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Modelling the role of SuDS management trains to minimise the flood risk of new-build housing developments in the UK

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By

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PhD

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A thesis submitted in partial fulfilment of the University's requirements for the Degree of Doctor of Philosophy

RESEARCH DECLARATION

I declare that this report is entirely my own work and that any use of the work of others has been appropriately acknowledged as in-text citations and compiled in the reference list. I also confirm that the project has been conducted in compliance with the University's research ethics policy.

Signed. C. Lashford Date: 18/7/2016

Abstract

In a changing climate with an increasing risk of flooding, developing a sustainable approach to flood management is paramount. Sustainable Drainage Systems (SuDS) present a change in thinking with regards to drainage; storing water in the urban environment as opposed to rapidly removing it to outflows. The Non-Statutory Standards for SuDS (DEFRA 2015a) presented a requirement for all developments to integrate SuDS in their design to reduce runoff. This research models the impact on water quantity of combining different SuDS devices to demonstrate their success as a flood management system, as compared to conventional pipe based drainage. The research uses *MicroDrainage*®, the UK industry standard flood modelling tool which has an integrated SuDS function, to simulate the role of SuDS in a management train. As space is often cited as the primary reason for rejecting SuDS, determining the most effective technique at reducing runoff is critical.

Detention basins were concluded as being highly effective at reducing peak flow (150 l/s when combined with swales), however Porous Pavement Systems (PPS) was nearly twice as effective per m^3, reducing peak flow by up to 0.075 $l/s/m^3$ compared to 0.025 $l/s/m^3$. This therefore suggests that both detention basins and PPS should be high priority devices when developing new sites, but that no matter what combination of modelled SuDS are installed a reduction in runoff in comparison to conventional drainage can be achieved.

A SuDS decision support tool was developed to assist design in *MicroDrainage*® by reducing the time spent determining the number of SuDS required for a site. The tool uses outputs from *MicroDrainage*® to rapidly predict the minimum and maximum peak flow for a site, in comparison to greenfield runoff, based on the site parameters of area, rainfall rate, infiltration, combined with the planned SuDS. The tool was underpinned by a model analysis for each site parameter and each SuDS device, which produced r^2 values >0.8, with 70% above 0.9. This ensured a high level of confidence in the outputs, enabling a regression analysis between runoff and each site parameter and SuDS device at the 99% confidence level, with the outputs combined to create the tool.

The final aspect of the research validated *MicroDrainage®* to analyse the accuracy of the software at predicting runoff. Using field data from Hamilton, Leicester, and laboratory data for PPS and filter drains, a comparison could be made with the output from *MicroDrainage®*. The field data created a Nash-Sutcliffe Efficiency (NSE) of 0.88, with filter drains and PPS providing an NSE of 0.98 and 0.94 respectively. This demonstrates the success with which *MicroDrainage®* predicts runoff and provides credibility to the outputs of the research. Furthermore, it offers SuDS specialists the confidence to use *MicroDrainage®* to predict runoff when using SuDS.

Keywords: SuDS, flood management, *MicroDrainage®*, management train, decision-support tool

Contents

Appendix	Content
A	Summary of Peer Reviewed Publications and Presentations
B	Ethical Approval
C*	Decision Support Tool and User Guide
D*	NSE results and field and laboratory data for Hamilton, PPS and Filter drains
	* Note those that are starred are only found on the attached CD

List of Figures

Figure

Page

List of Tables

Table

Page

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Abbreviations

DEFRA	Department of Environment, Food and Rural Affairs
DEM	Digital Elevation Model
DEX	Dunfermline Eastern Expanse
DST	Decision Support Tool
EA	Environment Agency
FEH	Flood Estimation Handbook
FSR	Flood Studies Report
FWMA	Flood and Water Management Act
GIS	Geographical Information Systems
HOST	Hydrology Of Soil Types
LID	Low Impact Development
LIDAR	Light Detection And Ranging
MOUSE	MOdel for Urban SEwars
MUSIC	Model for Urban Stormwater Improvement Conceptualisation
NPPF	National Planning Policy Framework
NSE	Nash-Sutcliffe Efficiency
PDP	Prior Deram Park
PIMP	Percentage IMPermeable
PPS	Porous Pavement Systems
SAAR	Standard Average Annual Rainfall
STTAT	SuDS Treatment Train Assessment Tool
SuDS	Sustainable Drainage Systems
SWMM	Surface-Water Management Model
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
WRAP	Winter Rainfall Acceptance Potential
WSUD	Water Sensitive Urban Design

1 Introduction

1.1 Background

Flooding in the UK is regularly in the media spotlight due to the risk it poses to people and infrastructure. Both pluvial floods due to excess rainfall and fluvial floods from river flooding have caused damage nationwide, with an estimated 5.2 million properties at risk in the UK (Bennett & Hartwell-Naguib 2014). Many hazards from flooding are as a result of land development (Swan 2010). Changing the ground use from rural to an urban settlement has caused greater amounts of overland flow due to the increased cover of impermeable surfaces.

1.2 Flooding

Flooding is often a consequence of urbanisation due to the installation of pipe based drainage systems and increased impermeable surfaces (Hamel, Daly & Fletcher 2013) (Figure 1-1). Pipe based conventional drainage efficiently directs water to an outflow, resulting in large outpourings of runoff in a short period of time (Elliot & Trowsdale 2007). This reduces the natural 'lag time' or the time it would typically take for water to reach a stream through ground water flows (Section 2.2).

Figure 1-1 The impact of urbanisation on the environment: a comparison between a green (a) and developed (b) site (Woods Ballard *et al*. 2007).

Pluvial flooding has two common causes. Firstly through high intensity short duration rainfall, termed 'flash flooding' (Sangati & Borga 2009), which is highly unpredictable and extremely localised for example the 2004 flood of Boscastle (Roca & Davidson 2010). Secondly, the source of pluvial flooding is as a consequence of low intensity high duration precipitation where the ground becomes saturated and limits infiltration causing overland flow or flooding (Priest *et al*. 2011), an example of this being the Tewkesbury summer floods of 2007.

1.3 2007 UK Summer Floods

The 2007 summer floods occurred as a result of 223% of average rainfall (based on an average between 1971–2000) from the beginning of May to the end of July (Marsh 2008; Pitt Review 2008), damaging 55,000 properties, causing 13 deaths and costing over £4 billion (Paranjothy *et al.* 2011, EA 2007a). Around one third of the flood events were due to river flooding whilst the remainder were a result of surface water flooding and drainage failure (Pitt Review 2008; Priest *et al.* 2011). Conventional drainage was built to mitigate events in city centres up to a 1 in 30 year return period (British Standards Institution 2008), however the 2007 floods were a 1 in 200 year scenario (EA 2007a). As a result the Government commissioned the Pitt Review (2008) to understand the causes of the floods and to generate recommendations to reduce future risk (Parker *et al.* 2011).

1.4 Pitt Review (2008) & the Government Response

The Pitt Review (2008) created a list of recommendations for the Government, focusing on improving flood defences through a 25 year plan. It followed on from the EU Floods Directive (European Union 2007) which was European legislation to assess and manage flood risk. The recommendations suggested by the Pitt Review (2008) that SuDS should be made mandatory, their benefits for flood management were discussed in the report. The subsequent Government responses to the report (DEFRA 2012; DEFRA 2009a; DEFRA 2009b; DEFRA 2008) contained minimal acknowledgment of the requirement for SuDS, therefore suggesting that more information regarding their ability to reduce flooding was needed. Subsequently the UK Government implemented the Flood Risk Regulation (2009) which provided statutory legislation for England and Wales to achieve the outcomes of the EU Flood Directive (European Union 2007). The legislation focussed on flood risk assessment, flood hazard mapping and management plans.

The Pitt Review (2008) acknowledged the necessity for legislation to deal with the issues raised. It advocated a flexible and adaptable Act that would result in necessary actions to a potential increase in flooding resulting from climate change. As a result of the EU Floods Directive (European Union Parliament 2007), the proposals in The Pitt Review (2008) and the Flood Risk Regulation (2009), in 2010 the Government passed the Flood and Water Management Act (FWMA) (2010)

The FWMA 2010 (Flood and Water Management Act 2010) governed the provision of water and the management of risk associated with flooding and presented a list of rules regarding stormwater management when developing or regenerating a site. The Act mandated that a national standard for SuDS should be developed to promote their use at the design phase. The subsequent consultation (DEFRA 2011a) and implementation (DEFRA 2015a) (section 2.10) support this research by stating that SuDS should be integrated at new sites to ensure runoff does not exceed greenfield rates.

1.5 Aims & objectives

With the introduction of the Non-Statutory Standards for SuDS (section 2.10) and an increased focus regarding sustainable methods, there is a need for defining the impact of different SuDS to ensure the most suitable devices are used in a management train. This can be further developed through a decision support tool (DST). A DST can assist practitioners by comparing predicted peak flow from different SuDS combinations and reducing the time spent re-designing a plan to achieve greenfield runoff, a requirement of the Non-Statutory Standards (DEFRA 2015a).

Although *MicroDrainage®* is the industry standard drainage modelling tool (Hubert, Edwards & Jahromi 2013), a publically available validation is required to demonstrate its accuracy with predicting runoff. This will give stakeholders further confidence in the program, engaging more to integrate SuDS as a suitable drainage option, as opposed to conventional drainage.

1.5.1 Aims of the research

The aims and objectives of this work are therefore:

> Aim 1: De-construct a SuDS management train to determine the effectiveness of each component

The research quantified the effectiveness of individual SuDS devices in a management train, a combination of linked SuDS (section 2.7.2). Although it was largely accepted that a SuDS management train was a superior method in comparison to individual devices for water quality improvement (Jefferies *et al*. 2009), little research exists with regards to water quantity. By presenting “best case” scenarios, better practice was generated that would ultimately further the implementation of SuDS management trains at new build sites, ensuring the most effective devices are integrated.

> *Objective 1a: Create a SuDS management train and a conventional pipe based drainage system at a case study site in MicroDrainage® to evaluate flow from each system.*

The intent of this objective was to determine how a conventional drainage system managed flow from the 1 in 100 year storm event in *MicroDrainage®*. This subsequently provided a comparison for each system in objective 1b, to compare the benefits of utilising SuDS.

> *Objective 1b: De-construct each component of the SuDS management train to determine the efficiency of each individual component.*

Deconstructing the management train by removing each SuDS component from the system in turn enabled a quantification of the impact of each device in the management train.

> *Objective 1c: Calculate the minimum and maximum impact per* $l/s/m^3$ *and* $l/s/m^2$ *of each device on peak flow.*

Measuring the impact of runoff per cubic metre and metre square of each device enabled a greater understanding of the effectiveness of each SuDS device, demonstrating which should be prioritised with regards to peak flow reduction.

Aim 2: Using the data from aim 1, create a Decision Support Tool identify the likely number of different SuDS needed to achieve a desired peak flow.

Providing a SuDS DST better engaged SuDS practitioners with the benefits of utilising SuDS. The tool provided a rapid assessment of the total number of each device required to achieve greenfield runoff for the 1 in 100 year 360 minute storm, as required by DEFRA (2015a).

Objective 2a: Analyse how the modelled site parameters of infiltration, rainfall and site scale each influence runoff in MicroDrainage®

This objective ensured the DST had wider applicability as it estimated peak flow for different scenarios of rainfall, infiltration and area of sites.

Objective 2b: Analyse how different coverage of the SuDS devices modelled in aim 1 impact runoff in MicroDrainage®

Analysing the role of each device by changing the total number and land take of each modelled SuDS system enabled a further understanding of how *MicroDrainage®* predicted flow.

Objective 2c: Using the outcomes of the regression analysis from objectives 2a and 2b, create a decision support tool that estimates maximum and minimum runoff for site and SuDS parameter

The results of objectives 2a and 2b enabled the creation of a decision support tool that could estimate runoff for different combinations of SuDS.

Objective 2d: Re-evaluate the decision support tool using data from the SuDS Management Train at Lamb Drove, Cambridgeshire.

Data was published for the peak runoff at Lamb Drove as a result of different rainfall events and SuDS combinations (Cambridgeshire County Council 2012). This was input into the DST to determine whether it replicated the findings of the report, and therefore whether the DST could accurately predict runoff.

> Aim 3: Validate the accuracy of *MicroDrainage* ® to determine the quality of the data underpinning the Decision support tool

The final aim of the research involved validating *MicroDrainage*®. Although the UK industry standard, the tool has not yet been widely validated using field data to determine its accuracy in a form that is widely available. This provided confidence in the outputs from aim 1 and 2, while also assuring SuDS practitioners of the accuracy of their models. Furthermore, stakeholders could gain additional confidence of the benefits of SuDS, engaging people that have not previously adopted the method, by demonstrating their benefit for flood management.

> *Objective 3a: Capture rainfall and flow field data at the Hamilton SuDS management train, Leicester.*

The Hamilton SuDS management train was used to monitor rainfall for different events, and the subsequent runoff at eight different sections of the site.

> *Objective 3b: Run laboratory simulations to determine the response of filter drains and porous paving to designed rainfall events.*

Alongside objective 3a, single device tests of porous paving and filter drains were completed to further determine the accuracy of *MicroDrainage*®.

> *Objective 3c: Using the data collected in objectives 3a and 3b assess the accuracy of MicroDrainage®.*

The data from objectives 3a and 3b enabled a validation of the accuracy of *MicroDrainage*® by comparing the outputs with modelled data.

In summary this research will demonstrate the benefits of different SuDS combinations, as opposed to previous research that has focussed on standalone devices with regards flood management (section 2.7). The study will also produce a novel support tool that will assist practitioners by quantifying the impact of the different number of devices when using *MicroDrainage*®. Finally, to further engage practitioners with the benefits of SuDS, an overall assessment of the validity of *MicroDrainage*® was completed by comparing modelled data with both field and laboratory data to determine the accuracy with which the program predicted runoff.

1.6 Definition of Key Terms

This study focussed on modelling the impact of new build and residential SuDS techniques on water quantity in comparison to conventional drainage. In this context, modelling was the computer aided hydrological simulation of the sites response to different characteristics, such as drainage, topography, rainfall and infiltration (Elliot & Trowsdale 2007; Mark *et al*. 2004). New build SuDS related to the installation of SuDS at new development and re-development sites, in contrast to retrofit SuDS which involved integrating SuDS into the existing landscape (Dickie *et al*. 2010; Moore *et al*. 2012). The focus of the study was new build as this provided greater potential for integrating a range of connected SuDS in a management train (section 2.7). However, the findings were likely to be transferrable to retrofit sites.

Detention basins were modelled throughout the research, as opposed to ponds (a justification is provided in section 5.2.). Detention basins are dry ponds that are utilised during large rainfall events, as opposed to ponds which permanently contain water (Woods Ballard *et al*. 2015). Conventional drainage is the term used to describe pipe based stormwater sewerage systems.

1.7 Structure of the thesis

Chapter one gives a brief summary of flooding and policy that has driven the implementation of SuDS, providing context to the research, before presenting the aims and objectives of the thesis.

Chapter two reviews the topics introduced in Chapter one in more detail, outlining the flood management capabilities of SuDS. The chapter also focuses on how flood modelling has previously been used for flood management, and the creation of previous DSTs.

Chapter three discusses the method used to achieve the aims and objectives of the research, alongside the computational and data requirements. Aim 1 is discussed in section 3.5, with the DST created in aim 2 covered in section 3.6, and the validation in aim 3 outlined in 3.7.

Chapter four presents the findings of the research. The results of the de-construction of the SuDS management train in comparison to conventional drainage for the different rainfall intensities is covered in 4.2.2-4.2.4, with the impact per m^3 and m^2 analysed in 4.2.5. The results of the model analysis that underpinned the DST are highlighted in 4.3, alongside the final DST design (section 4.3.4), with an accuracy assessment of the tool in 4.3.5. The findings of aim 3 are presented in 4.4, investigating the accuracy with which *MicroDrainage®* predicts runoff.

Chapter five discusses objectives 1b, 1c, 2a, 2b, 3c and addresses each aim of the research in the wider context of the literature. The key findings are presented and discussed to demonstrate the novel outputs of the research.

Chapter six discusses the extent to which the aims and objectives of the research have been met, summarises the key findings, outlines the limitations of the thesis and suggests future research.

2 Literature Review

2.1 Introduction

In line with the aims and objectives of the project (Section 1.5), the literature review identifies existing research regarding SuDS and modelling along with ways in which previous methodologies were adapted. A rationale for the implementation of SuDS will be discussed, with the focus on the Non-Statutory National Standards for SuDS (DEFRA 2015a) whilst also evaluating the effectiveness of individual SuDS devices.

Throughout history there has been an acknowledgement of the risk of flooding. During the 10th century AD settlements were built on high ground to limit fluvial flood risk with more fertile floodplains used for agricultural purposes (Galloway 2009). Increasing needs for new developments has since led to over 5.2 million properties being built on flood plains in the UK, and hence are at risk to flooding. Of these, 2.4 million are at risk of river and coastal flooding while 3.8 million are at risk of surface water flooding with 1 million of these at risk of both (Bennett & Hartwell-Naguib 2014). Urbanisation of floodplains has grown at a faster rate than development on any other sites in England (Committee on Climate Change 2012). This is coupled with an increasing amount of impermeable surfaces in urban areas which has resulted in a rise in the likelihood of flooding and a strain on conventional drainage (Torgersen, Bjerkholt & Lindholm 2014; Swan 2010). In addition to such development, climate change is impacting rainfall intensity, numbers of extreme winter events and consequently the number of flood events across the UK (IPCC 2013).

2.2 Urbanisation

Urbanisation is the expansion of an urban area, resulting from an increased population and a changing land use (Bell *et al*. 2012). By 2014 the total global urban population was 3.9 billion and this is expected to rise to 6.4 billion by 2050: 66% of global population (United Nations 2014). Urbanisation has caused soil to become compacted through development, leading to decreased infiltration rates (Bergman *et al.* 2011). Infiltration rates have been further exacerbated by vegetation removal, altering the porosity of soils, and the use of impermeable surfaces such as concrete and asphalt, which increased overland flow (Hooke & Sandercock 2012; Lundy & Wade 2011). Additionally, it has often resulted in the implementation of a hydraulically efficient pipe based drainage system (Elliot & Trowsdale 2007). These factors have reduced the natural ability to infiltrate stormwater and increased the amount that flows overland. Figure 2-1 demonstrates the impact of urbanisation on the storm hydrograph by decreasing lag time, increasing peak flow and a faster time to return to baseflow. Due to the efficient nature of a pipe based conventional drainage system, the lag time between a rainfall event and runoff reaching the river is reduced and results in an estimated increase of 75% of stormwater in stream flow, comparative to natural hydrological processes (Semadeni-Davies *et al.* 2008).

Figure 2-1 Hydrography before and after urbanisation, highlighting the shortened lag time and higher peak after urbanisation (Leopold 1968).

2.3 Conventional Drainage

The integration of pipe based drainage at new build sites is still part of typical design culture in England and Wales, focussing on reducing the impacts of pluvial flooding

(Woods Ballard *et al*. 2015). Runoff to the sewer system typically flows underground via gully pots and pipes before reaching the watercourse (Charlesworth 2010; Stovin & Swan 2007). This poses an increased flood risk for the outfall as a result of a reduced lag time and increased peak flow at the receiving water course (Qin, Li & Fu 2013). Additionally, the 'clogging' of conventional systems with debris inhibits their potential to effectively remove water, causing a back log through the system and an increased flood risk. Such scenarios were evident in the 2007 UK summer floods (Oliver 2009).

Table 2-1 outlines the design flood frequency for pipe based systems according to the British Standards (British Standards Institution 2008). All drainage systems in a city centre should manage all storms up to and including the 1 in 30 year storm scenario. However many cities in the industrialised developed world are at risk of flooding due to insufficient capacity, and this is exacerbated in less developed countries due to lower drainage standards (Fratini *et al*. 2012; Mark *et al*. 2004).

Table 2-1 Conventional drainage design storm frequency scenario for different locations (adapted from British Standards Institution 2008).

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As well as having the primary concern of increased flood risk at the source and the outfall, conventional drainage has also created a water quality issue. Improving runoff quality prior to being released into the watercourse is a neglected aspect of conventional drainage (Hoang & Fenner 2015). Consequently, runoff transports a variety of urban pollutants without treatment into the watercourse (Zhang, Zhang & Liu 2013) which has an impact on the biodiversity of urban streams (Charlesworth, Harker & Rickard 2003). Subsequently, other flood management methods have been utilised in England and Wales which are covered in the next section.

2.4 Existing Flood Management

The need for flood management in the UK was driven by an increase in urban areas (section 2.2), which resulted in impermeable surfaces along with a drive to develop on floodplains. Flood management across England and Wales is controlled and managed by both the EA and DEFRA (Burton, Maplesdon & Page 2012), with annual damage costs approximately £1.1 billion (Bennett & Hartwell-Naguib 2014), nearly double the budget for flood and coastal erosion management for 2015-2016 (DEFRA 2015b). Hard flood management has focused on engineered solutions that reduced flooding of the surrounding area. As a result of such strategies, many streams in towns and cities have been culverted or brick lined generating a dependence on them to retain runoff during periods of high rainfall (Werritty 2006). A number of other large scale hard abatement approaches such as flood walls, dredging, channel altering and dams, have been implemented both in the UK and internationally to manage flooding (Gumiero *et al*. 2013; Higgins *et al*. 2011; Jeuken & Wang 2010; Kenyon 2007; Saito 2014; Werritty 2006).

Constructing flood walls has been used as an alternative hard engineering measure to reduce flood risk, but have often been over-designed to mitigate the unknown impacts of climate change, or required increasing regularly maintenance to ensure continued effectiveness (Pitt Review 2008; Saito 2014). Kenyon (2007) surveyed public perception of different flood management methods in Scotland, finding that flood walls were the least popular option. Participants commented on their negative visual impact to a site, the need for re-development and the possibility of them trapping water behind the walls if overtopped. These fears were also presented by Song *et al*. (2011) who concluded that erosion of flood walls exacerbated the impacts of Hurricane Katrina in New Orleans.

Dredging streams reduces silt in the channel and therefore increases the carrying capacity of streams (Jeuken & Wang 2010). The method was widely used in the UK during the 1980s, however due to the high costs and short term benefits as siltation continues, along with an increased downstream flood risk, the process was restricted to urban streams from the 1990s (Pitt Review 2008). The use of dredging has also decreased internationally with it being seen as inappropriate and unsustainable in

Indonesia (Hufrord, Maksimović & Leitão 2010) while in Australia it is limited to estuarine environments (Wheeler, Peterson & Gordon-Brown 2010). Although it can achieve short term flood risk reduction, the process has a significant impact on the receiving ecosystem by displacing local habitats (Elliot *et al*. 2007).

Alongside dredging, some river courses have been altered, either straightened or diverted, to speed up flow or move it away from an area to provide flood management (Gumiero *et al*. 2013). Rivers typically meander, causing water to slow down, however removing these increases peak flow (Doubleday *et al*. 2013). Many previously channelised rivers in the UK have been restored to their natural process through river restoration, for example the River Eau in Lincolnshire (Gumiero *et al*. 2013). Rivers were also culverted or diverted to reduce the impact on urban areas (Brilly, Rusjan & Vidmar 2006). The River Sherbourne in Coventry was culverted to provide flood management, but also more space for growth.

Dams are used as a method to control flow rates and reduce the potential for flooding (Higgins *et al*. 2011). Although they can be an effective tool for reducing regional flood risk, they have incurred local environmental and social issues as a result of the disruption caused during the construction process (Yu 2010). They have typically been constructed to mitigate events up to the 10,000 year return scenario (Sordo-Ward *et al*. 2013), but with climate change impacting rainfall rates, the level of abatement is reduced (Veijalainen & Vehviläinen 2008). As they detain large volumes of water, when dams fail they result in large scale flooding (Bosa & Petti 2013).

