	1.45%