Existing hard engineering flood management solutions require a large economic outlay and continued maintenance (Werritty 2006). A more sustainable approach is required as many of the strategies discussed provide only short term solutions, particularly in light of climate change altering rainfall patterns in the UK (Sayers *et al*. 2014). There was however a paradigm shift after the 1998 English Easter floods, with less reliance on stopping floods, to focus on more “green” sustainable techniques that deal with flooding (van den Hoek, Brugnach & Hoekstra 2012; Werritty 2006). This was coupled with a realisation that absolute protection from flooding was not possible, that water should be utilised more efficiently and therefore adapting as opposed to managing flooding was required, for example flood proofing (Beddoes & Booth 2011).

Flood proofing involves retrofitting the property to reduce the existing level of flood risk, focussing on both wet flood proofing, (managing utilities if water gets into the home) and dry flood proofing (stopping water from entering the home) (Hayes 2004; Saito 2014). The Pitt Review (2008) also discussed the implementation of SuDS as a further solution for flexible adaptation to the impacts of flooding, particularly with the increased likelihood of events due to climate change.

2.5 Sustainable Drainage Systems

The increase in impermeable surfaces along with the implementation of conventional pipe based drainage is a common cause of flooding (section 2.1); SuDS provided an alternative approach to managing storm water (Ellis *et al.* 2004). While pipe based drainage is efficient for removing water from an urban environment to a watercourse, the aim of SuDS is to change the principle that water should be rapidly transported away from towns and cities (Jones & Macdonald 2007). They mimic natural hydrological processes such as infiltration, which were lost due to the high rate of urbanisation and resultant impermeable surfaces (Dearden & Price 2011).

There has previously been resistance to the implementation of SuDS devices across England and Wales (Goodson 2011) primarily due to the perception of high whole-life costs (Everett *et al*. 2016; Morrison & Brown 2011; Todorovic, Jones & Roberts 2008), and the loss of valuable land (Backhaus, Dam & Jensen 2012) combined with several unknowns, such as the possible level of water quantity reduction. There are also concerns surrounding health and safety, as an increased amount of open water increased the perceived risk of drowning (Bastien, Arthur & McLoughlin 2012).

However, the initial aim of SuDS was to reduce water quantity, improve water quality and provide an amenity benefit for the site, which was outlined in the SuDS Triangle (Figure 2-2a; Martin *et al*. 2000). This was further developed in the SuDS Rocket by Charlesworth (2010) who also demonstrated the wider benefits of SuDS, including carbon sequestration, urban cooling, and energy reduction (Figure 2-2b; Charlesworth 2010).

a)

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Figure 2-2: The role of SuDS a) The SuDS triangle provided the three key roles of SuDS: water quantity reduction, water quality improvements and to provide amenity (Martin *et al*. 2000) b) The SuDS rocket demonstrates the wide benefits that can be achieved by integrating SuDS. The SuDS triangle has now been replaced by The SuDS Square (Figure 2-3) (adapted from Charlesworth 2010).

In terms of water quality, there has been an associated risk of pollution with conventional drainage, as polluted urban water is often transported straight to the receiving water course. SuDS provide a natural capacity for pollutant removal in the design through the capture of pollutants from runoff, often as a result of slowing the flow prompting infiltration and therefore improving water quality (Ellis, Revitt & Lundy 2012; Jefferies *et al.* 2009). Some devices, for example porous paving systems (PPS), utilise geotextiles to further enhance the removal of pollutants (Koener & Koener 2015; Nnadi, Newman & Coupe 2014). An enhancement in biodiversity is created by increased green space which also provides amenity and ecological benefits (Zhou 2014). These aspects cover the four pillars of SuDS (Figure 2-3), referred to hereinafter as the “SuDS Square”, and developed in the updated SuDS Manual (Woods Ballard *et al*. 2015).

Figure 2-3 The SuDS Square highlights the four primary aspects of SuDS; water quantity, water quality, amenity and biodiversity and is developed from the SuDS Triangle (Figure 2-2a) (Woods Ballard *et al*. 2015).

Although SuDS could be implemented in a variety of ways, first and foremost they have commonly been used at new build sites (Charlesworth 2010) (section 2.8.5). For the drainage system to be suitable it must not exceed the greenfield runoff rate, the rate of infiltration or storage, before development (DEFRA 2015a)**.** SuDS can also be retrofitted to buildings or the existing development layout, for example integrating infiltration trenches or swales to bypass pipes (Fryd *et al*. 2010) (section 2.8.6). Conventional pipe based drainage that failed during storm events could be assisted by green roofs and green walls to provide additional resilience (Stovin & Swan 2007).

2.5.1 Water Quantity

Water quantity forms a critical component of the SuDS Square (Figure 2-3). Ideally all four aspects of water quality, quantity, amenity and biodiversity are equally weighted in their importance (Woods Ballard *et al*. 2015), however in practice this is rarely the case. More emphasis is typically placed on the potential for runoff reduction and quality improvements after urbanisation by returning a site to "greenfield runoff" as opposed to amenity benefits (Jose, Wade & Jefferies 2015; Zhou 2014). Water quantity reduction is acknowledged by stakeholders as the main factor for integrating SuDS into the drainage design of a site (Chahar, Graillot & Gaur 2012). SuDS therefore provide flood resilience (Charlesworth 2010; Everett *et al*. 2016) by:

- Promoting infiltration and ultimately groundwater recharge
- Re-cycling water
- Controlling peak flow
- Reducing reliance on conventional pipe based drainage
- Slowing down and retaining water in the drainage system.

Existing drainage systems were built to manage events up to the 1 in 30 year storm scenario, with some older systems dealing with even smaller events (Pitt Review 2008). This was largely in contrast to expectations of SuDS in England and Wales which are designing up to the 1 in 100 year storm return period (with an additional 30% for climate change; EA 2016b). The success of SuDS is however partially limited to site characteristics, most notably the capacity for infiltration (Woods Ballard *et al*. 2015) and examples of SuDS best practice are limited in England and Wales with a continued reliance on conventional pipe based systems.

2.5.2 Barriers to SuDS

Although research exists with regards the benefits of implementing SuDS (Ellis & Viavattene 2014; Stovin 2010; Scholz & Grabowiecki 2007), there is a reluctance from practitioners for their wider implementation. SuDS propose a divergence from traditional pipe based methods to integrating more natural open water management in the built environment (Jones & Macdonald 2007) and such a change in method has resulted in uncertainty with the approach. The range of barriers for SuDS are presented in Table 2-2.

Table 2-2: List of barriers to SuDS (Booth & Charlesworth 2016; Martin *et al*. 2001).

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Whilst traditional piped systems require maintenance, there is a general out of sight-out of mind attitude as they are typically hidden under the ground (Chocat *et al*. 2003). As SuDS are predominantly vegetated systems, they often require maintenance to ensure they continue to be successful; this ranges from cutting vegetation to un-clogging devices (Woods Ballard *et al*. 2015). SuDS remove pollutants through infiltration, however over time material can clog the devices, limiting their ability to remove pollutants and their effectiveness at reducing runoff (Freni, Mannina & Viviani 2009). There is a prevailing perception that the necessity for maintenance of SuDS largely increases costs in comparison to conventional drainage and therefore schemes are sometimes dismissed (Duffy *et al*. 2008).

There is a general lack of acceptance at governmental level for the benefits of SuDS, with the Non-Statutory Technical Standards for SuDS (DEFRA 2015a; section 2.10) being released after four years of consultation. This has resulted in a resistance from practitioners to implement SuDS as they were either not required to, or did not have a list of standards to design for when planning for SuDS. Table 2-2 states that typically SuDS are seen as untried and untested structures, with more research needed to define their role in flood management, but suggests that further guidance is required as to designing SuDS.

Table 2-2 also highlighted an issue with multiple specialists being involved in the process and that a more long-term approach is required to ensure the continued success of the devices. The Pitt Review (2008) suggested that this remains a problem, with a need to better define the roles of all associated stakeholders in both the design, implementation and long term maintenance of SuDS. Overall there are a number of different barriers that contribute to a reluctance to further utilise SuDS in the built environment, however there are case study examples whereby SuDS have been used both on their own or in combination (in a management train; section 2.7) in the UK and further afield.

2.6 History of SuDS implementation

As a result of a philosophy shift favouring sustainable management over hard engineered solutions, the concept of SuDS arose during the late-1980s and early-1990s (Pompêo 1999). It was driven by the push for sustainability from the Brundtland Commission where it was proposed that developments should meet the needs of both the present and the future (World Commission on Environment and Development 1987). Butler & Parkinson (1997) questioned the role that traditional urban drainage played in a developing urban environment which promoted “less unsustainable methods" and therefore concentrated on long-term benefits. The early implementation of SuDS focussed on source control, by capturing and detaining water at the building scale (Pompêo 1999). Pratt, Mantle & Schofield (1989) investigated the potential of PPS to reduce both flow volumes and pollution, concluding that in comparison to conventional drainage PPS was more effective at reducing both factors. As a result of the change in philosophy and the development of knowledge, Shaver *et al*. (1994) and CIRIA (1992) produced documentation dealing with the design and impacts of implementing sustainable drainage in the USA and UK respectively.

In 1994 the United States Environmental Protection Agency (USEPA) (Shaver *et al.* 1994) implemented a runoff control plan for Northern Virginia. The plan formed the early phases of SuDS by implementing open channels as opposed to pipe based drainage and promoting infiltration across the area. Field implementation of SuDS in Europe also occurred in the mid-1990s. Household rainwater harvesting systems were retrofitted to buildings across Berlin in 1995 to capture rainwater, reducing overland flow, but to also decrease household water costs through greywater recycling (Nolde 1999). The research concluded that the total amount of water used through toilet flushing (approximately 15-55 l/person/day) could be retrieved through greywater recycling.

As a result of increased understanding, two EA demonstration sites were developed that incorporated a number of different devices, Wheatley Motorway Service Station, Oxford (Charlesworth 2010) and Hopwood Motorway Service Station, Worcestershire (Heal *et al*. 2009). The site at Wheatley, Oxford, was a total of 16.7 ha, of which 4.2 ha was covered by the following SuDS devices:

- Permeable paving
- Filter drains
- Swales
- Filter strips
- Retention Pond
- Wetlands

The primary purpose of the site was to manage flood flows, while also enhancing water quality of the runoff leaving the site (SUSdrain *c.*2016). A combination of SuDS have also been implemented across the 9 ha Hopwood Service Station, Worcestershire (Figure 2-4). The primary aim of the development was to improve the quality of runoff entering the Hopwood Stream. The site consisted of a combination of the following devices:

- Grass filter strip
- Constructed wetland
- Balancing pond
- Infiltration trench
- Spillage basin
- Gravel collector
- Swales

Figure 2-4 The devices used and the configuration at the Hopwood motorway service area (Heal *et al*. 2009).

Overall, the implementation of the devices was a success, both in terms of enhancing water quality, and financially. The average annual cost of maintaining the site was £2500, in comparison to £4000 for a similar sized conventionally drained site (Heal *et al*. 2009). The site also reduced between 70-90% of the total pollutants by the time runoff reached outflow to the stream (Heal *et al*. 2009).

SuDS have also been implemented across Scandinavia, for example in Malmö, Sweden, where SuDS were used in new developments since the late-1980s (Stahre 2002). Open channels were constructed for new developments with water diverted into open overflows, engaging the public in the design process to ensure water quantity, quality and aesthetics needs were met. Away from the city centre, pre-existing conventional drainage was directed into new open channels (Figure 2-5) which reduced overloading of pipe-based systems; wetlands, detention basins and green roofs were also used (Forest Research n.d).

Figure 2-5 Open channel and mini-wetland taken from the Central Drainage Corridor in Malmö (Stahre 2008).

Semadani-Davies *et al*. (2008) discussed the implementation of sustainable water management over a ten year project in Helsingborg, Sweden, focussing primarily on potential climate change mitigation. The urbanised section of the catchment was 534 ha, of which 153 ha was impermeable. The management plan consisted of a combination of swales, permeable paving, green roofs, bio-retention devices and ponds to lessen the impact on the conventional pipe based system in the city. The findings concluded that the management train would be capable of managing runoff for all but the A2 climate change scenario which simulated an increase in intense rainfall events.

The approach taken to SuDS in Australia differs from the UK by focussing on Water Sensitive Urban Design (WSUD). This concept utilised similar techniques to SuDS, however due to drought issues in Australia, had a greater focus on the availability of water and utilising water resources (Morison & Brown 2011). This is exemplified by Figure 2-6 which highlighted the requirement to re-use and recycle water and therefore promoted the use of rainwater harvesting systems. Successful WSUD sites have been retrofitted in both Sydney and Melbourne, to ensure water is used effectively, primarily using rainwater harvesting, swales, bioretention zones and detention basins to store and capture runoff (Landcom 2009).

Figure 2-6 Interactions between WSUD and the environment (Melbourne Water 2005).

Whether devices are retrofitted or installed during new builds, SuDS can be incorporated into a system in two ways, as standalone devices or as part of a wider SuDS management train. It is acknowledged that designing a SuDS management train is a viable strategy in comparison to conventional drainage plans (Stovin & Swan 2007) however research regarding their ability to deal with high volumes of runoff is limited.

2.7 SuDS Treatment & Management Train

A SuDS management or treatment train is a system which utilises a range of SuDS in sequence to reduce flow and the overall level of pollution in runoff (Woods Ballard *et al.* 2015). When focussing on water quality, combinations are often termed treatment trains. The following section gives an outline of where treatment trains fit with regards the management of runoff, but the focus of study will be water quantity reduction and therefore the term *"SuDS management train"* will be used in all future sections.

2.7.1 SuDS Treatment Train

Improving the water quality of outflow is considered a key benefit for integrating SuDS, as is demonstrated by the SuDS square (Figure 2-3). D'Arcy & Frost (2001) identified that different SuDS were capable of improving runoff, with future research such as Stovin (2010) and Wade & Garcia-Haba (2013) (section 2.17.1 for more detail) quantifying and discussing the potential runoff quality enhancements of individual devices.

Rather than using individual devices, Jefferies *et al*. (2009) undertook computational analysis of the downstream implications of incorporating multiple connected SuDS with the primary aim of enhancing outflow quality, typically referred to as a SuDS treatment train. The study produced a DST (SuDS Treatment Train Assessment Tool: STTAT), the outputs of which are discussed in more detail in section 2.17.1. The research noted that further improvement of water quality was possible by using SuDS in sequence. The outcomes were in line with Scottish guidance for road based SuDS (Guz *et al*. 2009) which advocated using a treatment train to improve water quality and also achieve the other aspects of the SuDS square (Figure 2-3).

The success of the train relies on the conveyance of runoff between different SuDS components for treatment, a process that continues to other devices downstream (Stovin *et al*. 2013). Increasing the potential of infiltration and the use of vegetation throughout the treatment train enables the capture of pollutants and ultimately improves the quality of water leaving the system. The rest of the thesis will concentrate on SuDS Management Trains and their ability to reduce water quantity.

2.7.2 SuDS Management Train

Aside from water quality improvements, SuDS combined in a management train provide extra levels of resilience against flooding as more devices are used resulting in greater levels of water retention (O'Sullivan *et al.* 2012). It is not always feasible to utilise one large device at a site, therefore a series of smaller linked devices in a management train can be more practical, meeting the requirements of the SuDS square (Figure 2-3).

An initial component of a successful management train (Figure 2-7) is source control, where SuDS tackle water directly after precipitation, for example PPS (Zakaria *et al*. 2003). The remaining runoff in the system is conveyed to a site control device, usually via a swale (Stovin & Swan 2007). Such systems deal with greater amounts of runoff from multiple source control devices and allow for infiltration to the surrounding soil and evaporation (O'Sullivan *et al.* 2012). Runoff may then be conveyed to another location for regional control to store excess volumes of water from a series of site control devices before releasing runoff to an outflow, representing the last aspect of the train. Regional devices should allow for pollutant removal, although much should have been previously filtered out (Jefferies *et al*. 2009). An example of a regional control device is a detention pond (Bastien *et al.* 2010). After this step, water is either slowly released to a water body, infiltrates out of the SuDS system or evaporates (Woods Ballard *et al*. 2015).

Figure 2-7 SuDS management train: runoff is conveyed from source, to site to regional control systems to manage runoff. The figure also includes the devices that are associated with each phase of the train (Adapted from Charlesworth 2010; Woods Ballard *et al*. 2015).

2.8 SuDS devices in a SuDS management train

A SuDS management train can be an effective system for both runoff quantity reduction and quality improvement. Consequently a device should be integrated with others, with specific roles for maximum effectiveness, rather than being standalone (Charlesworth 2010; Ellis, Revitt & Lundy 2012). Limited research exists regarding which devices should be prioritised in a management train and how different devices work when combined, however certain devices are more common in management trains in England and Wales (Table 2-3). SUSDRAIN (2016) suggests that swales, detention basins, ponds and PPS are most commonly used in SuDS management trains.

When on their own, some SuDS devices perform roles more effectively than others. Table 2-4 provides a breakdown of the water quantity reduction capabilities of individual SuDS devices in terms of source, site and regional control, conveyance and their ability to efficiently reduce water quantity. However, although each device is classified as low, medium or high effectiveness at reducing runoff, no quantification for classifying the effect is provided by Woods Ballard *et al*. (2007).

Table 2-3 Examples of the devices used in SuDS management trains in England and Wales based on a list of case studies provided by SUSDRAIN (2016).

SuDS Management Trains	**Detention Basins**	**Filter Drains**	**Filter Strip**	**Green Roofs**	**Infil. Trench**	**PPS**	**Pond**	**Rainwater Harvesting**	**Soakaway**	**Swale**	**Wetlands**
Blythe Valley Park, Solihull, West Midlands							y			y	y
Bognor Regis Community College		y			y	y					
Bristol Business Park	y					y				y	
Elvetham Heath, residential, Hampshire	y						y		y	y	
Exwick Heights School, Exeter	y	y		y		y	y			y	y
Hamilton, Leicester	y						y			y	y
Hollington Old Lane, Hastings						y				y	
Holywell Primary School, Worcestershire	y						y			y	y
Hopwood Service Area, Worcestershire	**y**		**y**		**y**		**y**			**y**	**y**
Lamb Drove , Cambridge	y		y	y		y	y	y		y	

SuDS Management Trains	**Detention Basins**	**Filter Drains**	**Filter Strip**	**Green Roofs**	**Infil. Trench**	**PPS**	**Pond**	**Rainwater Harvesting**	**Soakaway**	**Swale**	**Wetlands**
Lutra House, Lancashire						y	y			y	y
Manor Ponds, Sheffield	y						y			y	
Matchborough First School, Worcestershire	y							y		y	y
Moor Park, Blackpool	y									y	
Olympic Park, London	y	y				y				y	y
Springhill Development, Gloucestershire	y					y	y			y	
Stebonheath Primary School, Llanelli	y					y				y	
University of the West of England, Bristol	y					y	y			y	y
Welcome Break, Wheatley		y	y			y	y			y	y
Wessex Water Operations Centre, Claverton Down						y		y	y	y	
Total number	**14**	**4**	**3**	**2**	**2**	**12**	**12**	**3**	**2**	**19**	**10**

Table 2-4 SuDS devices and their uses, highlighting their potential effectiveness as a standalone device and their potential for retrofit (Woods Ballard *et al.* 2007).

SuDS Device	**Source**	**Site**	**Regional**	**Conveyance**	**Effectiveness at reducing water quantity**	**Potential for retrofit**
Rainfall harvesting	X				Low*	Yes
Porous pavement systems (PPS)	X	X			High	Yes
Filter strip	X				Low/Medium	Yes
Swale	X	X		X	Medium	Limited
Pond		X	X		Medium/High*	Unlikely
Wetland		X	X	O	Low/Medium	Unlikely
Detention basin		X	X		High*	Yes
Soakaway	X				Medium	Yes
Infiltration trench	X	X		O	Medium/High	Yes
Infiltration basin		X	X		Medium*	No
Bioretention device	X	X			High	Yes
Sand filter		X	O		Low	Yes
Green roof	X				Medium	Yes

*Dependent on the size of the structure for water retention X – Most suitable O – Less suitable Blank – Not possible

Note that no robust justification is provided in Woods Ballard et al (2007) for high/medium/low effectiveness at reducing water quantity.

2.8.1 Source control

Table 2-4 showed that several SuDS devices were capable of working at the small scale. Both Kirby (2005) and Woods Ballard *et al*. (2015) suggested that PPS (Figure 2-8) was highly effective at dealing with runoff, and was incorporated into 60% of the case study management trains in England and Wales (Table 2-3). PPS was most suited to either car parks or pedestrian areas due to low load capabilities as heavy traffic loads increased clogging or could cause the sub-base to fail, limiting infiltration (Imran, Akib & Karim 2013; Gomez-Ullate *et al*. 2011). Water moved through different layers of sub-base and geotextile, improving water quality (Figure 2-9) (Scholz & Grabowiecki 2007). Based on 150 different storm scenarios there was the potential for PPS to reduce runoff flows by up to 75% (Viavattene *et al.* 2010).

Figure 2-8 PPS at the Act-UK building, Coventry University.

Figure 2-9 Schematic layout of a typical PPS, presenting each of the key sub-layers that aid infiltration (Scholz & Grabowiecki 2007).

Bioretention ponds also fell under the “highly effective” bracket and were vegetated sites (Figure 2-10) that reduced runoff quantity through retention (Woods Ballard *et al*. 2015). Research (Debusk & Wynn 2011) suggested that a bioretention system (4.6m long, 7.6m wide and 1.8m deep) was capable of managing runoff with no outflow for events with an inflow rate up to 12.5 l/s, outlining the potential of bioretention devices in a management train. They were engineered to enhance the water quality of the outflow by utilising geotextile and fine gravels to reduce pollutants (Figure 2-10) (Woods Ballard *et al*. 2015).

Figure 2-10 Schematic profile view of a bioretention system that promotes infiltration (Woods Ballard *et al*. 2007).

Green roofs (Figure 2-11) were categorised as having 'medium' effectiveness at reducing water quantity. One of their primary benefits in terms of installation in the urban environment was that no additional land-take was required beyond the scope of the building (Stovin 2010). However, their integration into existing SuDS management trains remained limited (Table 2-3). Based on the same 150 storm scenarios used to model the benefits of PPS, Viavattene *et al*. (2010) calculated that a green roof had the potential to reduce runoff by between 45-60%. Green roofs slowed down the time rainfall took to reach an outflow through interception by the surface plants (Figure 2-12) (Lamera *et al*. 2014). Dependent on storm intensity, rainfall that had not been evaporated was then infiltrated into the substrate and either attenuated or conveyed out of the system (Stovin 2010). However, if the storm intensity exceeded the infiltration rate, runoff occurred, reducing the positive impact of the green roof. Similarly, if the slope of the green roof was too steep, retention capacity was reduced, further promoting runoff (van Woert *et al*. 2005).

Figure 2-11 Green Roof on the Students Union at Coventry University.

Figure 2-12 Schematic diagram of a green roof, showing how runoff can be managed through infiltration and evapotranspiration (Stovin 2010).

2.8.2 Site control

Runoff from multiple source control devices was typically conveyed to large site control devices. Table 2-4 identified several SuDS devices that were capable of working as site control devices and three of these; bioretention devices, infiltration trenches and swales were also suitable devices at source level, dependent on their size (Woods Ballard *et al*. 2007). Other highly effective devices for reducing runoff were detention basins (dry) and ponds (wet) (Chan, Yang & Yang 2011; van der Sterren 2009), as they could store large amounts of water and encourage groundwater recharge through infiltration (Datry, Malard & Gilbert 2004). The effectiveness of detention basins and ponds was reflected in Table 2-3 as they were the most commonly used device at the site scale occurring at 70% and 60% of the analysed management trains, respectively. Strecker, Quigley & Urbonas (1999) estimated that ponds and detention basins were capable of reducing runoff by up to 30% based on ‘significant storm events’, however more detail of the nature of the modelled events was not provided. It should be noted that detention capabilities were relative to size and infiltration rate (Scholz 2004).

2.8.3 Regional control

As regional control devices are required to retain larger amounts of water, fewer devices are capable of working at this level as is evident from Table 2-4. Detention basins were the most proficient device for regional control, reducing runoff to a ‘high’ standard (van der Sterren 2009).

Ponds were also a useful device for retaining water and ultimately reducing runoff levels, but as with detention basins their capability is dependent on size (Scholz 2004). As other devices suitable for regional scale implementation are less effective at reducing runoff peaks, including both detention basins and ponds are a priority when developing the SuDS management train at regional control level.

2.8.4 Conveyance

Table 2-4 suggests that swales are most suitable for conveying water, whilst they also provide a ‘medium’ capacity for reducing flood flows (Viavattene *et al.* 2010) and are commonly integrated at existing SuDS management trains (Table 2-3). Swales mimic natural drainage by utilising vegetated channels for transporting water (Allen *et al*. 2015) (Figure 2-13; Figure 2-14). Strecker, Quigley & Urbonas (1999) calculated that swales reduced peak flows by approximately 10% on a storm-by-storm basis; however similar to detention basins, the details of the modelled storm scenario were not provided. The research does nevertheless suggest that swales were not overly successful at reducing peak flows and that their primary role is to transport runoff around a site. Other devices that could be considered include infiltration trenches, wetlands and rainfall harvesting, but these are not as capable of conveying water (Woods Ballard *et al*. 2015).

Figure 2-13 Swale at Hamilton SuDS Management Train, Leicester, that conveys runoff from detention basins and wetland areas.

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Figure 2-14 Schematic diagram of a swale, demonstrating their water quantity and quality benefits (Woods Ballard *et al*. 2007).

Although literature exists regarding the generic abilities of various SuDS devices (Woods Ballard *et al*. 2015), much of the research has centred on the abilities of standalone devices as opposed to combining devices in a management train (Duchemin & Hogue 2009; Viavattene *et al.* 2010; Strecker, Quigley & Urbonas 1999). There has been little research into understanding management trains and ultimately modelling their abilities at both new build and retrofit sites, therefore the current research presents a novel approach to analysing these processes.

2.8.5 New build

Integrating SuDS in the design of new developments reduces the amount of impermeable surfaces and consequently can reduce flood risk. DEFRA (2009a), in their response to the Pitt Review (2008), acknowledged that flood mitigation needs to be in place for new build developments to ensure they do not negatively impact greenfield runoff rates (Charlesworth 2010). Research by Bastien *et al*. (2011) showed the potential water quality benefits of different combinations of a SuDS management train (Figure 2-15). They determined that by combining regional ponds, swales, infiltration trenches, green roofs and soakaways, there is the potential reduction of between 93-97% in total nitrogen, total phosphorus and total suspended sediment.

Figure 2-15 Water quality reduction of different combinations of SuDS devices; TN: Total Nitrogen, TP: Total Phosphorus, TSS: Total suspended solids, RP: Regional pond, SW: Swale, IT: Infiltration trench, GR: Green roof, SO: Soakaway, CBP: Concrete block pavement (Bastien *et al*. 2010).

Bastien *et al.* (2010) acknowledged that when integrating SuDS into new build design, source and site control devices were largely sufficient at dealing with storm scenarios up to the 1 in 30 year return rate for the Clyde Gateway study site. Nonetheless once this is exceeded, larger attenuation devices such as ponds are paramount in ensuring the site deals with runoff. Large attenuation devices reduce the space available for houses, which is typically an issue for developers as houses provide the profit for the site.

2.8.6 Retrofit

Retrofitting SuDS is a process whereby stormwater is disconnected from an existing conventional drainage system and routed into a SuDS device (Stovin & Swan 2007). The process forms a tool for mitigating flooding in the built environment (Lamond, Rose & Booth. 2015). As pluvial flooding is increasingly an issue in urban settings (Priest *et al*. 2011; Sharples & Young 2008), devices are required to reduce the risk (EA 2007b). Approximately 5.2 million houses are currently at risk of flooding (Committee on Climate Change 2012) with new builds contributing 1% of all buildings in the UK. Consequently a combined strategy for dealing with both new and old build is essential to manage flooding (EA 2007b). Table 2-5 illustrates the potential for implementation of various retrofit devices across England and Wales.

Table 2-5 Coverage estimates for retrofitting PPS, rainwater harvesting, water butts and different conveyance devices in England and Wales (adapted from EA 2007b).

Balmforth *et al*. (2006) show that integrating retrofit SuDS into the urban environment can prove troublesome, with the restraints of existing buildings, paths and roads limiting the space available for implementation. However, Stovin & Swan (2007) calculated that installing retrofit SuDS could reduce construction and whole-life costs.

There are limited examples of SuDS retrofit across England and Wales. Stovin *et al*. (2013) suggest that this is largely due to the complexity and disturbance associated with disconnecting runoff from the conventional system and ensuring runoff is channelled into SuDS. For this reason, much of the current focus surrounds creating an integrated SuDS and conventional drainage approach. The difficulties of installing SuDS retrofit was also discussed in a US context by Shaver *et al*. (2007) whereby a lack of space in the urban environment with high land values made it expensive to integrate SuDS retrofit into urban stormwater management.

Backhaus & Fryd (2012) discussed an example of designing a large-scale 1500 ha SuDS retrofit project in Copenhagen, Denmark. While the implementation of the project was not covered, they provided a methodology for designing large scale plans that could be utilised elsewhere. They also highlighted a series of challenges, such as the complexity of designing a project at a range of scales to ensure the solution is achievable and effective. A further assessment by Stovin *et al*. (2013) analysed the potential of retrofitting a SuDS train in the Thames Tideway Catchment to reduce the cost of modifying the existing conventional drainage plan. Although a model was presented, the research identified a number of challenges:

- The lack of pilot sites to determine implementation challenges
- The size of the study area was too large, therefore would have resulted in significant disruption
- A continued need to utilise conventional drainage alongside the SuDS system.

Table 2-4 outlined the devices that were most suitable for retrofit installation. All devices, apart from infiltration basins, have the potential to be incorporated through retrofit design however swales, ponds and wetlands are less possible and have limited potential due to their size (Woods Ballard *et al*. 2015). To ensure continued integration of SuDS, a series of frameworks and guidance documents have been formulated to assist stakeholders and these are reviews in the following sections.

2.9 National Planning Policy Framework

The National Planning Policy Framework (NPPF) (DCLG 2012) focuses on ensuring development is underpinned by sustainability, suggesting that plans that are “sustainable” will be approved without delay. The document is primarily focused on factors such as sustainable transport and economy, however SuDS form a component of the document. The NPPF advocates prioritising SuDS to ensure sustainable flood resilience. Vice versa, flooding is considered throughout the document. A long term plan for flood risk reduction is suggested, particularly with respect to climate change and a tightening of flood risk assessments are also called for. Subsequently, and along with the Flood & Water Management Act (2010), guidance has been developed (section 2.10; DEFRA 2015a) to further ensure the wider implementation of SuDS.

2.10 Non-Statutory Technical Standards for Sustainable Drainage Systems

The Technical Standards for SuDS (DEFRA 2015a) hereinafter referred to as ‘The Standards’ were developed in accordance with requirements of The Flood and Water Management Act 2010 to create legislation regarding sustainable flood management (Flood and Water Management Act 2010). They were developed from a three year consultation period after the Draft National Standards for SuDS (DEFRA 2011a) and took effect from the 6th April 2015. As a result of the consultation, much of the detail and flood specifics of the draft have been removed. The published version of The Standards state that SuDS should be utilised for developments of 10 or more properties, unless they are demonstrated as being inappropriate for the site, as defined by the local planning authority. In terms of peak flow control, SuDS should be implemented at new build sites to ensure that runoff up to and including the 1 in 100 year 360 minute storm does not exceed greenfield runoff rates. For existing developments runoff for the same storm event must be reasonably close to the greenfield runoff rate, but not exceed the rate prior to development. The same stipulations are also proposed for volume control. For risk within the development, flooding must not occur during the 1 in 100 year 360 minute storm and sufficient flow routes away from buildings must be used for larger storms.

The Flood & Water Management Act 2010 (Great Britain Parliament 2010) advocates the development of SuDS advisory boards to ensure SuDS are considered for new developments. These have now been scrapped by the new Standards with approval being sought through the development planning process with the Lead Local Flood Authority as a statutory consultee. As a result of The Standards, the Planning Practice Guidance for flood risk and coastal change was updated with regards to SuDS.

2.11 Planning Practice Guidance

The Planning Practice Guidance for Flood Risk and Coastal Change (DCLG 2015) attempts to clarify key terminology for flood risk mitigation and assessment. It was updated as a result of The Standards to focus on the ability of SuDS to reduce flooding, providing practitioners with additional guidance when dealing with flood risk.

The original Draft National Standards (DEFRA 2011a) suggested a hierarchical system for preferred runoff destination, similar to DCLG (2010) and DCLG (2009), which should be followed at all new build sites. These were subsequently transferred to the Planning Practice Guidance (DCLG 2015).

1. *Discharge into the ground*

The most desirable destination for runoff is into the ground, if possible. This replenishes groundwater, contributes little to downstream flooding, and improves water quality (Duffy *et al.* 2008; Robinson *et al.* 2010). Infiltration is however not always possible and therefore other options have to be considered, for example when the geology or soil type might not permit sufficient infiltration (Dearden, Marchant & Royse 2013; Ward & Robinson 2000). An additional constraint for infiltration is site location. Dechesne, Barraud & Bardin (2004) acknowledge that sites previously used for landfill are heavily polluted and therefore a cap or detention tank is required to stop infiltration into the polluted layer. Discharge into the ground is also not advisable if infiltration creates a risk, for example ground instability or a groundwater flood risk. If none of these options are viable, water should be discharged into a surface water body.

2. *Discharge to a surface water body*

Discharge of water into a surface water body refers to, for example, a river or detention pond. As this can have downstream flooding implications due to an increase in peak river flow it is not deemed as effective as promoting discharge into the ground. When discharging into a watercourse there are also issues associated with water quality as it is not always entirely possible to filter out all pollutants in runoff. Treatment should therefore be utilised to minimise pollution. Some sites however do not have a water body nearby and hence other options have to be considered.

3. *Discharge to a surface water sewer*

If methods one and two are unavailable, then the next best option is to discharge runoff into a surface water sewer. Surface water sewers collect runoff in large pipes and convey it to a water body. This method is less desirable than the previous two due to the lack of on-site water treatment which can result in increased water pollution. As pipes have limited retention capabilities and are usually built to withstand events up to a 1 in 30 year return period (British Standards Institution 2008) they are susceptible to failure (Semadeni–Davies *et al*. 2008). If this option is unavailable at the site, discharge to a combined sewer is acceptable.

4. *Discharge to a combined sewer*

The final option if the previous three methods are unavailable is to discharge the water into a combined sewer. A combined sewer collects both rain and foul water, sending it for treatment. These systems typically have an overflow in case of heavy rainfall events which usually direct flow straight into a watercourse with no treatment occurring, resulting in water quality issues and possibly causing localised flooding. The only constraint in place from the planning policy guidance is that discharge to a combined sewer must not allow runoff to discharge into a foul sewer.

Alongside the hierarchal runoff destination, the guidance suggests that SuDS can be overlooked if the costs for implementation are significant and there is limited risk of flooding. Furthermore, the use of flow control devices are also encouraged throughout the guidance to ensure flow rates are controlled.

2.12 Flow control

According to Woods Ballard *et al.* (2015) flow control devices can be used to regulate runoff and outflow through the drainage system and are common methods of obtaining the outflow rate required by The Standards as runoff volumes are sometimes greater than greenfield, after development. Provisions must be made to deal with a back filling of water through the system to ensure the process is successful (Woods Ballard *et al*. 2015). There are different devices that can be used to control flow rates throughout a SuDS management train, and two examples are given next.

2.12.1 Hydro-brake®

The *Hydro-brake®* uses an upstream hydraulic head through a vertical chamber to create a vortex limiting flow through the device (Figure 2-16a) (Cataño-Lopera, Waratuke & Garcia 2010; Hydro-International 2006). They are the most commonly used stormwater attenuation and flow control device (Figure 2-16b) (O'Sullivan *et al*. 2012). In terms of their site benefits, they have the ability to reduce the need for stormwater storage by up to 30% and due to the vertical vortex and size of the outlet, they reduce the chance of blockages (Hydro-International 2011).

b

Figure 2-16 a) design of a Hydro-brake® (Hydro-international 2006) b) a Hydro-brake® installed at the outflow of a pond (Cataño-Lopera, Waratuke & Garcia 2010).

2.12.2 Weir

Weirs are overflow structures that are built perpendicular to a channel and are designed to limit flow through a certain point, reducing the risk of downstream flooding (Figure 2-17) (Tullis & Neilson 2008; Zahiri, Azamathulla & Begheri 2013).Weirs are widely used as a method of regulating flood flow, however their role remains primarily associated with river channels although adoption in a SuDS management train is also viable (Graham *et al*. 2012). Semadeni-Davies *et al*. (2008) present how the potential implementation of SuDS in Helsinborg, Sweden could limit the impact of increased rainfall generated by climate change. The design suggested utilises a network of weirs to regulate flow throughout the site, providing flood management for Helsingborg.

Figure 2-17 Weir at the SuDS management train in Hamilton, Leicester that causes runoff to backfill through the system, utilising vegetated ponds to manage flood events.

2.13 Monitoring the SuDS management train

Much of the field research has focussed on the site benefits that are generated from individual SuDS devices, with little research monitoring the impacts of a combined SuDS management train. For example Gonzalez-Angullo *et al*. (2008) monitored the infiltration capacity of a laboratory PPS rig, concluding that the infiltration rate decreased to 50 mm/hr from 64 mm/hr when clogged. Stovin (2010) also monitored green roofs and found that it was possible to reduce peak runoff by up to 57%. However, less field research has been conducted on monitoring devices in a management train. A focus on monitoring water quality was applied by Heal *et al.* (2009) by analysing the longer term impacts of installing a SuDS management train, consisting of multiple ponds, filter strips, swales and wetlands at the Hopwood motorway service station. The research monitored the quality of runoff through varying stages of the management train by measuring NH_4-N, biochemical oxygen demand, total suspended solids (TSS), total copper and total zinc. Each chemical parameter reduced by between 70-90% along the management train.

SNIFFER (2004) monitored the three aspects of the SuDS triangle (Figure 2-2) for different individual SuDS and management trains in Scotland, providing evidence of the reduction of flood events. The Dunfermline Eastern Expanse (DEX), Scotland, site consisted of six ponds, a wetland and a series of detention basins that provide regional water management. The project monitored the 3,200m^2 Halbeath pond, which had a contributing area of 13.5 ha, and the 10,200m^2 Linburn pond with a contributing area of 67.5 ha using permanent in situ level and flow meters at the inlet and outlet of both ponds and a nearby rain gauge. The Halbeath pond reduced upwards of 30% of runoff, whilst the Linburn pond had limited impact with regards percentage runoff reduction. However both ponds increased the lag time by 100 and 130 minutes respectively, therefore retaining runoff in the system for longer. The Linburn pond was not measured in terms of percentage peak reduction, but the Halbeath pond reduced 100% of the peak. The report also monitored individual source control devices, such as PPS and filter drains, concluding that they were also as successful at reducing both runoff peak and volume.

The Lamb Drove, Cambridgeshire, England SuDS management train was monitored after implementation in 2006, focussing on all aspects of the SuDS square (Figure 2-3). The management train consisted of a green roof, detention pond, filter strip, swale, water butts, permeable paving and a retention pond. Continuous rainfall measurements were captured using two tipping gauge buckets with attached data loggers and flow was monitored using a series of eight in situ v-notch weir level monitors and pressure transducers linked to a data logger. Overall, it was observed that the SuDS management train reduced runoff in comparison to an impermeable pipe based control site, with peak discharge reaching 0.02 m^3/s for the SuDS management train, in comparison to 0.14 m^3/s for the pipe based control. Furthermore, the SuDS system achieved peak nearly two hours later than the control. The report also analysed the role of different devices, finding that the retention pond reduced runoff most effectively, bringing it down to 3 l/s/ha in comparison to 95 l/s/ha where only nine water butts were used. However the impacts of other devices at the site were not quantified (Cambridgeshire County Council 2012).

2.14 Flood Modelling

For the purpose of this research, computational flood modelling is the desk based analysis of the characteristics of a site, such as drainage, rainfall and topography (Ellis, Revitt & Lundy 2012), allowing the user to model a variety of different hydrological scenarios before the site is developed (section 1.6). Rainfall-runoff modelling is an example whereby simulations are run to determine areas that are likely to flood as a result of a given storm event (Tramblay *et al*. 2011). There are three common methods of environmental modelling: 1-dimensional, 2-dimensional and 3-dimensional methods.

2.14.1: 1-dimensional modelling

One-dimensional modelling is a simplistic model that analyses the environment across one plane (Mahdizadeh, Stansby & Rogers 2012). It is typically used as a first pass attempt, requiring limited computational power due to the simplicity of the parameters modelled (Judi, Burian & McPherson 2011). It provides users with flood extent across a channel, however does not calculate depths (Henonin *et al*. 2013), enabling an initial outline of the scope of flooding. Henonin *et al*. (2013) state that one-dimensional modelling is not suitable for measuring overflow due to the simplicity of the model but can give an indication of potential ponding sites. A further dimension is required to provide a more comprehensive model of the floodplain (Bates & De Roo 2000).

2.14.2: 2-dimensional modelling.

Two-dimensional flood modelling acts as the current benchmark for fluvial flood simulation (Costabile & Macchione 2015; Henonin *et al*. 2013). Models are typically run using elevation data to compute runoff extent and depth at a site after a storm (Bates & De Roo 2000). The method is however unable to model underground drainage which is often estimated, causing uncertainty, and is therefore unable to model pluvial flooding (Henonin *et al*. 2013). Qi & Altinakar (2011) use a method of calculating the impact of a flood event in Georgia, USA to offer stakeholders information on the likely damage and subsequently what flood-proofing is required. However to provide a more detailed simulation incorporating overland flow and pipe channel flow, a combination one-dimensional and two-dimensional method can be used (Mahdizadeh, Stansby & Rogers 2012).

2.14.3: 1-dimensional + 2-dimensional modelling

Incorporating both 1D and 2D modelling enables a more detailed model involving both an analysis of overland flooding of both extent and depth, alongside a simple 1D pipe channel model and is frequently used for both pluvial and fluvial flood simulation (Henonin *et al*. 2013; Pathirana *et al*. 2011). Ellis, Viavattene & Chlebek (2011) suggest that the method identifies critical inundation areas of a site, enabling stakeholder evaluation of the mitigation methods. The major limitation with the method is that a coupled 1D and 2D model assumes runoff is a result of surcharging of the sewer system (Zhou *et al*. 2012). Consequently, 3-dimensional modelling software was developed to provide more accurate data.

2.14.4: 3-dimensional modelling

A three dimensional model involves more parameters than the previous methods as geomorphology and site conditions are included alongside more detail of pluvial flooding not due to a surcharged sewer system (Chen & Liu 2014). Limited research has been undertaken into this method using software such as *MicroDrainage®*. To the author's knowledge, the only peer-reviewed research to use the software to measure the impact of SuDS is Hubert, Edwards & Jahromi (2013), likely due to the large computational power required (Microdrainage n.d.). However it provides a detailed simulation of rainfall-runoff, the likely areas of inundation, including depth and extent, and methods of mitigation (Lee, Birch & Lemckert 2011; Merwade, Cook & Coonrod 2008).

2.14.5 Modelling Uncertainty

As a result of the number of parameters that can impact site runoff (Table 2-6), there is an associated level of uncertainty with modelling (Bales & Wagner 2009; Refsgaard *et al.* 2007). To reduce the level of uncertainty, field based validation is required by comparing results to real-life scenarios to determine the overall accuracy of the model. This adds further confidence to the results, and ultimately the model (Nativi, Mazzetti & Geller 2013).

Table 2-6 Primary uncertainty factors associated with modelling.

Uncertainty
Climatic conditions
Soil conditions
Infiltration rate
Geology
Topography
Channel characteristics

2.15 Modelling SuDS at Scale

Tools are now being created and added into existing flood modelling programs that enable the assessment of individual SuDS devices and larger management trains (Zhou 2014). Modelling SuDS replicates the reductions in water quantity and improvements in water quality (Moore *et al.* 2012) and is an effective way of understanding likely impacts prior to development (Elliot & Trowsdale 2007). Modelling enables an understanding of the abilities of SuDS by examining site characteristics alongside the attributes of different SuDS devices, to understand runoff reduction (Viavattene *et al.* 2010). To obtain the full benefits, site characteristics need to be added to the model to define more detailed data. There are a series of levels where modelling can occur: regional, strategic and local (Figure 2-18).

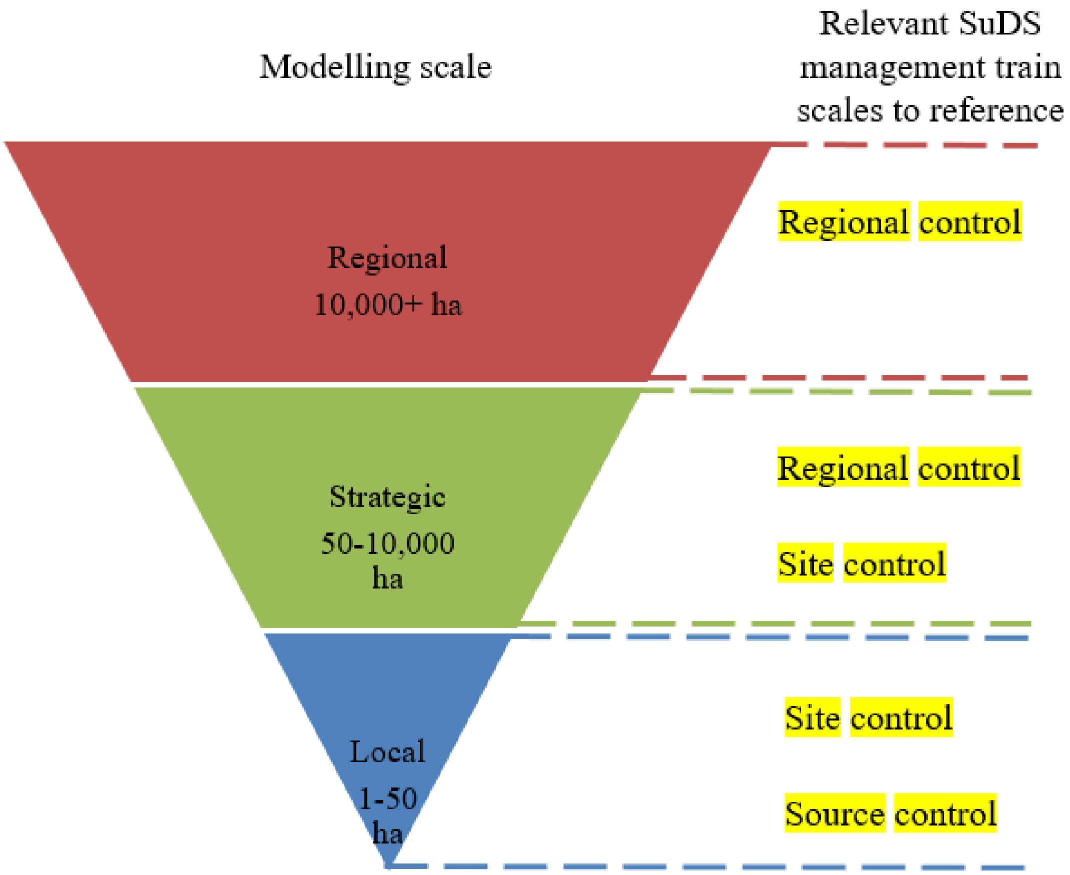


Figure 2-18 The modelling scale: as resolution changes, model capabilities differ and enable different outputs. The associated level of a SuDS management train (Figure 2-7) that is relevant to each modelling scale is also included. Note that different scales of the SuDS management train can work at multiple modelling scales.

2.15.1 Regional level modelling

Regional analyses are of large catchment scale areas. Usually they are associated with a reduction in resolution due to the amount of data required. Consequently, much of the modelling is related to overall flood risk or the modelling of a single characteristic of the hydrological cycle as opposed to the overall impacts of SuDS (Wheater 2002). For example research by Bell *et al*. (2012) used 25 km resolution climate data to model the impact of climate change on flooding in the Thames Basin. By reducing the scale of modelling, an increase in resolution can be achieved. Glendenning & Vervoort (2011) used a multi-parameter model to simulate the impact of integrating multiple rainwater harvesting devices on separate sub-catchments of the Arvari River in India (in total 47600 ha). They acknowledged that inaccuracies are prevalent in their research due to the resolution and scale simulated, for example aquifer storage capacity is taken as homogenous across the site.

2.15.2 Strategic level modelling

The next phase of modelling is strategic or sub-catchment level and allows more focus regarding SuDS. Previous research at this level has been undertaken by Warwick (2013) who created a SuDS feasibility map to suggest where different SuDS devices could be implemented across a local planning authority area, Coventry (9600 ha). The study created a model that accounted for different site characteristics, such as geology, to build a SuDS selection tool. It is essential to know what devices are suitable for implementation prior to local level modelling (Section 2.15.3), which analyses the impact of such devices. Modelling at the strategic level provides information regarding locations for various SuDS devices, but is at too coarse a scale to give information on the impacts that are probable (Moore *et al*. 2012).

Other research at the strategic level has been completed by Doubleday *et al*. (2013), modelling the role that Low Impact Design (LID) has had at an 8800 ha residential site in Texas, USA. The investigation focussed on how green channels and reservoir storage altered peak flows, concluding that peak flows would increase by approximately 250% without the devices. However, 5 m resolution LIDAR data together with DEM data was used (the DEM data was resampled at 30 m resolution) to ensure the site could be modelled.

Strategic level modelling often provides information regarding site selection; where certain SuDS can be located. Due to the size of the area, assessment regarding the impacts that each device could have is limited as a significant amount of data is required. Nevertheless, Semadeni-Davies *et al*. (2008) attempted to simulate the impact of installing detention basins in the Lussebäcken Catchment, Helsingborg, Sweden (2474 ha). They used separate sub-catchments to develop the model and focussed on the role an overall increase in total impermeable surfaces would have and therefore where need was greatest, demonstrating the impact it could have on runoff volumes. However only standalone detention basins were modelled across the catchment due to the scale of modelling and resultant volume of data.

2.15.3 Local level modelling

Local modelling can be broken down into two further subsections; site and building scale. Site modelling involves much smaller areas than at the strategic level but can take information generated from the strategic level and design a drainage system to understand the impacts. This scale requires more detail in comparison to the previous two so that the information is of a high enough quality (Chen & Liu 2014; Zhou 2014). Site level modelling varies in terms of focus with models previously created for simulating one device at the building scale or combined devices in a management train.

Much of the research to date has been of standalone SuDS devices, for example Versini *et al*. (2015) analysed the potential role of installing a green roof (35 m^2) at the building scale. The model was developed using the Storm Water Management Model (SWMM) (section 2.16.1) and concluded that green roofs could reduce up to 90% of runoff. Lamera *et al*. (2014) also modelled green roofs, with similar conclusions to Versini *et al.* (2015). Khastagir & Jayasuriya (2010) modelled the impacts of a single rainwater harvesting device at the building scale to improve water quality reaching stormwater drains using the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (section 2.16.2). They concluded that the overall water quality of runoff could improve due to the installation of rainwater harvesting devices.

Bastien *et al*. (2010) and Hubert, Edwards & Jahromi (2013) focussed on the benefits of a SuDS management train in relation to the SuDS square. Due to the breadth of the research, in terms of all aspects of the SuDS square (Figure 2-3), there was a lack of detail regarding the results for quantifying water quantity, water quality and amenity or biodiversity benefits. Furthermore Bastien *et al*. (2010) did not account for site characteristics such as topography which are required to model runoff routes and potential ponding sites. Ellis & Viavattene (2014) focussed on the local water quantity impacts of SuDS at two sites; one in Birmingham, the other in Coventry, UK. This research was part of the SuDS selection and location tool (SUDSLOC) (section 2.17.1), and concluded that using PPS at the 12 ha site in Birmingham could reduce runoff by 30% for the 1 in 200 year rainfall event. Installing three disconnected infiltration basins at the 37 ha residential Coventry site could reduce runoff by 55% for the 1 in 200 year event. There is however limited research concerning modelling a SuDS management train and its ability to reduce runoff.

2.15.4 Issues with SuDS modelling

Modelling can supply information regarding the impacts of a development or the installation of a device before completion, therefore allowing for the maximisation of space (Moore *et al*. 2012), however there are limitations. Although a variety of variables can be measured or factored into the model, there are still differences when replicated in real-life resulting in inaccuracies of the original modelled data (Merwade, Cook & Coonrod 2008; Wheater 2002).

There are also specific uncertainties surrounding modelling SuDS. The type and density of vegetation used in the devices may vary over a large area, which is typically too complex to model and can produce varying results (Burszta-Adamiak & Mrowiec 2013; Elliot & Trowsdale 2007). Additionally, the results from a modelled system are of a “perfect” scenario, whereas SuDS become clogged throughout their life-span and maintenance is often intermittent, therefore their impact is altered (Bergman *et al*. 2011; Gonzalez-Angullo *et al*. 2008).

Model validation can be undertaken to determine the level of uncertainty (Burszta-Adamiak & Mrowiec 2013; Cloke & Pappenberger 2009; Dotto *et al.* 2011) whereby field data is compared to modelled data and analysed using, for example, the NSE (EQ 2.1) developed by Nash & Sutcliffe (1970) or the coefficient of determination (Dotto *et al*. 2011). The NSE was developed specifically for validating a hydrological model using EQ 2.1. Using this method enables an assessment of the software's capabilities, therefore selecting a suitable model is critical as different packages complete different tasks more effectively than others. For example Burszta-Adamiak & Mrowiec (2013) suggested the Stormwater Management Model (SWMM) (section 2.16.1) had an accuracy of 0.59 for modelling green roofs, while Gaborit *et al*. (2013) achieved 0.91 when using the same software to model detention basins.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right] \qquad \text{EQ: 2.1}$$

where

Y_i^{obs} is observed discharge at time

Y_i^{sim} is the model discharge at time

Y^{mean} is the mean value of observed discharge

i is value for each measured sample

n is total number of samples

2.16 Drainage Modelling Software

Computer packages are required to run models at different scales, as outlined in section 2.15. Software typically analyses variables to simulate a pre-determined event (Ellis, Revitt & Lundy 2012). SWMM (Rossman 2010), MUSIC (Wong *et al*. 2002), MOUSE (DHI 2002), Infoworks (Salarpour, Rahman & Yuspo 2011) and *MicroDrainage*® (Hubert, Edwards & Jahromi 2013) are examples of commercially available packages used to model drainage and storm events.

2.16.1 SWMM

SWMM is a rainfall-runoff model designed by the USEPA that enables a quantification of possible water quantity and quality improvements (Rossman 2010). It has become a widely used freeware model that can simulate both single and continuous rainfall scenarios (Burszta-Adamiak & Mrowiec 2013). The software has a limited range of SuDS that can be incorporated: green roofs, PPS, swales, infiltration trenches, bio-retention zones and rain barrels (Liao *et al*. 2013). Research by Lee *et al*. (2012) presents a method of using SWMM with infiltration trenches and rain barrels to reduce flooding for the 50 year return period in Korea. The research also validated the model, with error margins of up to 13.3%. The accuracy of the software for measuring water quantity reduction was questioned by Burszta-Adamiak & Mrowiec (2013) who concluded that SWMM under estimated outflow from green roofs for over half of their experiments. This coincides with Elliot & Trowsdale (2007) who concluded that infiltration from swales and infiltration trenches in SWMM is not added to the soil and therefore not counted in groundwater flow.

2.16.2 MUSIC

The Model for Urban Stormwater Improvement Conceptualisation (MUSIC), developed by the Cooperative Research Centre for Catchment Hydrology in Australia, is an urban stormwater modelling tool (Ellis, Revitt & Lundy 2012; Wong *et al*. 2002) that allows for the input of devices to give expected runoff results (Bastien *et al.* 2011). It is used for research purposes focussing on the assessment of stormwater and the impacts of SuDS (Beck & Birch 2013; Khastagir & Jayasuriya 2010). The software has a variety of SuDS integrated into the package and so can be modelled without the need for much configuration (Elliot & Trowsdale 2007). Dotto *et al*. (2011) cast doubt over MUSIC's rainfall/runoff module's ability to accurately predict stormwater flows in a highly urbanised catchment. This is echoed by Imteaz *et al*. (2013), who completed a series of tests to validate the software and concluded that MUSIC grossly over-estimates several of the results.

2.16.3 MOUSE

MOUSE (Model for Urban Sewers) was developed by the Danish Hydraulic Institute (DHI 2002) and presents a good representation of urban runoff, however is not overly user-friendly (Viavattene *et al*. 2008) and therefore the software is not commonly used in the UK (DEFRA & EA 2005). In terms of integration of SuDS, MOUSE is limited to PPS, bio-retention devices, rain tanks, swales and infiltration trenches, however like SWMM, it is unable to incorporate groundwater flows with the infiltration of certain devices (Elliot & Trowsdale 2007). For this reason the use of the package in research is restricted to modelling surface flow from impermeable surfaces, negating the need to measure groundwater characteristics (Semadeni-Davies *et al*. 2008). A review of models by Elliot & Trowsdale (2007) concluded that the model was more successful than others in simulating water quality reductions, but less effective regarding water quantity.

2.16.4 Infoworks

Infoworks is a hydrodynamic package that allows for modelling a series of hydraulic structures (Salarpour, Rahman & Yuspo 2011). The software's primary purpose is to model flow and runoff routes (Moore *et al*. 2012), but it can also model runoff reductions that are possible through implementing SuDS (Bastien *et al*. 2010). Moore *et al*. (2012) used the software to investigate the impact of installing retrofit SuDS to a site, calculating 78% of combined sewer overflow could be reduced by disconnecting conventional drainage

2.16.5 MicroDrainage®

MicroDrainage® is a commercially available urban stormwater drainage design model (MicroDrainage 2009) and the UK flood and drainage industry standard system (Hubert, Edwards & Jahromi 2013). It was not reviewed by Elliot & Trowsdale (2007) as at the time it focussed on incorporating just source control devices, but has since developed a wider suite of available SuDS systems. The software enables interaction of a design procedure through data input by drawings as opposed to a spread sheet which provide visual animations and ease of transferring data between Geographical Information Systems (GIS) packages (Afshar 2007; MicroDrainage n.d.). It is generally used to develop new designs, although it has the capability to incorporate SuDS retrofit (Atkins 2008; Moore 2006) and to produce outflow hydrographs based on a pre-determined rainfall event, accounting for topographical features and the input of housing (Bassett *et al.*2007). *MicroDrainage*® is often used by stakeholders and consultancies (Moore 2006) when creating flood risk assessments e.g. Mott Macdonald Ltd & Medway Council (2009). Furthermore, the software has been used to complete a flood risk assessment for a site at the Canley Regeneration plan, Coventry (RPS Group 2012). The software was used in the report to calculate the outflow as a result of installing ponds and site runoff. Hubert, Edwards & Jahromi (2013) used the software to compare the overall site benefits of installing a SuDS management train to an office site, in comparison to conventional pipe based drainage. However, throughout all of the research and industry based information, there is no published peer-reviewed data regarding the accuracy of *MicroDrainage*®. Also, there has been no research comparing data generated from *MicroDrainage*® with field data, therefore the outputs from the software contain levels of uncertainty.

2.17 Decision Support Tools

DSTs are an aid for practitioners to reduce the time during any decision making process (Stovin & Swan 2007), they are not designed to make a final decision, but to assist the process (Newton *et al*. 2014; Scholz & Uzomah 2013). The methodology adopted by Todini (1999) broadly attempted to improve flood mapping and ultimately flood management processes across Europe using the method presented in Figure 2-19. The research was undermined by the complexity of the support system which required a high powered computer, but nonetheless accurately simulated flood flows and presented potential management options.

Figure 2-19 Flood mapping and management DST: adapted from the method used by Todini (1999) to create flood risk maps.

Other systems, such as the support tool created by Shim, Fontane & Labadie (2002) have also attempted to enhance the flood management selection process, with a focus on river basin catchment systems in South Korea. However neither Shim, Fontane & Labadie (2002) nor Todini (1999) have attempted to produce a simplified version with the inclusion of SuDS.

2.17.1 SuDS Decision Support Tools

Due to the desired requirements of SuDS devices (Figure 2-3), and the complexity of creating a DST that accounts for them, a SuDS DST focussing on providing specific numerical values for all four aspects of the SuDS squares does not exist. However there have been attempts at producing a system that supports one or multiple facets of the square.

2.17.1.1 Wade & Garcia-Haba

The DST created by Wade & Garcia-Haba (2013) was part of a Centre for Expertise for Waters (CREW) research project to review urban diffuse pollution control measures. The project integrated SuDS in a wider tool that aimed to provide case studies that were ranked based on their associated confidence (theoretical for new and novel ideas, piloted for local level with relative uncertainty and established for those that were accepted by practitioners) for different management measures for a range on land use types. The tool was the output of a review that analysed the literature regarding both structural, of which SuDS were one component, and non-structural, for example environmental regulations, methods for reducing pollution. Users were able to select their desired land use to define what options were available to them, providing a simple and concise method for defining possible management approaches suitable to different land use types.

2.17.1.2 SuDS for Roads

SuDS for roads provided a selection tool for installing SuDS on roads (Guz *et al*. 2009). The process included three key phases: scoping, where a site analysis is undertaken to understand the site characteristics, evaluation, which involves defining any drivers, barriers and costs and final selection, which is the selection of appropriate SuDS. Compiling site data develops an understanding of the appropriate devices for a site, the tool then analyses the general capabilities of different SuDS, focussing on all aspects of the SuDS triangle (Figure 2-2), which was later superseded by the SuDS Square (Figure 2-3). The tool quantified the capabilities of different devices into low/ medium/ high and discussed any likely future changes. Although an extremely comprehensive assessment of the multiple facets of different SuDS with regards the SuDS Triangle, the tool was unable to place a numerical value to the overall impact of installing each device, with regards the components of the SuDS triangle.

2.17.1.3 SuDS Treatment Train Assessment Tool

Jefferies *et al*. (2009) created the SuDS Treatment Train Assessment Tool (STTAT) for the Scottish Environmental Protection Agency as a method of quantifying the impact of both single SuDS and individual components of a wider treatment train on water quality. The tool utilised a scoring system to determine the level of risk posed by contamination, which was calculated by combining a score that was provided for the receiving water conditions with a catchment land use score. The level of risk was then compared to the likely reduction in contaminant risk created by integrating either individual SuDS or different combinations of SuDS in a train. An accuracy assessment of the tool was completed using field data from twenty-two study sites that utilised both treatment trains and individual components. This provided a degree of certainty of the outputs of the research and enabled a re-assessment of the values originally used for each device, to better reflect their role in a wider treatment train.

2.17.1.4 Stovin & Swan DST

Stovin & Swan (2007) presented a method for quantifying hydraulically efficient cost-effective solutions for SuDS retrofit to provide stakeholders with a quick understanding of eventual costs, in an attempt to further incentivise the implementation of SuDS. The tool concentrated on a range of SuDS solutions, however was more focussed on a standalone assessment rather than determining the cost implications of combined devices. The research made a number of assumptions, as key contributory factors for overall cost were not accounted for due to their uncertainty. Although the system was successful in presenting potential cost-savings, it did not enable the total area to be quantified therefore making it difficult to estimate the number of devices required. Furthermore actual land purchase costs were not included, which is likely to alter the ranking of devices significantly. Nonetheless, the report concluded that infiltration basins were the cheapest form of SuDS to integrate at a site.

2.17.1.5 Rainwater Harvesting Decision Support System

Kahinda *et al*. (2009) developed a tool for assessing rainwater harvesting systems. RHADESS (Rainwater Harvesting Decision Support System) was developed to indicate site suitability for systems in South Africa, using a combination of ArcView 3.3 and

Microsoft Excel. An overview of the data requirements is presented in Figure 2-20. The overall aim of the project was underpinned by the focus of water security in the Millennium Development Goals and therefore promoted the wider application of rainwater harvesting. However, the research did not determine the impact that would be achieved after site selection, while focussing simply on rainwater harvesting limits the wider applicability of the tool.

Figure 2-20 Outline of the GIS based processes used for the RHADESS DST method by Kahinda *et al*. (2009) to create a rainwater harvesting suitability map.

2.17.1.6 SUDSLOC

SUDSLOC is an ArcGIS-based selection tool that integrated both 1D and 2D modelling to determine the hydraulic performance of different SuDS devices (Ellis, Revit & Lundy. 2012; Ellis & Viavattene 2014; Viavattene *et al*. 2010). Figure 2-21 outlines the key processes undertaken to achieve the outputs of the tool. The method provided an advanced tool to analyse the impact on runoff and water quality, along with site selection of different SuDS devices (Viavattene *et al*. 2010). However, the tool was reliant on the availability of detailed site information, primarily high resolution LIDAR data which slowed down the decision making process.

Figure 2-21 The key inputs and process required for the SUDSLOC DST to determine the impact of SuDS as a result of different storm event (adapted from Ellis & Viavattene 2014).

2.17.1.7 Scholz & Uzomah DST

Scholz & Uzomah (2013) presented a rapid assessment system to quantify the ecosystem improvements possible by implementing PPS and trees. The aim of the tool was to increase the implementation of PPS and enhance the ecology of the urban landscape. The tool focussed on ecosystem services, therefore although an assessment of the runoff reduction potential was presented, it was not the primary purpose of the tool.

2.17.1.8 SuDS DST overview

The integration of a successful SuDS DST can ensure a more resilient site, whether for flooding or pollution, or provide more amenity potential, assisting in the design aspect of a site. Tools have been developed to support the adoption of single devices (Kahinda *et al*. 2009; Scholz & Uzomah *et al*. 2013), and to include more devices in a management train (Ellis & Viavattene 2014). However, although some of the tools are capable of making predictions for runoff, those that provide detail of multiple devices are complex and require a large amount of additional data. They also typically integrate unconventional GIS methods, or modelling packages that are uncommon in the UK drainage planning industry. For this reason, a tool to support the UK industry standard drainage modelling suite *MicroDrainage*®, is likely to have a greater level of uptake, working alongside existing systems.

2.18. Site design

Designing a site that effectively integrates SuDS to achieve the requirements of the SuDS square is critical (Charlesworth 2010). Ensuring they are designed successfully reduces the likelihood for large future maintenance costs (Jefferies *et al*. 2009), ensures they do not deteriorate too quickly (Wilson, Bray & Cooper 2004) and that they meet site requirements (Woods Ballard *et al*. 2015). Factors that need to be considered to ensure the site is designed effectively are the optimal rainfall scenarios that will be modelled, the impact of climate change and the overall site characteristics.

2.18.1 Designing optimal rainfall scenarios

The storm event that will have the greatest impact on the site, termed the critical storm duration, is the event that produces the largest amount of discharge (Kang *et al.* 2009). In the UK this is broken down into two events; summer and winter. The winter event provides the greatest severity of runoff due to changes in ground conditions which further promote runoff. The duration of the event is also a key factor to be considered, and Scholz (2004) discovered that shorter events of about one hour usually triggered the critical storm duration. In addition, the scale or return period need to be selected to determine the magnitude of the event that swill be modelled and therefore provide a magnitude to mitigate. The Standards suggest that runoff should not exceed greenfield rates for the 1 in 100 year 360 minute event.

It is accepted that climate change will have an effect on the climate of the United Kingdom (IPCC 2013) throughout the design life of the management train. For this reason, the EA require a percentage increase to be added to any storm event to provide resilience towards the impacts of climate change. Practitioners add between 20-35% to storm events dependent on the region, as this provides a sufficient level of resilience against the anticipated climate change to 2080 (EA 2016b).

2.19 Conclusion

It is apparent that there is a potential requirement for SuDS devices in new developments to reduce flood risk. However although there is an appreciation of the benefits of SuDS in terms of reducing flood flows, much of the research (Table 2-1) has centred around the capabilities of each individual device. A SuDS management train is an option to provide a site with added resilience and capacity to deal with a large storm event (Lamond, Rose & Booth 2015). While attempts have been made to model a SuDS management train (Bastien *et al.* 2010; Hubert, Edwards & Jahromi 2013), their inability to quantify runoff reduction has not been addressed. Research indicates that a SuDS management train is an effective strategy for mitigating flood risk (Hubert, Edwards & Jahromi 2013) but significantly the relative water quantity reduction of individual structures in the management train is unknown. As there are barriers due to the perceived lack of effectiveness of SuDS (Jose, Wade & Jefferies 2015) related to monetary costs and health and safety of the public (section 2.5) (McKissock *et al*. 2003; Todorovic, Jones & Roberts 2008), it is critical that the most effective devices are installed for maximum benefits.

The benefits of a SuDS management train can also be examined using a DST. Previous tools have been used to support decision making around cost benefits (Stovin & Swan 2007), or commonly, individual devices (Kahinda *et al*. 2009; Scholz & Uzomah 2013), whilst Ellis & Viavattene (2014) attempted to use highly localised data to define the impacts of potential SuDS. However the latter relied heavily on data inputs, utilising a modelling interface, making the tool slower to create outputs. A rapid-decision making DST is therefore necessary to provide stakeholders with a quick and simple assessment of the total number of SuDS required to achieve greenfield runoff.

Whilst previous research has utilised MUSIC and Infoworks (Bastien *et al.* 2010), *MicroDrainage*® is more widely used by practitioners for new build sites (e.g. Atkins 2008; Mott Macdonald Ltd & Medway Council 2009) and is the industry standard for

UK drainage and flood systems (Hubert, Edwards & Jahromi 2013). However the real-world accuracy of *MicroDrainage®* is relatively unknown, therefore the accuracy of resultant outputs are unknown.

The next chapter constructs a methodology to answer the aims and objectives. It will describe the method taken to obtain results, building on information from the literature review. It will provide an in depth consideration of how the method was devised and the software that was used.

3 Methodology & Research Design

3.1 Introduction

This chapter presents the methodology that addresses the aims and objectives given in section 1.5 and is therefore split into three sections related to each aim. Phase one (section 3.5) will present a deconstruction of a SuDS management train, highlighting the components that can most effectively reduce runoff characteristics. This will enable practitioners to achieve an understanding of devices that should be prioritised with regards to flood management. Chapter two demonstrated a lack of research regarding a SuDS management train's ability to reduce water quantity (section 2.7). Therefore an output of the research will be an investigation of the potential water quantity reduction of individual SuDS devices linked into a SuDS management train.

Phase two (section 3.6) consists of the correlation between infiltration rainfall rates, site area and peak flow to determine how each parameter influences runoff. This is then used in combination with data generated from aim 1 to determine the likely runoff at a range of different site conditions under varying rainfall scenarios, creating a DST.

Finally, phase three (section 3.7) is a validation of *MicroDrainage*®, which has limited research exposure (Hubert, Edwards & Jahromi 2013). Field data is thus used to determine the quality of the results from aims 1 and 2. Section 3.7 focuses on comparing data produced through *MicroDrainage*® with field data from Hamilton, Leicester and laboratory data for both PPS and filter drains. This will provide added accuracy to data generated in aim 2.

The methodology for modelling the site adapted previous methods (Bastien *et al.*2010; Hubert, Edwards & Jahromi 2013), whereby a drainage plan was created by integrating SuDS and calculating the possible reduction in peak flow. In addition to the methods, ethical issues of the research will be outlined (section 3.3), along with an explanation of the software and hardware used (section 3.4).

3.2 Conceptual Framework

A conceptual framework presents the development of ideas to show how the scope of this research was identified through a review of alternative options (Miles & Huberman 1994). The focus of the study was on flooding due to the likely increase in events, particularly in the

UK, as a result of climate change (Evans *et al*. 2008). As 5.2 million properties are exposed to flooding in the UK (Bennett & Hartwell-Naguib 2014) it is valuable to understand sustainable solutions to reduce future risk.

Different global flood management techniques were analysed (section 2.4) to understand their suitability to manage increased flooding as a result of a changing climate. Whilst hard engineering measures such as dredging and constructing flood walls have been adopted historically (Jeuken & Wang 2010; Kenyon 2007), a recent shift to a more holistic, soft approach has been undertaken in various parts of the world (section 2.6). Beddoes & Booth (2011) discussed the role of property-level flood protection; a method whereby houses increase their resilience to flooding by “proofing” their property (section 2.4). However whilst this provides a method of adapting to flooding and increasing property resilience, SuDS offer a more sustainable solution to managing flood risk, by promoting natural processes lost through an increase in impermeable surfaces and through the installation of conventional drainage (section 2.5). Therefore although property-level flood protection remains an effective measure for increasing resilience, SuDS, if designed correctly, offer flood management for events up to a pre-determined return period.

Having defined that SuDS would be the full scope of the research, an exercise was taken to determine the detailed scope of the research. Figure 3-1 shows the key decision making processes that were undertaken to define the aims of the research (section 1.5.1). It presents a flow through each aim defining the context and scope of the project, providing the main factors that were either adopted (blue) or rejected. The key decision making processes undertaken to define aim 1 are shown in the left hand portion of Figure 3-1. Aim 1 focussed on a quantitative analysis of the modelled impact on runoff of different SuDS in a management train. It was therefore important to define which devices were to be modelled and in what configuration, along with the most appropriate software for the analysis. The middle section of Figure 3-1 focusses on aim 2, the creation of the DST to support *MicroDrainage*®. The primary decisions focussed on the type of DST; flow diagram or numerical output, the interface and software for the tool and the method for validation. Aim 3 was the overall validation of *MicroDrainage*®. As demonstrated in Figure 3-1, the key decision making processes for the aim focussed on the specific method of statistical analysis and the data that would be used to validate the program. The following sections discuss the main concepts and factors explored for each aim of the research.

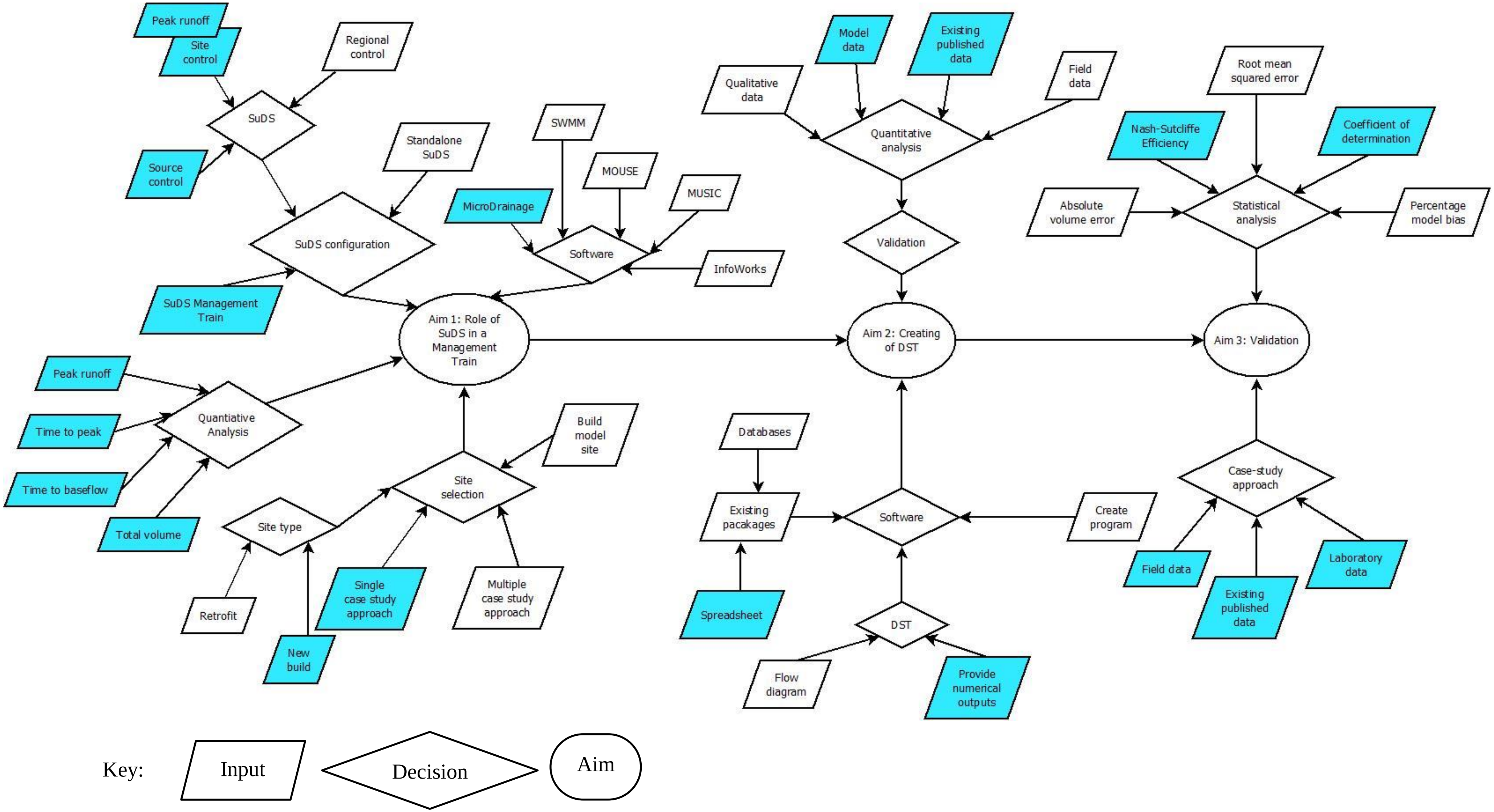


Figure 3-1: Conceptual framework outlining the key approaches and questions raised by the research. Adopted approaches highlighted in blue. Decisions are the aspects of the methodology. Inputs are the possible options that were considered.

3.2.1 Conceptual framework: Aim 1

Each contributing factor that has defined aim 1, as presented in Figure 3-1, is discussed in turn in the following sections.

3.2.1.1 SuDS

As discussed in section 2.7, a combination of devices is typically regarded as the most efficient method for improving downstream water quality through added resilience (O’Sullivan *et al.* 2012). This was therefore applied to flood management by analysing the influence of individual components of a wider management train. Based on the literature and examples of existing SuDS management trains (section 2.8), PPS and detention basins were the most common at the source and site control level, respectively, with swales typically used to convey runoff. Green roofs were added, as research by Stovin (2010) suggests that they have the capacity to reduce 57% of runoff. Other devices discussed in section 2.8 were not considered as they were either not as effective as shown in previous research or were less common in existing examples of SuDS management trains.

3.2.1.2 Quantitative analysis

The outflow of a designed SuDS management train as a result of the 1 in 100 year rainfall event, plus 30% for climate change, was compared to the conventional system (section 3.5). The outflow for the different SuDS combinations could have been measured for different return periods, for example the 1 in 30 year event. However maintaining parity with the Non-Statutory Standards for SuDS (DEFRA 2015) ensures the findings of the research are in line with and can ultimately be adopted by industry (section 6.8.1). The quantitative analysis of the outputs focussed primarily on the aspects of peak flow: total peak flow, time to peak (section 4.2.1) as this is the variable stipulated in the Non-Statutory Standards (DEFRA 2015). To further analyse the quantitative data, the time to baseflow and total volume for each SuDS combination were also analysed.

3.2.1.3 Software Used

Different drainage modelling programs were discussed in section 2.16; however *MicroDrainage*® (section 2.16.5) is the UK industry standard drainage modelling tool (Hubert, Edwards & Jahromi 2013). Therefore *MicroDrainage*® was used (section 3.4.1) to ensure the results of the research had the opportunity to have a wider influence over industry and policy (section 6.8.1 and 6.8.2).

3.2.1.4 Site selection

Previous research has focussed on both new build design (Bastien *et al*. 2011) and retrofit design (Stovin & Swan 2007). Designing SuDS for new build affords an opportunity to plan for maximum capacity and fully analyse their role. The impact of each device with regards flood management can then be applied to retrofit design.

A single case study approach was adopted for the research with Prior Deram Park, Coventry, England, the chosen new build site (section 3.5.1). The site was chosen after consultation with Coventry City Council with regards future areas for development. Adopting a case study approach enabled an in-depth understanding of this particular site. Site specific characteristics however reduce the wider applicability of the findings. Focussing on one site was a more feasible approach than using multiple case studies as although it would have demonstrated the role of SuDS at different sites, the outputs would still have only been specific for those modelled sites. A similar issue would also have occurred if a model design was used with no link to an existing site. Therefore a single site was used as a starting point with key runoff determining factors (rainfall and infiltration) altered and re-simulated to increase the wider application of the outputs by reducing the effect of individual site characteristics.

3.2.2 Conceptual framework: Aim 2

As defined in Figure 3-1, the choice of software and the method of validation were both considered when formulating aim 2 of the research. Both factors are discussed in the coming sections to justify the adopted approach.

3.2.2.1 DST software

Existing research has demonstrated the user benefits for creating a DST, with particular focus on SuDS (section 2.17.1). Previous methods have focussed on their role with regards water quality improvements (Jefferies *et al*. 2009) or attempted to outline the suitability of individual devices (Wade & Garcia-Haba 2013). SuDS focussed DSTs have ranged from providing specific values for a combination of devices, for example SuDSLOC (section 2.17.1.6; Viavattene *et al*. 2010), to quantifying the relative impact of devices in comparison to others, such as SuDS for Road (section 2.17.1.2; Guz *et al*. 2009). Both methods are capable of supporting decision making but have associated issues (section 2.17.1).

Discussions with XP Solutions, the developer of *MicroDrainage*®, highlighted a desire to have a support tool to further engagement with the SuDS selection aspect of the software. The software currently requires training to effectively use the program, therefore creating a tool to simplify the process would be useful. This was further highlighted through discussions with users of *MicroDrainage*® whereby the existing approach to design is trial-and-error with regards the number and type of devices used to achieve greenfield runoff. Using the method outlined in section 3.6 enabled the calculation of peak flow based on site conditions and a specific number of each device. This method provides a similar output to that of Viavattene *et al*. (2010), however it simplifies the process and as the data used is underpinned by outputs from *MicroDrainage*®, it ensures that the DST works in conjunction with the software. Creating a numerical output for the tool was more effective for the purpose of this project as it provided the likely value for each combination of SuDS, as opposed to Guz *et al*. (2009) which used a flow based decision approach to rank the potential role of different devices.

Previous methodologies for constructing a DST have used different interfaces and programs as their output (section 2.17). Viavattene *et al*. (2010) for example designed an entirely new tool and user interface for SuDSLOC, whilst Wade & Garcia-Haba (2013) used MS Excel (Microsoft Corporation 2010). Although programming a new tool or creating a database was considered, the aim of the DST was to simplify the overall decision making process, therefore using MS Excel was the preferred method due to its availability and consistent user-interface. The software was also capable of running the necessary statistical calculations to define peak flow and run macros to navigate the tool in the most user-friendly method (section 3.6.2).

3.2.2.2 Validation of the DST

A validation of the DST was required to ensure the accuracy of the outputs and to give users confidence in the tool. This concept was previously applied to a DST by Jefferies *et al*. (2009) in that the STTAT tool mirrored the site configuration of twenty-two different SuDS treatment trains and individual devices (section 2.17.1.3). Although the focus of the research by Jefferies *et al*. (2009) was water quality enhancement, the validation of the tool enabled a re-assessment of the results to better replicate field data leading to enhancements being made to the STTAT DST. This approach was therefore adopted to ensure the accuracy of the DST in this research and ultimately to benefit future users (section 3.7). This approach was chosen as opposed to comparing the outputs directly to *MicroDrainage*®. As the tool was underpinned by the outputs of *MicroDrainage*®, it would ultimately result in circular validation where a model validates a model. For this reason, comparing the data to field results is the most appropriate method.

3.2.3 Conceptual framework: Aim 3

Aim 3 involved the validation of *MicroDrainage*® to assess the accuracy of the outputs of aim 1 and aim 2. The decision making that underpinned the aim focussed on the most appropriate source of data to support the validation and the statistical analysis that would provide a robust assessment of the program (Figure 3-1).

3.2.3.1 Data

Additional data was required to support the validation of *MicroDrainage*®. Further to the case study used for Prior Deram Park, the Hamilton SuDS Management Train, Leicester, England, was monitored. A case study approach for analysing SuDS and validating a model was also applied by Versini *et al*. (2015). This approach provides detailed, typically only site specific data, however the purpose of the site monitoring was to further understand the accuracy of *MicroDrainage*®. The role of the site therefore had less influence as Hamilton could be designed in the program to compare flow between field and model data. Acknowledging the potential inaccuracies of using flow at one site and the issues associated with validating a model over a 16 ha site, laboratory data was also used to further test the accuracy of *MicroDrainage®*. A method similar to that applied by Principato *et al*. (2015) was used for measuring outflow for different rainfall events for PPS and filter drain rigs.

An additional method for validating *MicroDrainage®* would involve using previously published data. Field data was previously collected for Lamb Drove (Cambridgeshire County Council 2011) with the site plans also included in the report. Peak outflow data is presented in the report as a response to different rainfall events. It is possible that this information could be used, if the site were designed in *MicroDrainage®*, to compare the outputs and therefore further validate the software. This method relies on the accuracy of the data in the report and requires the detailed design of the whole site. However as the DST was underpinned by data from *MicroDrainage®* as a result of the 1 in 100 year 360 minute event, in line with the National Standards (DEFRA 2015a), the data for Lamb Drove was not compatible as the events monitored were no greater than a 1 in 5 year event (section 3.6.3.1). Therefore assuming a strong NSE and r^2 value for the outputs of aim 3, the Hamilton site was modelled in *MicroDrainage®* for the 1 in 100 year 360 minute event and compared to the DST, providing an accuracy assessment of the tool.

3.2.3.2 Statistical analysis

A range of statistical approaches have been adopted in the literature with regards model validation. The most commonly used methods in hydrological modelling are the Nash-Sutcliffe Efficiency (NSE) (Principato *et al.* 2015; Versini *et al*. 2015; De Vleeschauwer *et al*. 2014; Gaborit *et al*. 2013; Dotto *et al*. 2011; Kang *et al*. 2009) and the coefficient of determination (Nawaz, McDonald & Postoyko 2015; Dotto *et al*. 2011; Freni, Mannina & Viviani 2009; Kang *et al*. 2009) which were subsequently used for this research. The NSE was a formula proposed by Nash & Sutcliffe (1970), specifically for hydrological models by comparing field data and model data at a specific time (section 2.15.4). The coefficient of determination is a statistical output of a regression analysis that defines the variance between dependent and independent variables.

Other methods considered included absolute volume error (Versini *et al*. 2015), percentage model bias (De Vleeschauwer *et al*. 2014) and root mean squared error (Principato *et al.* 2015; Kang *et al*. 2009). However as these methods were less common in the literature, it was decided that the NSE and coefficient of determination would be most appropriate.

The NSE was the desired method of validation as it was specifically designed for hydrological modelling and is widely used in other validation research. The coefficient of determination was also used to support the NSE as it is another common method used, therefore using a dual statistical analysis provides increased certainty in the outputs. Calculating the accuracy with which *MicroDrainage®* predicted runoff provided validity to the results of aim 1 and aim 2, but also confidence in the model for all SuDS stakeholders.

3.2. 4 Conceptual framework overview

The previous sections have compiled the various concepts, theories and frameworks that have been considered prior to the research and provided a justification for the adopted approach. An overview is provided in Figure 3-1. A quantitative approach has been taken throughout the research that was assisted by a case study approach, using data for Prior Deram Park, Coventry, England to define the site characteristics for Aim 1 of the research and the Hamilton SuDS Management train, Leicester, England, for Aim 3. The following sections will discuss the methods used to generate the outputs of the research.

3.3 Ethical Approval

Ethical approval for this research was obtained and followed as per the procedures required of research at Coventry University (Appendix B). The main issues that arose were health and safety based, ensuring care when undertaking the field research as part of aim 3.

3.4 Software

3.4.1 MicroDrainage®

MicroDrainage® (version 2015.1.1) was used to model flow for designed conventional and SuDS drainage systems, as it was the industry standard drainage modelling software (Hubert, Edwards & Jahromi. 2013; MicroDrainage n.d.). Furthermore outflow hydrographs generated through simulations of different pipe and SuDS combinations were integral when producing the results (section 3.5 and 4.2). As a 3-dimensional model (section 2.16.5), *MicroDrainage®* modelled drainage patterns through both a SuDS and pipe based network (Hubert, Edwards & Jahromi 2013).

MicroDrainage® has been adopted as a stormwater model by industry and was capable of developing a SuDS management train (Hubert, Edwards & Jahromi 2013; Mott Macdonald Ltd & Medway Council 2009). The software comprised of multiple modules that enabled the modelling of different phases of SuDS design, and for this research the DrawNet suite was used. DrawNet enabled the user to add other *MicroDrainage®* modules into the package to undertake other roles, therefore by adding the Simulation suite results were generated by testing the designed drainage plan. The module also allowed for several SuDS at both new build and retrofit level to be linked together to form a SuDS management train. To run *MicroDrainage®* efficiently, a high powered, gaming specification computer was required (Section 3.4.2)

The limited use of *MicroDrainage®* for research and lack of a publically available validation questioned its accuracy and ultimately its suitability to underpin the findings of both this research and SuDS based planning applications. For this reason, aim 3 was created to provide user and stakeholder confidence in the accuracy of *MicroDrainage®* by comparing modelled data with field and laboratory tests (Section 3.7).

3.4.2 Computer Power

Due to the requirements of *MicroDrainage®*, a high power specification computer was required to run the software to its maximum capabilities to deal with the high volumes of LIDAR data and drainage data, as well as running simulations (Table 3-1).

Table 3-1 Computer requirements to run MicroDrainage®. (adapted from XP Solutions 2016).

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lancester Library, Coventry University.

3.4.3 LIDAR Data

LIDAR data defined the topography of the study site (Prior Deram Park, Coventry, section 3.5.1) to determine runoff routes and areas susceptible to ponding. The data was obtained from the Geomatics-Group (Geomatics Group 2011) at a resolution of 1 m^2, the finest resolution available for the site.

3.5 Aim 1: Deconstructing the SuDS management Train

Aim 1 of the research involved designing the site and deconstructing the modelled devices to gain an understanding of the impact of specific devices on water quantity. This was also compared to a control, pipe based drainage, which further demonstrated their benefits. Figure 3-2 presents a flow diagram outlining each stage of aim 1.

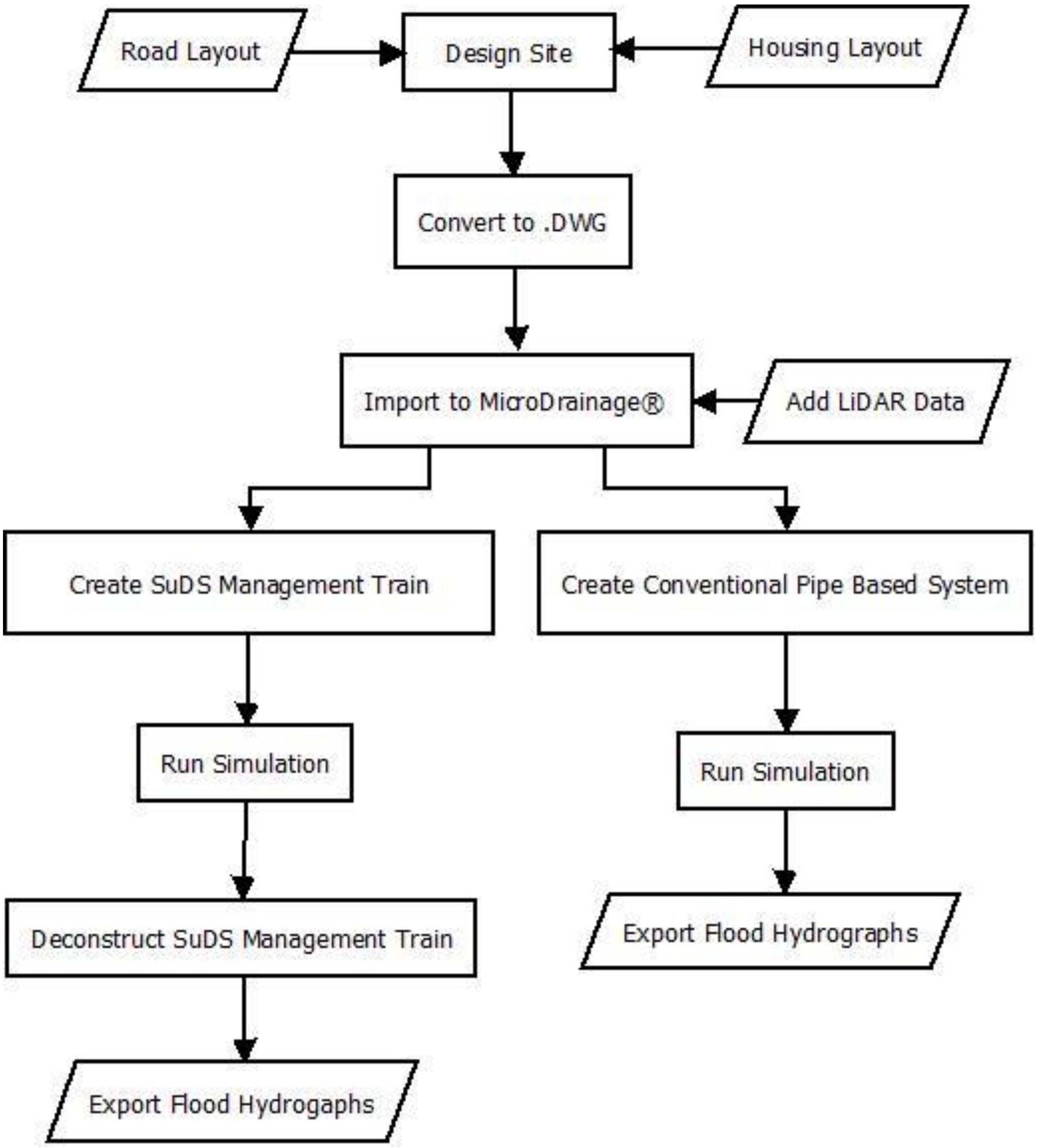


Figure 3-2 Flow diagram of the methods used to achieve aim 1. The inputs for site design are presented, with the method diverging once the site was designed, to model both conventional drainage and a SuDS management train.

3.5.1 Design of the site

Although aim 1 analysed runoff for different infiltration scenarios, the initial plan was based on the Canley Regeneration Site which included in the plan the 5 ha Prior Deram Park (PDP), which was the focus of aim 1 providing a template to run the model (Figure 3-3). The site was located 4 km south west of Coventry City Centre (Figure 3-3) in the West Midlands.

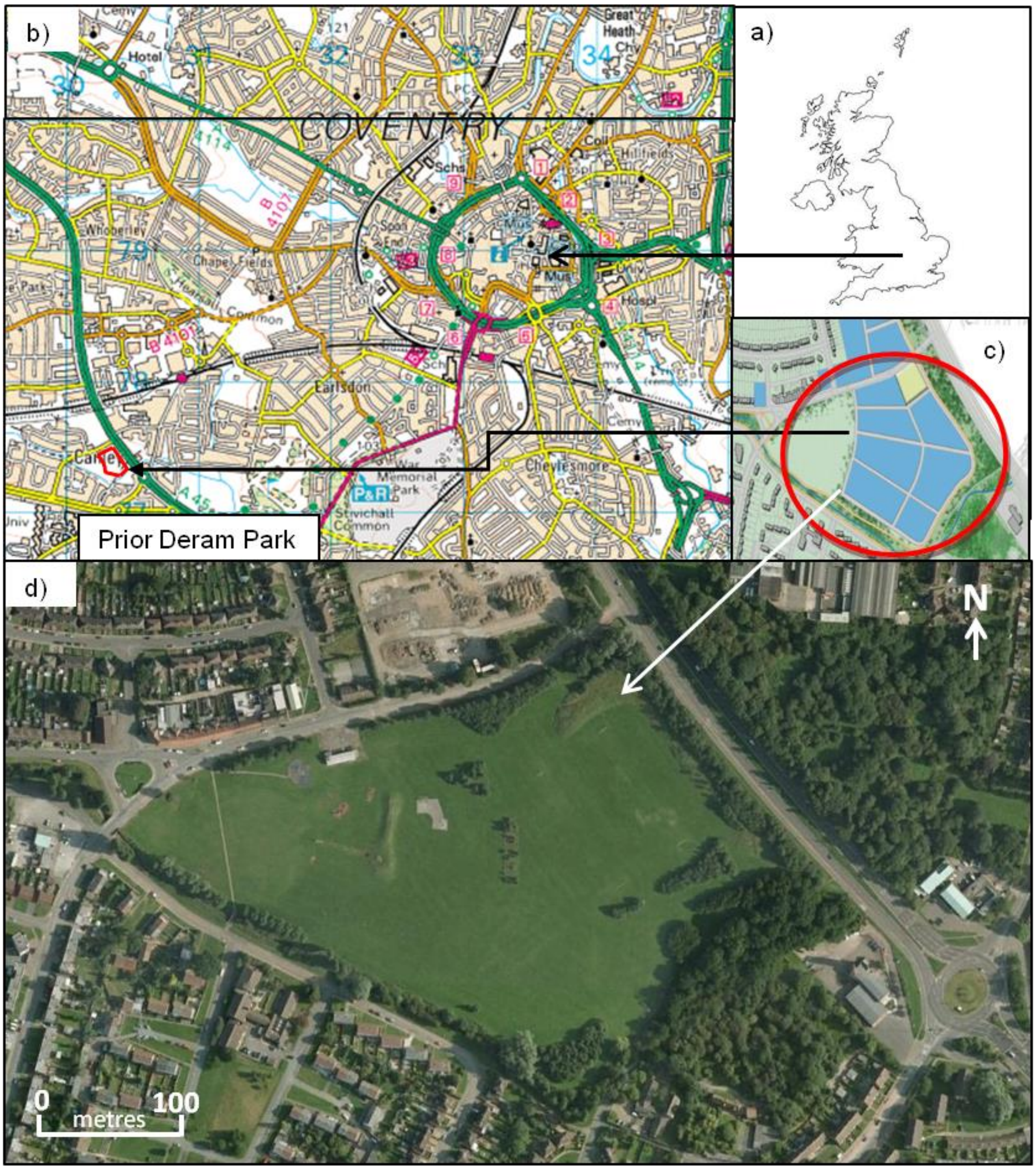


Figure 3-3 The locations of: (a) Coventry; (b) Prior Deram Park (Ordnance Survey 2013); (c) a map of Prior Deram Park with the designed 250 house area and roads adapted from WSP Environmental Ltd. & Coventry City Council (2008) and (d) a photograph of Prior Deram Park (Google Earth 2013).

The plan for PDP included 250 new houses being built across 5 ha, and with a community centre also constructed. The outline planning proposal provided only a layout for the roads (Figure 3-3c) with no design or plan for the potential housing layout. Three sections to the east of the site currently had planning permission for three story housing with the remaining four zones on the west designated for two story housing. There was also a requirement to build affordable social accommodation in keeping with the current development of Canley (Alliance Planning & Coventry City Council 2008). A flood risk assessment for the site (Coventry City Council & Halcrow Group 2008) indicated that it was partially classified under the EA's Flood Zones two (between 0.1% – 1% likelihood of flooding) and three (greater than 1% chance of flooding) due to the Canley Brook to the south of the site, any development had therefore be designed to deal with rainfall scenarios up to a 1 in 100 year, plus 30% to account for climate change (EA 2009).

A potential housing layout was created for PDP to add accuracy to the eventual model. Although the Canley Masterplan (WSP Environmental Ltd & Coventry City Council 2008) proposed the road layout, limited housing information was given aside from the number of floors of each house. Developing a housing layout enabled an improved understanding of runoff by suggesting potential flood flow paths. Information regarding housing size in terms of number of floors provided an insight into what type of houses were possible in certain areas of the site. From investigating new developments around Canley using Google Earth (2012), the average width of a three storey house was 4 m and the length was approximately 10 m with a 6 m drive. Gardens were also accounted for, which were on average 9 m long. A standard two floor house in Coventry was 5 m wide and 7.5 m long with a 6m drive and 13 m long garden, whilst pavements were 1.5 m wide and roads were 6 m wide.

ArcGIS (ESRI 2009) was used to design the site as it was compatible with *MicroDrainage*®. The road layout had already been decided in the original masterplan (WSP Environmental Ltd & Coventry City Council 2008) and gave the site structure, with 50 houses per ha to fit the initial site requirements. Information from the surrounding area regarding the size of each property was used to plot developments at the site. Areas of open space were allowed when possible to provide a more realistic environment. Once the roads, houses and gardens were created, the site was converted into a .DWG file (Figure 3-4), the main file type used in *MicroDrainage*®. This enabled the design of a pipe based drainage plan for the site.

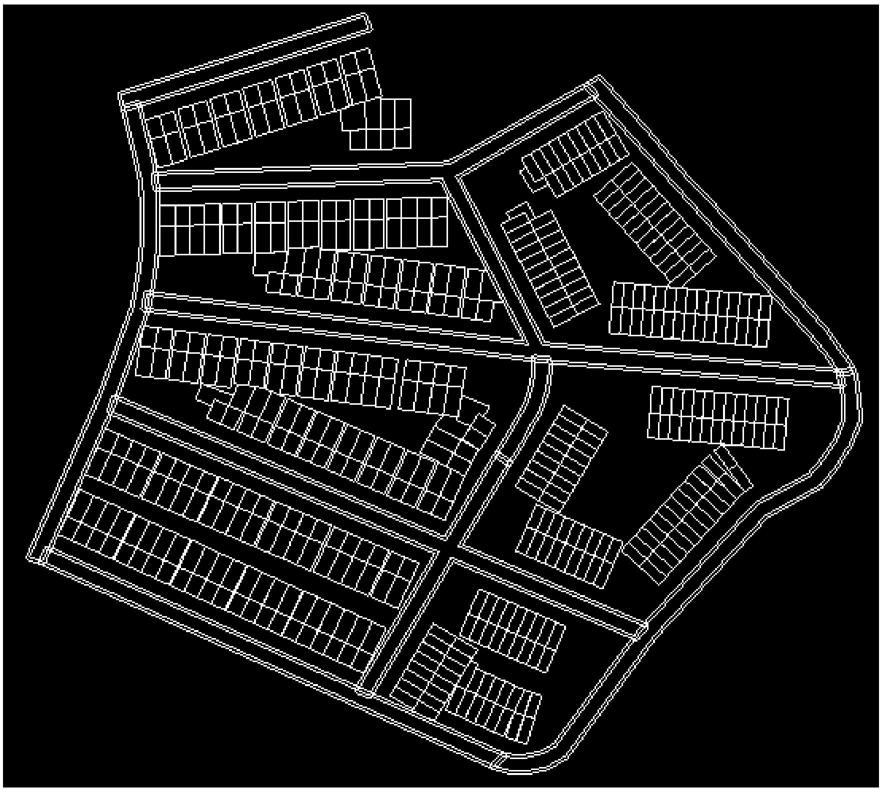


Figure 3-4 DWG file for Prior Deram Park in *MicroDrainage®*, based on data created in ArcGIS to outline the houses, gardens and roads.

3.5.2 Simulate the outflow with conventional drainage

The expected outflow into the Canley Brook through conventional drainage was simulated as a control. Outflow data was compared to other combinations of SuDS management trains (Section 3.5.3) to quantify the total change possible by integrating SuDS. No antecedent conditions were applied to any of the simulations, to ensure a direct comparison between all scenarios. Although *MicroDrainage®* could include percentage wetness for the site (XP Solutions 2016), defining the amount added uncertainty (Cloke & Pappenberger 2009), consequently all simulations were run dry. Additionally *MicroDrainage®* could not allocate certain devices being dry and others being wet, therefore a consistent approach was required.

DrawNet in *MicroDrainage®* was used to model the site's response to rainfall. The .DWG file created in 3.5.1 was combined with LIDAR data (Section 3.4.3) to accurately represent the site. The LIDAR data provided elevation information to run the flood flow analysis in DrawNet which accounted for topography and generated a detailed breakdown of ponding zones at the site, with depth of pooling, velocity and flow direction, based on the 1 in 100 year return period event. A pipe based drainage system was then designed to convey runoff to the Canley Brook, with each pipe having a roughness value of 0.6 (Figure 3-5). British Standards Institution (2008) for conventional pipe based drainage dictated that runoff in cities from all events up to a 1 in 30 year return period must be dealt with without flooding; this was the benchmark used. The PIMP (Percentage IMPervious) area for each pipe was then allocated as a result of flood flow analysis where PIMP areas were the impermeable sites that flood water travelled from to reach a drain.

Figure 3-5 Pipe based system design for Prior Deram Park. The central development is the proposed housing layout, with the existing layout integrated outside of Prior Deram Park (Gill 2015).

Once the site had been designed, it was simulated to model the likely runoff as a result of the 1 in 30 year event, with 30% extra added to account for potential impacts of climate change (EA 2009). The simulation results returned information regarding the status of each pipe, which reflected its ability to deal with the storm event. Pipes could be classified in *MicroDrainage®* as:

- Flood: it failed during the storm as pipe capacity was exceeded.
- Flood Risk: it was possible that the pipe could flood during the event while
- Surcharged: the pipe was overloaded however there was limited danger that the pipe could fail
- Ok: the pipe had been successful at dealing with the modelled storm event.

All pipes had to be classified as 'Ok' as a result of the 1 in 30 year event to ensure the site was suitable; if any pipes failed, additional pipes were added (Figure 3-6). An additional simulation was completed to compare against SuDS (section 3.5.3) once the simulation results suggested the site was free from flooding. The 1 in 100 year rainfall event was used to compare flow between both the conventional and SuDS based systems as it was the largest event the drainage plan must mitigate against based on The Standards (2015), with an additional 30% added to account for climate change (EA 2009). The simulation was re-run for the new storm scenario, generating a hydrograph based on the modelled outputs. The model outputs were exported to MS Excel (Microsoft Corporation 2010) for further analysis and comparison (section 4.2) to quantify the amount of water entering the Canley Brook,

Figure 3-6 Pipe layout created in MicroDrainage at Prior Deram Park, Coventry. Yellow lines are the pipes, the green areas are the contributing runoff areas.

3.5.3 Simulate flow from a SuDS management train

The SuDS management train was then developed using DrawNet to demonstrate its impacts regarding reducing peak flow. The .DWG file (created in 3.4.1) was added alongside the LIDAR data to enable a flood flow analysis.

A SuDS management train was developed (Figure 3-7) by utilising the information compiled in section 2.8. Green roofs with 5mm depression storage and an overall depth of 100 mm were added to each roof at the site, as recommended by Stovin (2010), with the runoff being conveyed into a swale. All structures at source and site level were implemented after the swale had been laid down. As the pavement was designed to be 1.5 m wide (section 3.5.1) there was enough space for a minimum 600 mm wide swale, with a maximum 3000 mm used where possible. Wider swales were more common away from the roadside when conveying flow away from detention basins. Designing swales alongside pavements reduced the amount of open space that the SuDS devices accounted for (Bastien *et al.* 2010). For safety reasons a 1:3 swale was used, which limited gradient, nevertheless the diameter of the swale could be adjusted to fit the site (Woods Ballard *et al*. 2015).

PPS were added to all driveways at the site with an infiltration coefficient consistent with overall site infiltration and therefore varied dependent on the Winter Rainfall Acceptance Potential (WRAP) value. The porosity of each device was 0.3, as suggested by Woods Ballard *et al*. (2015). A safety factor of two was used as suggested by Woods Ballard *et al*. (2007), with a maximum membrane percolation of 1000 mm/hr and a total depth of 450 mm, in line with the British Standard Institution (2009). The British Standards have evolved from Eurocodes, designated BS EN, and where possible these have been referred to. Specifically relating to SuDS, other BSs exist that are not BS EN, for example PPS. In this example, the British Standard 7533-13:2009 is used, in keeping with Woods Ballard et al. (2015).

All source control devices were channelled into detention basins which were located to the east of the PDP site where more land was available. The size of the basin was based on land availability and site requirements. Calculating open space at the site provided information regarding potential basin sizes and was completed in ArcGIS. This was then applied to DrawNet to define the size of each basin. Each basin utilised an outflow orifice to control flow rates leaving the system which allowed for the backfilling of water, ensuring each detention basin was used to its full potential.

Pipes were used whenever necessary, for example when water was conveyed below a road. Once runoff from a source control device was collected in a detention basin, it was conveyed to the Canley Brook at the outflow point. Four detention basins were modelled to capture runoff as a result of large rainfall events. Figure 3-7 presents the final SuDS management train design, while Table 3-2 presents the volume and area of devices incorporated at the site.

Figure 3-7 SuDS management train at Prior Deram Park that includes swales, pipes, detention basins, PPS and green roofs, with all houses (Gill 2015).

Table 3-2: Total volume and area of each device integrated into the design at Prior Deram Park (Figure 3-7).

Device	**Total volume (m^3)**	**Total area (m^2)**
Detention basin	6,059	2,189
Green roof	1,017	10,170
PPS	1,568	3,380
Swale	1,322	1,692

The flow generated by the site was far greater than the greenfield runoff rate required by The Standards (DEFRA 2015a). The site was therefore designed to manage runoff with flow controls at the outflows for events up to the 1 in 100 year scenario for the swale configuration, with the additional SuDS further enhancing the sites capabilities.

However using flow control at each outflow point for the purpose of this study would produce consistent outflow volumes, irrespective of the configuration, and therefore not allowing a comparison between devices. Consequently the outflow flow controls were removed when undertaking the final study, enabling a comparison between devices, with flow controls only used after the four detention basins to ensure they worked correctly in *MicroDrainage*®. The design drew inspiration from existing sites, for example Hamilton, Leicester (Berwick n.d.) and Lamb Drove, Cambridgeshire (Cambridgeshire County Council 2012).

Once the devices were integrated, the PIMP zones were allocated to determine runoff contributing area, utilising information from the flood flow analysis (Figure 3-8). Infiltration values using WRAP data were again added to provide more realistic modelling of the site. The results of the simulation were exported to MS Excel (Microsoft Corporation 2010) to provide a comparison between the SuDS management train and conventional drainage.

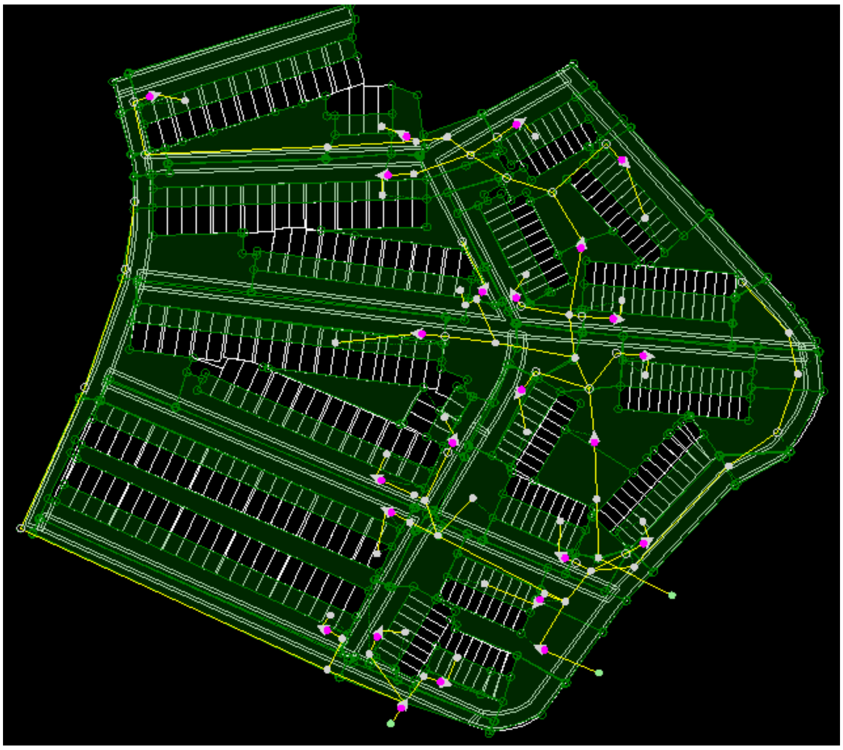


Figure 3-8 Designed SuDS Management train in MicroDrainage at Prior Deram Park, Coventry. Yellow lines are either pipes or swales, the triangles are either PPS or detention basins. Figure 3-7 for more detail.

3.5.4 Deconstructing the management train

As well as quantifying the benefits of modelling a SuDS management train consisting of green roofs, PPS, swales and detention basins, the ability of each individual device designed into a management train was calculated, as per aim 1. By removing different components, more information regarding which devices performed best in the management train was calculated. The only consistent SuDS device used in each management train was swales as they were required to provide conveyance across the site. As was the case for the full management train (section 3.5.3), the detention basins again had an orifice modelled into the outflow to ensure they worked correctly. Table 3-3 outlines the combinations that were used. An additional pipe based system was also simulated whereby all swales used in Figure 3-7 were converted to pipes. This provided a further comparison using a similar number of pipes to swales, therefore offering more information regarding the effectiveness of SuDS in comparison to an over-designed piped drainage system.

Table 3-3 Combination of SuDS devices modelled, based on the layout in Figure 3-7.

Devices Used
Swale
Green roof & Swale
PPS & Swale
Green roof & PPS & Swale
Swale & Detention basin
Green roof, Swale & Detention basin
PPS, Swale & Detention basin
Green roof, PPS, Swale & Detention basin

3.5.5 Altering site conditions

Additional simulations were completed where infiltration and rainfall parameters were changed to further understand the impact of using SuDS rather than conventional drainage. This provided an understanding of the role of each device in response to differing rainfall intensities and under different infiltration rates.

3.5.5.1 Rainfall

The primary method of calculating rainfall in the UK is by using The Flood Estimation Handbook (FEH) (Institute of Hydrology 1999) which superseded the Flood Studies Report (FSR) (Institute of Hydrology 1975). It provided a set of catchment descriptors that could be used to interpret rainfall for a site given a depth-duration-frequency curve. To provide a more detailed understanding of the role of SuDS, all simulations were run using the 1 in 100 year 30 minute high intensity, short duration event and the 1 in 100 year 720 minute low intensity long duration event, in addition to the 1 in 100 year 360 minute storm required by the Standards, as discussed in section 2.10 (DEFRA 2015). The focus prior to DEFRA (2015) was on the critical storm duration; the duration of rainfall at the 1 in 100 year scenario that produced the most amount of flooding (DEFRA 2011b; Woods Ballard *et al*. 2007). The critical storm duration provided more precise site information as opposed to using the 360 minute event as it enabled flexibility in modelling for specific rainfall events. Woods Ballard *et al*. (2007) suggested that small sites with limited gradient were most likely to achieve peak runoff during high intensity 30 minute events. Larger sites typically require a longer duration, with DEFRA (2011b) specifying between 3 - 24 hours being necessary for SuDS designs. Contrasting intensity events were therefore used to demonstrate the changing role of SuDS in flood management in comparison to pipes over differing rainfall intensities.

3.4.5.2 Infiltration

MicroDrainage® used the WRAP method for determining soil characteristics (Institute of Hydrology 1975). It categorised soil types into five different variables dependent on their capacity for infiltration (Table 3-4), but was superseded by the Hydrology of Soil Types (HOST) (Boorman, Hollis & Lilly 1995) which was more robust, identifying twenty-nine different soil classifications. Although more robust, it has not been adopted by *MicroDrainage*® and therefore cannot be used in this study. However to analyse how infiltration determined runoff in the software, each simulation for the different drainage scenarios was also modelled using changing WRAP values along with the changing rainfall intensities. A high infiltration (0.15 WRAP), medium infiltration (0.3 WRAP) and low infiltration (0.5 WRAP) scenario was applied.

Table 3-4 WRAP classifications (adapted from Boorman, Hollis & Lilly 1995).

Water Regime Class (as per Figure 3-11**)**	**Soil Classification**	**Winter Rain Acceptance Class**
1	0.15	Very High
2	0.3	High
3	0.35	Moderate
4	0.4	Low
5	0.5	Very Low

3. 6 Aim 2: Model Analysis and Decision Support Tool

A DST provides a user-friendly interface for assimilating modelled data to assist the user in making judgments (Moore *et al*. 2012). Different tools have been created when developing a site, and for highlighting the cost benefits of SuDS (section 2.17). A SuDS tool can reduce the time practitioners spend designing sites, therefore engaging more developers with the benefits of different devices (Viavattene *et al*. 2008; Scholz & Uzomah 2013). A tool that demonstrated the total possible flow reduction through implementing SuDS in comparison to conventional drainage might persuade developers to use SuDS at their sites.

As outlined in section 2.15.2, Warwick (2013) created a DST that determined site suitability of different devices. Alongside this system, a method for estimating likely runoff based on the devices highlighted by Warwick (2013) could reduce the decision making time for stakeholders. Figure 3-9 outlines the main methods used to achieve aim 2. Four key parameters were modelled to create the DST; storm scenarios, infiltration, the size of the site and SuDS devices, to determine how runoff varied as a result of changing each parameter.

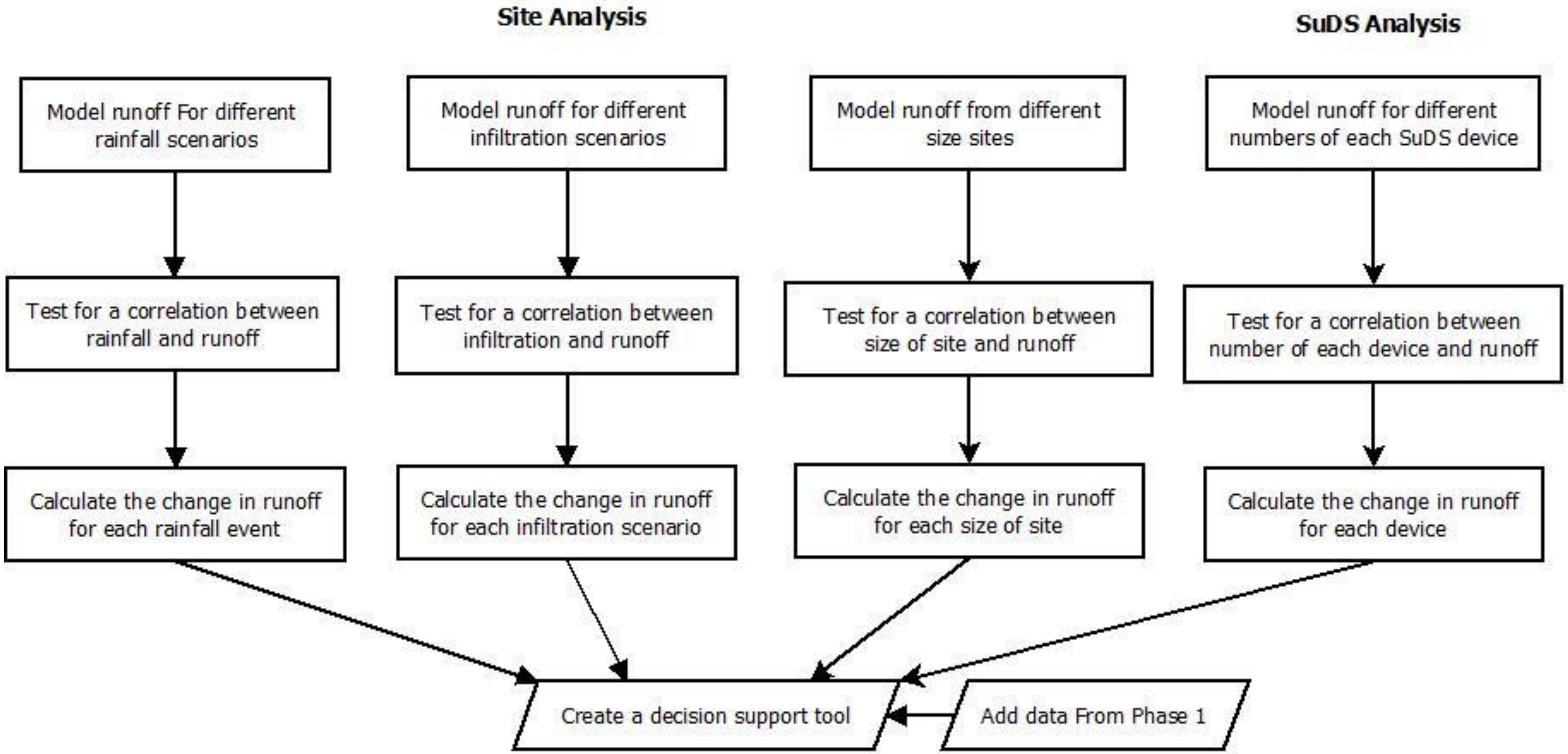


Figure 3-9 A flow chart outlining the main methods used to achieve aim 2.

3.6.1 Model Analysis

To analyse the outputs of *MicroDrainage*® in further detail, rainfall, infiltration and site area were altered to generate data for the site under different conditions. Rainfall and soil type, which ultimately influenced infiltration rates, were site specific variables (Cloke & Pappenberger 2009) with both the standard average annual rainfall (SAAR) and soil type differing by location. By simulating multiple rainfall scenarios and different soil types, peak flow at sites across England and Wales could be predicted. Additionally, the influence of site area on flow was modelled to determine whether runoff could be predicted based on pre-determined site size. Each SuDS device used to achieve aim 1 was further analysed to define the change in runoff as the number of green roofs, PPS and swales or volume of detention ponds reduced, enabling the creation of the DST.

3.6.1.1 Rainfall

Incorporating rainfall into the DST ensured that it could be used to determine flow at sites across England and Wales as rainfall varied significantly (Figure 3-10). The FEH (Institute of Hydrology 1999) provided rainfall depth for different return periods and durations for UK catchments; the likely amount of rainfall for a specific return period and duration of a storm. Therefore to ensure the tool was in line with The Standards (DEFRA 2015a), the 1 in 100 year 360 minute storm was used for different catchments across the UK to determine the likely runoff in *MicroDrainage*®. The runoff for fifty different rainfall intensities (range of rainfall depth between 44.7 mm to 139.8 mm) was then compared to determine the level of certainty for predicting the runoff for a specific event. A regression analysis of the data at the 99% confidence level provided coefficient values for the minimum and maximum influence on runoff with a high degree of certainty. To quantify rainfall intensity, the likely rainfall depth for the 1 in 100 year 360 minute storm, as calculated by the depth-drainage-frequency model in the FEH (Institute of Hydrology 1999) was used.

Figure 3-10 Rainfall across the UK, based on an average between 1981-2010 (Met Office 2015).

3.6.1.2 Soil Type

Soil and consequently infiltration rate varied across the UK (Figure 3-11) therefore an analysis was required to determine how soil influenced runoff to ensure the DST was applicable across England and Wales. An analysis of flow through the conventional pipe based scenario was completed in *MicroDrainage®* based on each of the five soil types provided in the WRAP analysis (Table 3-4). The conventional, pipe based scenario was chosen as it acted as the first level of classification, with the introduction of SuDS having further impact on runoff. The resultant correlation between infiltration and flow was used to determine the likely flow at the site based on the different soil scenarios.

Figure 3-11 UK WRAP map; light-dark colour scale reflects high-low infiltration (adapted from Institute of Hydrology 1975).

3.6.1.3 Site Scale

The capability to input the size of the desired site added a further dimension to the DST. To determine the role that site scale played on runoff, runoff from different size sites was modelled. Based on Kellagher (2012), it was determined that the DST would assist sites at the local scale (1-50 ha, section 2.15). Consequently runoff was simulated in *MicroDrainage®* based on conventional pipe based drainage for each scenario from 1 ha-50 ha by increasing the contributing area. A correlation between runoff and different site scales enabled the calculation of amount of runoff likely from a given size site. This was then applied to the DST, with different rainfall scenarios (FEH) and infiltration (WRAP), to present the likely runoff from a conventional system dependent on site conditions.

3.6.1.4 SuDS

To ensure the DST allowed users to input a specified number of the modelled SuDS, a regression analysis was carried out to determine how runoff altered with differing numbers of each device. The SuDS combinations used for aim 1 were simulated to estimate runoff based on a specific number of each device. As a large number of green roofs, PPS and swales were used at the site (Figure 3-7), 10% of the total number of devices (Table 3-2) were progressively removed and remodelled until each device was removed for all combinations. As only four detention basins were modelled, the total size of each basin was reduced by 10% of the original volume for each combination to include the device. The flow control for each detention basin was also similarly altered as maintaining the same orifice would have retained the same flow rate.

Each device was reduced for every combination given in Table 3-3. Modelling how each SuDS management train responded to reducing different components enabled a greater understanding of the role of each device in the management train and subsequently added detail to the DST, enabling a prediction of the runoff for a specific amount of each system. Combining SuDS data with the estimated runoff at a precise size of the site, using specific rainfall and infiltration values, provided the underlying calculations for the DST.

3.6.2 Decision-Support Tool

The outputs from 3.5.1 were combined to create the DST. Figure 3-12 shows the necessary user inputs to use the DST. Each regression analysis provided a maximum and minimum coefficient value which related to the role of each modelled parameter (either site or SuDS; Appendix C) with 99% confidence. The following sections provide the equations that underpin the DST.

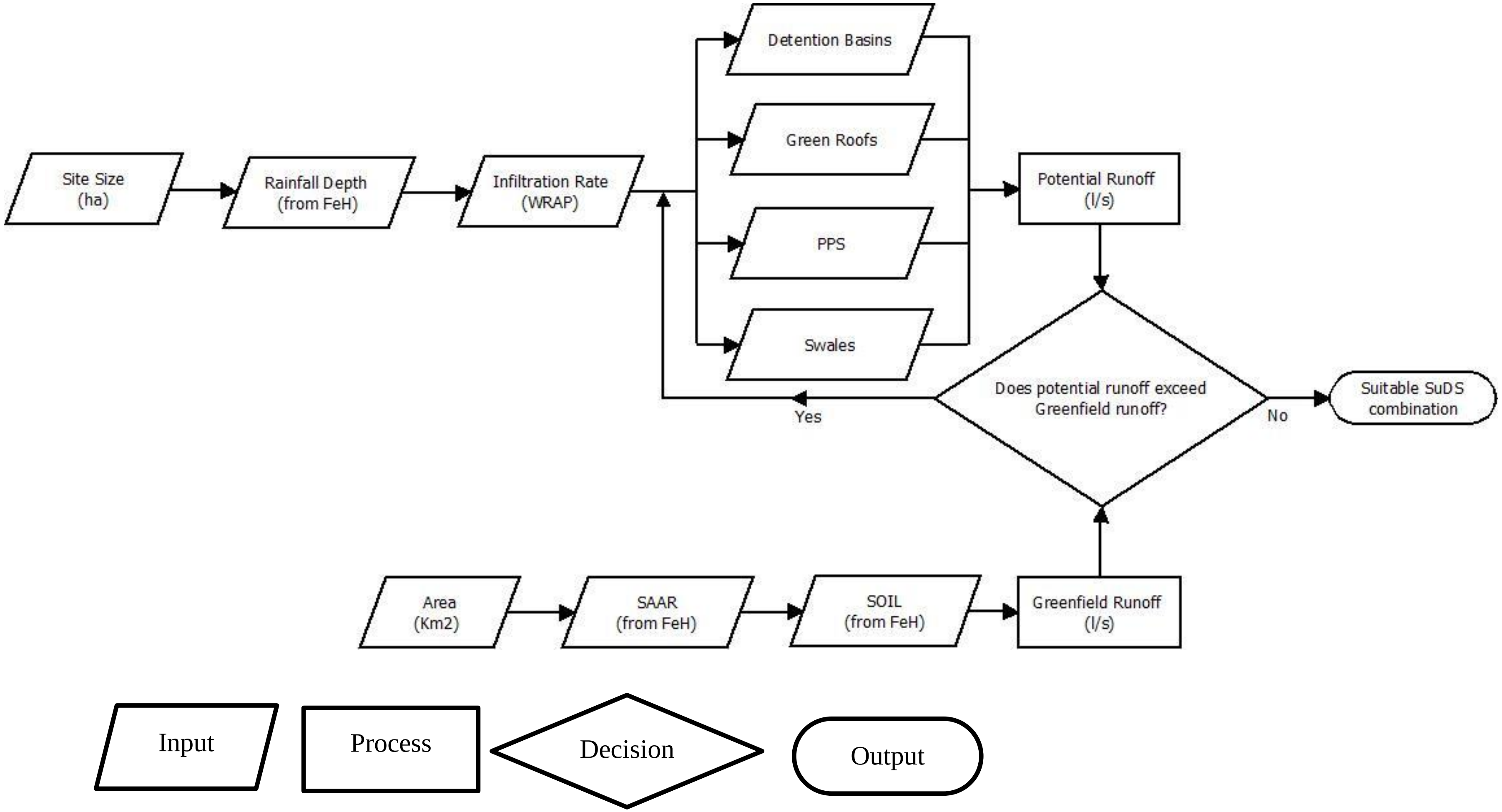


Figure 3-12 Necessary inputs and processes for the DST.

3.6.2.1 Site parameter equations

Interpolations were made to determine peak flow as a result of different rainfall (EQ 3.1 and EQ 3.2), infiltration (EQ 3.3 and EQ 3.4) and site size scenarios (EQ 3.5 and EQ 3.6). This acted as the first stage of user-inputs for the tool which outlined the likely runoff for a conventional system (Figure 3-4). EQ 3.1 and EQ 3.2 predicted the likely runoff for the site as a result of a user defined rainfall event. This was dependent on the coefficient value calculated in section 3.5.1.1 for the maximum and minimum influence of rainfall on runoff (Appendix C).

$$\mathrm{P_{max}} = \mathrm{P_{FEH}}\,\mathrm{x}\ \mathrm{Psens_{max}} \qquad \text{EQ 3.1}$$

where

P_{max} = runoff for a user-defined rainfall depth (l/s)

$\mathrm{P_{FEH}}$ = rainfall depth taken from FEH (Institute of Hydrology 1999) (mm)

Psensmax = 4.15288139 taken from rainfall sensitivity analysis (Appendix C).

$$\mathrm{P_{min}} = \mathrm{P_{FEH}}\,\mathrm{x}\ \mathrm{Psens_{min}} \qquad \text{EQ 3.2}$$

where

P_{min} = runoff for a user-defined rainfall depth (l/s)

$\mathrm{P_{FEH}}$ = rainfall depth taken from FEH (Institute of Hydrology 1999) (mm)

Psensmin = 3.76529297415439 taken from rainfall sensitivity analysis (Appendix C).

Once the influence of runoff was predicted, the DST then integrated the WRAP value (section 3.6.1.2) for both the maximum and minimum impact of infiltration on runoff (EQ 3.3 and EQ 3.4). The combination of WRAP and rainfall values created a combined infiltration and rainfall runoff value.

$$\mathrm{I}_{\mathrm{max}} = \mathrm{WRAP}_{\mathrm{max}} \text{ x } \mathrm{P}_{\mathrm{max}}$$ EQ 3.3

where I_{max} = combined runoff based for infiltration and rainfall (l/s)
$WRAP_{max}$ = the maximum runoff likely based on a user defined WRAP value
P_{max} = the output of EQ 3.1.

$$\mathrm{I}_{\mathrm{min}} = \mathrm{WRAP}_{\mathrm{min}} \text{ x } \mathrm{P}_{\mathrm{min}}$$ EQ 3.4

where
I_{min} = combined runoff based for infiltration and rainfall (l/s)
$WRAP_{min}$ = the minimum runoff likely based on a user defined WRAP value
P_{min} = the output of EQ 3.2.

The final aspect of the site based calculations incorporated the size of the site into the analysis (section 3.5.1.3). This resulted in the likely minimum and maximum runoff for a conventional drainage system as a result of user defined rainfall, infiltration and site size scenarios (EQ 3.5 and EQ 3.6).

$$\mathrm{RC}_{\mathrm{max}} = \mathrm{I}_{\mathrm{max}} \text{ x } \mathrm{A}$$ EQ 3.5

where
RC_{max} = the likely maximum runoff for a conventional drainage system (l/s)
I_{max} = the output of EQ 3.3
A = area (ha).

$$RC_{min} = I_{min} \text{ x } A$$ EQ 3.6

where

RC_{min} = the likely minimum runoff for a conventional drainage system (l/s)

I_{min} = the output of EQ 3.4

A = area (ha).

3.6.2.2 SuDS equations

The following section presents the equations that were used to calculate the total volume of each SuDS device. EQ 3.7 is the standard formula for calculating the volume of a detention basin by using the area (m^2) for each depth of the detention basin. EQ 3.8 is the calculation for the total volume of all four detention basins.

$$\sum_{0}^{4} DB_n = \left(\frac{1}{3}\right) \pi \text{ x } d \text{ x } (rTop^2 + rTop \text{ x } rBase + rBase^2)$$ EQ 3.7

where

$\sum_0^4 DB_n$ = the volume of up to four detention basins (m^3)

d = the difference in depth between the top and bottom of each area in the detention basin

rTop = $\sqrt{\frac{Atop}{\pi}}$

where

Atop = top area of detention basin (m).

rBase is $\sqrt{\frac{Abase}{\pi}}$

where

Abase = base area of detention basin (m).

EQ 3.8

$$\mathrm{DB_{tot}} = \sum \mathrm{DB}_0^4$$

where

$\mathrm{DB_{tot}}$ = the total volume of all four detention basins
(m^3).

EQ 3.9 and EQ 3.10 are associated with the calculation of the total volume of green roofs. The user was able to define the total number and mean width (m) and length (m) of each green roof at a detached, semi-detached and terraced house. This was combined to calculate the total area (m^2) of green roofs for each housing type. EQ 3.10 used the outputs of EQ 3.9 to calculate the total volume of green roofs; the depth of green roofs was pre-determined at 100mm, as suggested by (Mentens, Raes & Hermy 2006; Stovin 2010; Uhl & Schiedt 2008).

EQ 3.9

$$\mathrm{GR_D} = \mathrm{H_n}\ \mathrm{x}\ (\mathrm{W}\ \mathrm{x}\ \mathrm{L})$$

$$\mathrm{GR_{SD}} = \mathrm{H_n}\ \mathrm{x}\ (\mathrm{W}\ \mathrm{x}\ \mathrm{L})$$

$$\mathrm{GR_T} = \mathrm{H_n}\ \mathrm{x}\ (\mathrm{W}\ \mathrm{x}\ \mathrm{L})$$

where

$\mathrm{GR_D}$ = area of green roofs on detached houses (m^2)

$\mathrm{GR_{SD}}$ is area of green roofs on semi-detached
houses (m^2)

$\mathrm{GR_T}$ is area of green roofs on terraced houses (m^2)

Hn is total number of houses

W is mean width (m)

L is mean length (m).

$$\mathrm{GR_{tot}} = 0.1\,(\mathrm{GR_D} + \mathrm{GR_{SD}} + \mathrm{GR_T}) \qquad \text{EQ 3.10}$$

where

GR_{tot} = total volume of green roofs (m^3)

0.1 = the depth (m) of green roof (section 3.4.3)

GR_D = area of green roofs on detached houses (m^2)

GR_{SD} = area of green roofs on semi-detached houses (m^2)

GR_T = area of green roofs on terraced houses (m^2).

A similar method to that which was applied for green roofs was used for PPS. The user was able to define the number of houses and mean length (m) and width (m) of driveways for detached, semi-detached and terraced houses to calculate the area (m^2) for each housing type (EQ 3.11). This was then combined and multiplied by 450 mm, as per the British Standard Institution (2009) for typical depth of PPS.

$$\mathrm{PPS_D} = \mathrm{H_n}\ \mathrm{x}\ (\mathrm{W\ x\ L}) \qquad \text{EQ 3.11}$$

$$\mathrm{PPS_{SD}} = \mathrm{H_n}\ \mathrm{x}\ (\mathrm{W\ x\ L})$$

$$\mathrm{PPS_T} = \mathrm{H_n}\ \mathrm{x}\ (\mathrm{W\ x\ L})$$

where

PPS_D = area of PPS on driveways for detached houses (m^2)

PPS_{SD} = area of PPS on driveways for semi-detached houses (m^2)

PPS_T = area of PPS on driveways for terraced houses

Hn = total number of houses

W = mean width (m)

L = mean length (m).

$$\mathrm{PPS_{tot}} = 0.45\ (\mathrm{PPS_D} + \mathrm{PPS_{SD}} + \mathrm{PPS_T})$$ E.Q 3.12

where

$\mathrm{PPS_{tot}}$ = total volume of PPS (m^3)

0.45 = the depth (m) of PPS (section 3.4.3)

$\mathrm{PPS_D}$ = area of PPS on driveways for detached houses (m^2)

$\mathrm{PPS_{SD}}$ = area of PPS on driveways for semi-detached houses (m^2)

$\mathrm{PPS_T}$ = area of PPS on driveways for terraced houses (m^2).

EQ 3.13 was the calculation for the total volume of swales to be installed. The user was to define the width (m), depth (m) and length (m) of each swale. The sum of all swales was then calculated (EQ 3.14) to determine the total volume (m^3).

$$\sum_{1}^{n} \mathrm{Sw} = \mathrm{W\ x\ D\ x\ L}$$ EQ 3.13

where

$\sum_1^n$ Sw = the volume of one or more swales (m^3)

W = width (m)

D = depth (m)

L = length (m).

$$\mathrm{Sw_{tot}} = \sum \mathrm{Sw_1^n}$$ EQ 3.14

where

$\mathrm{Swt_{ot}}$ = the total volume of all swales

$\sum \mathrm{Sw_1^n}$ = the volume of one swale.

EQ 3.15 and EQ 3.16 is the total number of each SuDS device, multiplied by the coefficient outputs (Appendix C) generated from the regression analysis (section 3.5.1.4) for the corresponding SuDS device, dependent on the SuDS management train. The calculation provided a maximum (EQ 3.14) and minimum (EQ 3.16) runoff.

$$RR_{devicemax} = Device_{tot} \text{ x } Coeff_{max} \qquad \text{EQ 3.15}$$

where

$RR_{devicemax}$ = maximum runoff for each individual SuDS device (l/s)

$Device_{tot}$ = DB_{tot}, GR_{tot}, PPS_{tot} or Sw_{tot}

$Coeff_{max}$ = the maximum coefficient value (Appendix C) for each SuDS device in each management train (Table 3-3).

$$RR_{devicemin} = Device_{tot} \text{ x } Coeff_{min} \qquad \text{EQ 3.16}$$

where

$RR_{devicemin}$ = minimum runoff for each individual SuDS device (l/s)

$Device_{tot}$ = DB_{tot}, GR_{tot}, PPS_{tot} or Sw_{tot}

$Coeff_{min}$ = the minimum coefficient value (Appendix C) for each SuDS device in each management train (Table 3-3).

EQ 3.17 and EQ 3.18 was the calculation of the total combined reduction on peak flow possible by integrating SuDS.

$$\mathrm{SuDS}_{\mathrm{totmax}} = \mathrm{DBto}_{\mathrm{tmax}} \text{ x } \mathrm{GR}_{\mathrm{totmax}} \text{ x } \mathrm{PPS}_{\mathrm{totmax}} \text{ x } \mathrm{Sw}_{\mathrm{totmax}} \qquad \text{EQ 3.17}$$

where
$\mathrm{SuDS}_{\mathrm{totmax}}$ = combined maximum runoff reduction possible for all SuDS device (l/s)
$\mathrm{DB}_{\mathrm{totmax}}$ = maximum runoff reduction possible for detention basins (l/s)
$\mathrm{GR}_{\mathrm{totmax}}$ = maximum runoff reduction possible for green roofs (l/s)
$\mathrm{PPS}_{\mathrm{totmax}}$ = maximum runoff reduction possible for PPS (l/s)
$\mathrm{Sw}_{\mathrm{totmax}}$ = maximum runoff reduction possible for swales (l/s).

$$\mathrm{SuDS}_{\mathrm{totmin}} = \mathrm{DBto}_{\mathrm{tmin}} \text{ x } \mathrm{GR}_{\mathrm{totmin}} \text{ x } \mathrm{PPS}_{\mathrm{totmin}} \text{ x } \mathrm{Sw}_{\mathrm{totmin}} \qquad \text{EQ 3.18}$$

where
$\mathrm{SuDS}_{\mathrm{totmin}}$ = combined minimum runoff reduction possible for all SuDS device (l/s)
$\mathrm{DB}_{\mathrm{totminimum}}$ = minimum runoff reduction possible for detention basins (l/s)
$\mathrm{GR}_{\mathrm{totmin}}$ = minimum runoff reduction possible for green roofs (l/s)
$\mathrm{PPS}_{\mathrm{totmin}}$ = minimum runoff reduction possible for PPS (l/s)
$\mathrm{Sw}_{\mathrm{totmin}}$ is minimum runoff reduction possible for swales (l/s).

3.5.2.3 Final runoff calculation

The following formulas (EQ 3.19 and EQ 3.20) used the runoff for conventional drainage (EQ 3.5 and EQ 3.6) and subtracted the value from EQ 3.18 and EQ 3.19 to calculate the maximum and minimum amount of runoff likely in *MicroDrainage®*.

$$\mathrm{RSuDS}_{\mathrm{max}} = \mathrm{RCmax} - \mathrm{SuDS}_{\mathrm{totmax}}$$ EQ 3.19

where

$\mathrm{RSuDS}_{\mathrm{max}}$ = total maximum runoff as a result of integrating the user defined SuDS management train (l/s)

$\mathrm{RC}_{\mathrm{max}}$ = output from E.Q 3.5 (l/s)

$\mathrm{SuDS}_{\mathrm{totmax}}$ = output from E.Q 3.14 (l/s).

EQ 3.20 $$\mathrm{RSuDS}_{\mathrm{min}} = \mathrm{RCmin} - \mathrm{SuDS}_{\mathrm{totmin}}$$

where

$\mathrm{RSuDS}_{\mathrm{min}}$ = total minimum runoff as a result of integrating the user defined SuDS management train

$\mathrm{RC}_{\mathrm{min}}$ = output from E.Q 3.6

$\mathrm{SuDS}_{\mathrm{totmax}}$ = output from E.Q 3.15.

3.5.2.4 Greenfield runoff estimation equation

The greenfield runoff rate could also be calculated by inputting area (ha), SAAR and SOIL (EQ 3.21), which could be compared to the runoff of the SuDS management train. This analysed whether the site exceeded greenfield runoff, as required by The Standards (DEFRA 2015a).

$$\mathrm{QBAR}_{100} = (0.00108\mathrm{AREA}^{0.89} \text{ x } \mathrm{SAAR}^{1.17} \text{ x } \mathrm{SOIL}^{2.17})$$ EQ 3.21

where

QBAR = greenfield runoff (l/s)

AREA = the site size (ha)

SAAR = the standard average annual rainfall (mm)

SOIL = the infiltration value provided in the FSR (Institute of Hydrology 1975).

The aim of the DST was to provide practitioners with an estimation of the likely runoff, starting from the information generated by Warwick (2013) which presented a SuDS suitability tool. The tool was developed using MS Excel (Microsoft Corporation 2010) to ensure compatibility with the Revitalised Flood Hydrograph (ReFH) model which provided greenfield runoff hydrographs dependent on the rainfall scenario (Kjeldsen 2007; Miller *et al*. 2014).

3.6.3 Uncertainty in the Decision-Support Tool

The DST contained a number of uncertainties as it was based on a regression analysis for each modelled parameter in *MicroDrainage*®. The regression analysis was carried out at the 99% confidence level to reduce the level of uncertainty, enabling upper and lower certainty thresholds to be integrated providing the user with a maximum and minimum range for peak flow.

Both the DST and *MicroDrainage*® were validated to ensure they accurately predicted peak flow. The validation of *MicroDrainage*® followed the method outlined by Cloke & Pappenberger (2009) who used field data to analyse the quality of the outputs from an ensemble flood forecast. Calculating the coefficient of determination (r^2) and the NSE provided two methods for evaluating a correlation between field and modelled data. The validation of *MicroDrainage*® ensured that the DST was effective when implemented alongside the software (aim 3).

3.6.3.1 Validating the DST with Lamb Drove, Cambridgeshire

Objective 2d (section 1.5) proposed using published data to validate the DST from Lamb Drove, Cambridgeshire (section 2.13) which included 3400 m^2 of permeable paving, fourteen detention basins, 704 m of swales, 162 m^2 of green roofs, 282 water butts and one retention pond across 5 ha (Cambridgeshire County Council 2012). The rationale for this method was to determine whether the DST predicted flow from a specific rainfall event at a different site. However, the DST was designed to predict runoff as a result of the 1 in 100 year 360 minute event (DEFRA 2015a) rather than a monitored rainfall scenario, which may have been an inaccurate validation of the model.

As the likelihood of capturing rainfall data for a 1 in 100 year 360 minute storm and measuring the outflow at a SuDS management train was minimal, modelling the likely runoff was more appropriate than comparing that with the DST. Hamilton, Leicester (aim 3) was therefore validated to determine the overall accuracy in *MicroDrainage*®. The model could be simulated to determine the likely outflow for the 1 in 100 year 360 minute event at Hamilton assuming a strong correlation between field data and model data.

Using modelled data to calibrate the DST, which was powered by modelled data, was an untraditional method, as using actual data was a more accepted approach to determine the accuracy of a tool (Versini *et al*. 2015). However, assuming the validation of *MicroDrainage*® in aim 3 concluded a strong correlation between field and modelled data it provided a suitable method for determining the accuracy of the DST.

3.7 Aim 3: Validating *MicroDrainage®*

The validation phase (Figure 3-13) related to aim 3 (section 1.5) by assessing the accuracy of the outputs of *MicroDrainage*® and consequently the accuracy of the findings of aims 1 and 2 of the research. A comparison between model and both field and laboratory data enabled an assessment of the accuracy prediction of runoff (Mark *et al*. 2004). Validating the UK industry standard drainage modelling tool may also assist SuDS users and engage a wider audience with the benefits of using SuDS and ultimately provided further confidence in the software. Field data was collected at a 16 ha section of a SuDS management train in Leicester, United Kingdom (Figure 3-14) that incorporated vegetated swales, rock-lined swales, vegetated ponds and detention basins. Channel flow was monitored (section 3.7.2) across the site and compared to a modelled version in *MicroDrainage*®. Laboratory based tests were also undertaken using PPS and filter drain rigs whereby outflow was monitored and compared with simulations in *MicroDrainage*®.

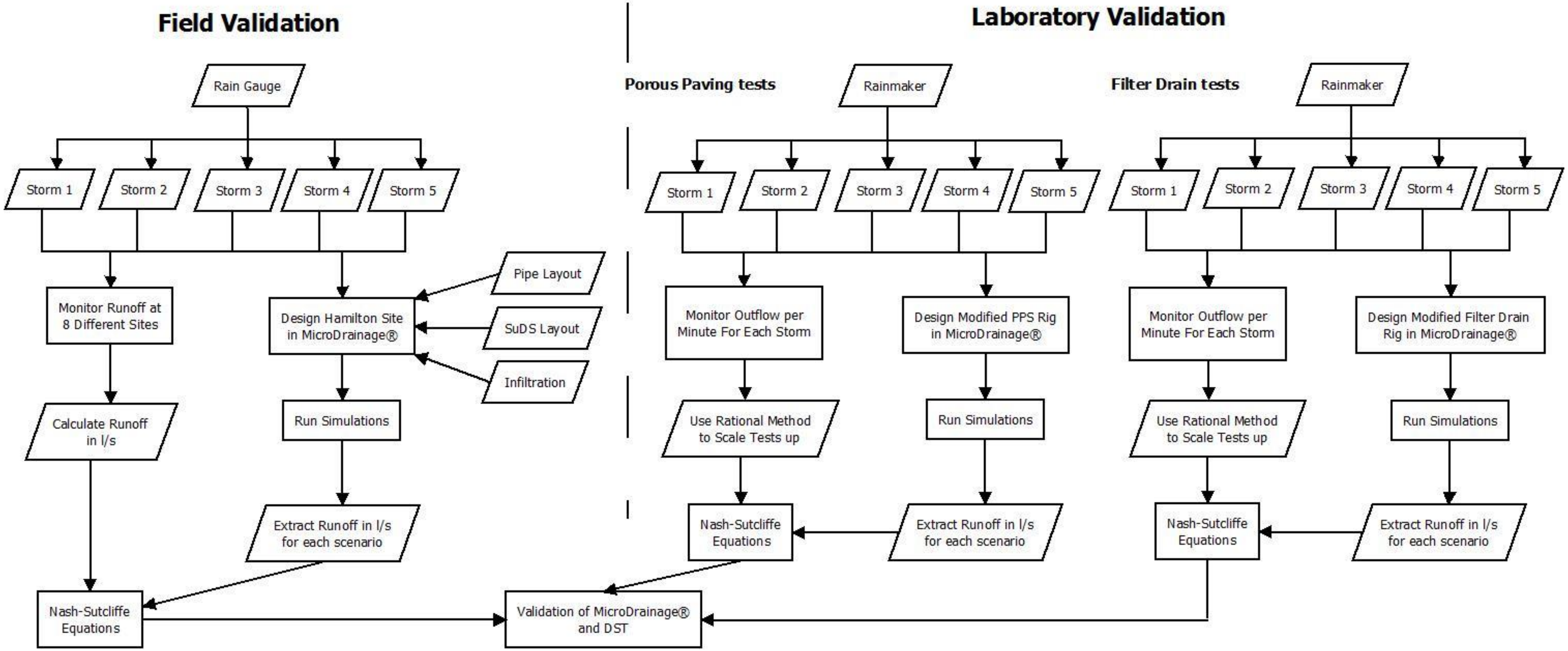


Figure 3-13 A flow diagram outlining the key aspects of aim 3.

Figure 3-14 a) Map of Hamilton in relation to Leicester (Ordnance Survey 2016), b) In relation to the UK c) Hamilton management train (Berwick nd), marking site of the rain gauge with an asterisk.

3.7.1 Field Equipment

A Casella Tipping Bucket (Casella 2014) and OTT MF Pro spot Velocity Meter (OTT Hydromet 2014), purchased from Environmental Monitoring Solutions were used to collect data in the field. In addition a metre rule was used to take depth measurements and a 30 m tape measure was used for width.

A telemetered tipping bucket (Figure 3-15) was sited at Hope Hamilton Primary School (Figure 3-14b) and was used for its reliability and ease of data collection by collecting data for each tip and remotely uploading it to an online server (Hill 2013). It was preferred over the weighted gauge method of collection due to its enhanced accuracy by using a 0.2 mm tipping gauge, capturing high resolution data (Colli, Lanza & Berbera 2013; Semadeni-Davies *et al*. 2008). Duchon, Fiebrich & Grimsley (2013) acknowledged that tipping buckets presented uncertain results due to the likelihood of under catch, rainfall that occurs during the tipping process, however the device was suggested by the Met Office (2010) as being the most effective method for capturing rainfall and is used for precipitation calculations in the UK (Colli *et al*. 2014; Duchon, Fiebrich & Grimsley 2013).

Figure 3-15 Casella tipping bucket rain gauge installed at Hope Hamilton School, Leicester.

The OTT MF Spot Velocity Meter (Figure 3-16) was used to measure flow which, with the wetted perimeter calculation, enabled the calculation of discharge volume (Shaw *et al*. 2010). The velocity meter monitored flow as low as 0.001 m/s, and therefore accurately measured flow speed. Siting in-situ flow meters permanently outside of the pipes could have resulted in tampering with or theft of the equipment and ultimately inaccurate data; several metal weir plates have been stolen from the site, whilst rock covered rip-rap that lined the swales was also disturbed. Each flow measurement was therefore taken by hand during or after rainfall.

Figure 3-16 OTT MF Pro Spot Velocity Meter used at Hamilton, Leicester.

3.7.2 Study Site

Field data was collected between November 2014 – January 2016, from Hamilton, Leicester, approximately 5 km from Leicester city centre (Figure 3-14). Hamilton was previously farmland, with construction beginning on the SuDS management train in

2001 and the housing (1500 houses, 26 ha) in 2002 (Berwick n.d.). As the development was built on a greenfield site that was located in flood zone 1 (EA 2016a), three SuDS management trains consisting of swales, ponds and basins were installed to ensure the site remained close to the greenfield runoff rate. Runoff is managed throughout each train, and flow is controlled through weirs at the junction between devices. Flow is conveyed to the north of the site, from east to west and then into the Melton Brook through a series of constructed wetlands.

The central swale train (Figure 3-14c) was monitored with flow measured repeatedly at eight points from the start of the central train at the south of the site to the confluence with the stream at the north, which also conveyed runoff from the other management trains. The site consisted of an arrangement of swales, rock lined swales, inflow pipes, vegetation filled ponds, detention basins and weirs, as shown in Figure 3-17, however the estate did not utilise either PPS or green roofs.

Although the site was maintained by the Greenbelt Group, due its age its effectiveness has reduced; some parts of the SuDS have become clogged with sediment, limiting infiltration and subsequently runoff reduction (Berwick 2014 pers. comm.). Furthermore, when the site was constructed, part of the swale train was not implemented correctly with the falls being greater than anticipated. This has caused substantial erosion, requiring the swale train to be filled with rocks and rip-rap to limit the impacts. Both factors have impacted the train’s ability to reduce runoff and added further complexity when comparing to simulated data for the validation of *MicroDrainage*® (section 3.7.3.1).

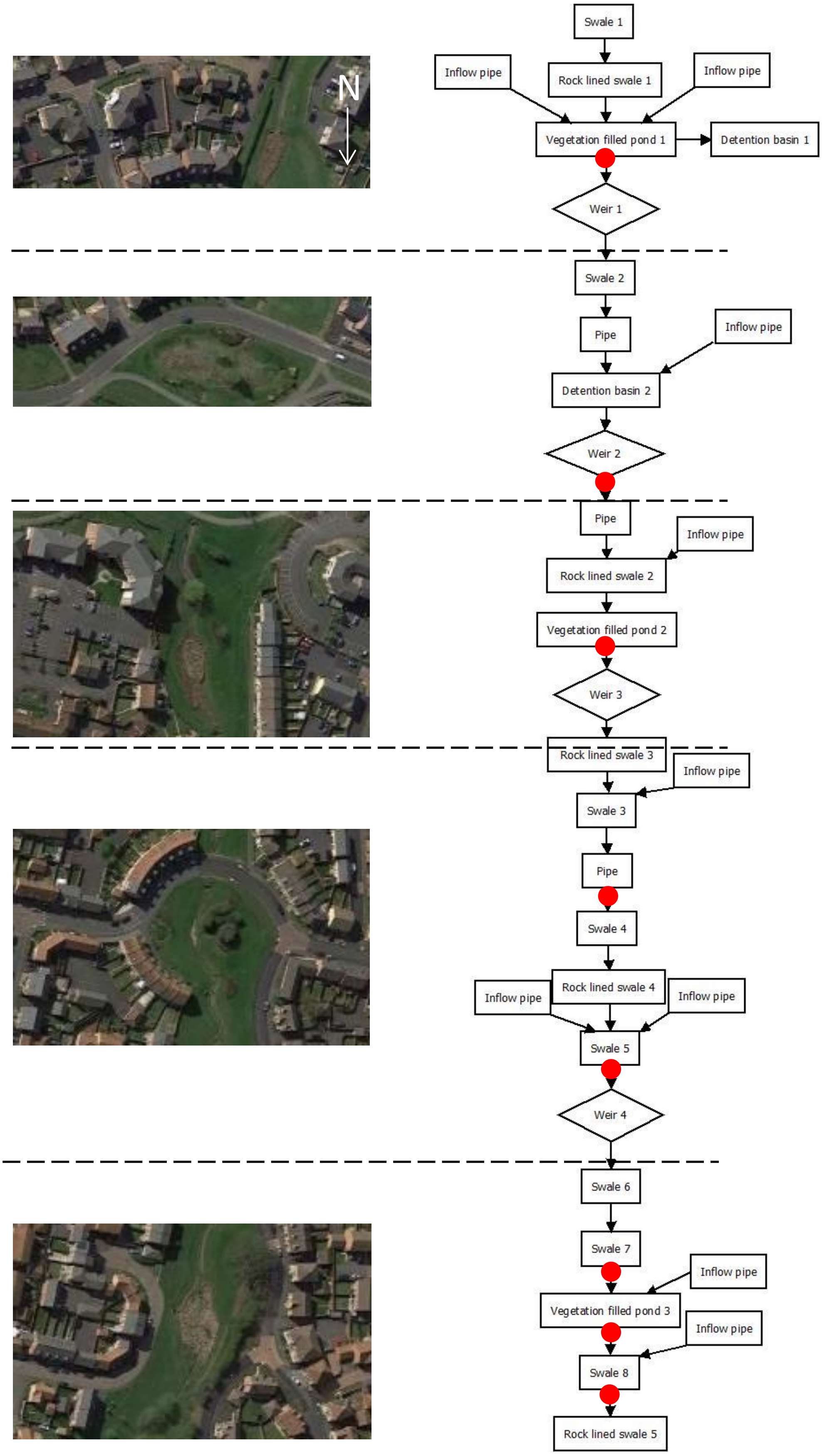


Figure 3-17 Configuration of SuDS Management train at Hamilton, Leicester with a Google Earth (Google 2015) image of the site. The monitoring points highlighted in red.

3.7.2.1 Geology

The geology of Hamilton is predominantly Wilmcote Limestone, while the site pedology ranges from clay to clayey loam (Persimmon Homes 2010), reducing the capacity for infiltration (Lewis, Cheney & O’Dochartaigh 2006). However, there are two overflow dry detention basins used to store water during a large rainfall event. The topography of the site also largely influences runoff due to the steep slopes surrounding the management train and the overall 24 m gradient from the top to the bottom of the train. This results in flashier peaks with runoff entering the system rapidly, therefore requiring detention to slow down runoff.

3.7.2.2 Swale

Two types of swales were used; grass-lined with low growing vegetation and rock-lined (Figure 3-18). The vegetation provided multiple benefits as it regulated flow speed, promoted infiltration and improved water quality, whilst the swales conveyed runoff around the site and enabled infiltration (Woods Ballard *et al*. 2015). Each swale modelled from the central swale train is listed in Table 3-5. Although the predominant size of the swales was 3 m wide, swales 3-5 were considerably narrower, navigating more constricted parts of the site and were the areas of poor design whereby the falls were greater than predicted (Berwick 2014 pers. comm.).

Figure 3-18 Swale 1 at Hamilton SuDS Management Train, Leicestershire.

Table 3-5 Swales installed at Hamilton, based on the site configuration present in Figure 3-17 (mean width n=5; mean depth n=3).

Swale	Length (m)	Mean width (m)	Mean depth (m)
Swale 1	32.86	3	0.50
Swale 2	3.71	3	0.50
Swale 3	50.47	0.60	0.25
Swale 4	3.19	0.50	0.20
Swale 5	13	0.50	0.30
Swale 6	37	3	0.40
Swale 7	6.35	0.5	40
Swale 8	26.15	0.80	0.30

3.7.2.3 Rock lined swale

Five sections of swales throughout the site were rock lined (Figure 3-19 Rock-lined swale 1 with rip-rap on the base to limit erosion.). Table 3-6 presents the sections of the management train that consisted of rock lined swales. Due to the additional engineering, the majority of the rock lined swales were homogenous, particularly in width. Rock-lined swale 4 was smaller and irregular in shape compared to the rest of the site due to more erosion, it was also narrower (0.5 m) and shallower due to being rock-filled. Since *MicroDrainage®* does not have a function to incorporate rock lined swales, a vegetated swale was used and the roughness coefficient altered accordingly to 0.045 in accordance with Chow (1959).

Figure 3-19 Rock-lined swale 1 with rip-rap on the base to limit erosion.

Table 3-6 Rock lined swales installed at Hamilton. (mean width n=5; mean depth n 3).

Rock lined swale	Length (m)	Mean width (m)	Mean depth (m)
Rock lined swale 1	55.93	3	0.50
Rock lined swale 2	7.01m	3	0.55
Rock lined swale 3	3	3	0.55
Rock lined swale 4	28.12	2.10	0.50
Rock lined swale 5	19.20	3	0.20

3.7.2.4 Vegetation filled pond

There are three online vegetated ponds used in the central swale train at Hamilton (Figure 3-20 and Table 3-7). Each pond contained dense low growing vegetation with the aim to slow down and retain runoff, enhancing water quality (Woods Ballard *et al*. 2015). All ponds were 1 m deep, and as their primary role was to limit flow speed as opposed to retaining large volumes of runoff, they were filled with dense vegetation. Over the course of the research, limited site maintenance was undertaken, with natural seasonal changes simply maintaining the ponds.

Figure 3-20 Vegetation filled pond 1, a densely vegetated pond with the offline detention basin to the left of the picture.

Table 3-7 Vegetation filled ponds installed at Hamilton.

Vegetation filled pond	Volume (m^3)	Area at surface (m^2)
Vegetation filled pond 1	50.4	220
Vegetation filled pond 2	1307	1700
Vegetation filled pond 3	642	750

3.7.2.5 Detention basins

Due to the limited depth, the three vegetated ponds provided restricted retention during large events. Thus, two large detention basins were added at the start of the central SuDS management train to capture overflow from the system. These two basins were much larger (Figure 3-21 and Table 3-8) and therefore retained significant amounts of runoff. Detention basin 1 was an offline system that was rarely used (Berwick 2014 pers. comm.) and acted as overflow storage during extreme events. Detention basin 2 was online and had a ditch which conveyed water through the device and along the management train. It was heavily vegetated and had a large capacity (749 m^3) for detaining high volumes of runoff.

Figure 3-21 Detention basin 2: a large open pond that is densely vegetated. A small channel runs through the detention basin to direct runoff through the system.

Table 3-8 Detention basins installed at Hamilton.

Detention basin	Volume (m^3)	Area at surface (m^2)
Detention basin 1	715	640
Detention basin 2	749	550

3.7.2.6 Weir

As outlined in section 2.12.2, four weirs regulated flow (Figure 3-22), ensuring runoff was backed up to utilise the full capacity of the management train to control rates of flow (Newton *et al*. 2014). A metal orifice plate was incorporated into the design to control flow (Table 3-9 for more detail). Effectiveness was compromised as the metal flow plate from weir 4 was stolen, leaving behind the wooden structure. To ensure consistency between results, the weir was modelled without an orifice if the orifice plate had been taken and not replaced before data was collected. Each weir was the same size, controlling flow to a consistent rate, therefore no site was monitored directly after a weir.

Figure 3-22 Weir 1 at start of management train, used to back up flow into the vegetated pond during large rainfall events.

Table 3-9 Weirs installed at Hamilton.

Weir	Orifice (mm)
Weir 1	150
Weir 2	150
Weir 3	150
Weir 4	n/a

3.7.2.7 Pipes

There were nine concrete inflow pipes conveying runoff from the surrounding housing estate and a further two concrete pipes that conveyed runoff below a road. The pipes were of different sizes, ranging from 300 mm – 600 mm. Two of the inflow pipes were covered with a metal grill which increased clogging.

Measuring the size and characteristics of all devices, both SuDS and pipes, provided the underlying information for creating a model of Hamilton in *MicroDrainage*®. This therefore enabled a validation of the software by comparing the field data to simulation data. There were a number of maintenance issues that were recorded during each monitored event, litter was frequently dumped at the site as well as breeze blocks and traffic cones, which all served to alter the flow dynamics of the system and could potentially further increase uncertainty in the model.

3.7.2.8 Additional site characteristics

The vegetation at the site was commonly *Typhus latifolia* and *Chamerion angustifolium* (Table 3-10) but also contained *Urtica dioecia* and *Lolium* sp. at the margins of the swales. As discussed previously, some swales were rock lined to counter increased erosion at the site (3.7.2.3). The igneous rocks were sub-angular with a mean size of 247.8 mm (n=10).

Table 3-10 Vegetation data for Hamilton

	Density (m^{-2})	**Mean height (cm)**
Typhus latifolia	930.4 (n=1,163)	120 (n=25)
Chamerion angustifolium	7.2 (n=9)	171.6 (n=9)

The site was routinely maintained during the monitoring period of the research: self-set vegetation was removed on a three monthly basis from the SuDS system, with debris removed from several headwall aprons during this period. Weed control, using herbicide, was also applied in April 2015 to control growth in the swale systems. However human interaction interfered with the site in-between maintenance, with litter, sometimes in large quantity, and debris frequently entering the management train potentially interfering with flow. The limitations this presented are discussed in section 5.4.1.

3.7.3 Validation methodology

Figure 3-13 outlined the methodology used to validate *MicroDrainage*®. Hamilton utilised swales, both vegetated and rock lined, detention basins and vegetated ponds therefore additional laboratory tests were set up to model the outflow from PPS and a filter drain. This added more devices to the validation and further examined the validity of *MicroDrainage*®.

3.7.3.1 Validation Stage 1.1: Field data collection at Hamilton, Leicester

Eight sections of the management train were measured (Figure 3-17) at different storm events to provide comparison with modelled data, to enable a validation of *MicroDrainage*®. Previous methods for monitoring SuDS management trains were presented in section 2.13 and have been adopted to suit this research. Rainfall was continuously monitored at Hope Hamilton School (Figure 3-14) from November 2014 to analyse the response of the SuDS management train during a range of storms. The gauge was between 230 m and 360 m from the closest and furthest point of the study site respectively. As in situ flow monitoring was not possible (section 3.7.1), local weather forecast data from the Met Office was used to predict the timings for large rainfall events to ensure that the extent of the storm was suitably monitored.

Flow was measured at the same eight sections of the site highlighted on Figure 3-23 for each monitored rainfall scenario. The wetted perimeter was calculated, with depth measurements taken at 5 cm intervals across the channel using the method outlined by Shaw *et al*. (2010). Measuring consistent short intervals enabled a detailed understanding of the channel shape. Four flow measurements were taken at equal distances across the channel, ensuring that flow was measured at 2/3 the depth of water, to gain a mean channel flow speed in m/s (Shaw *et al*. 2010). All flow measurements were time-stamped. This data was then analysed to calculate volume of flow through each study site for each observed event.

Figure 3-23 Monitored sites at Hamilton, Leicester: 8 sites were monitored at the central swale train (Google Earth 2015).

There were however problems associated with collecting data at Hamilton. The rainfall event monitored on 14th May 2015 produced low flows at the site. Although capturing data for a small event ensured that the validation encapsulated different rainfall intensities, the reduced flow increased the level of uncertainty with the findings. The flow meter (section 3.7.1) was capable of measuring flow to 0.001 l/s, however further accuracy was needed to ensure enhanced reliability of the data. This was exacerbated during low flows, as the flow meter was required to be at 2/3 the depth of the water (Shaw 2010); however, flow at the previously discussed event was as shallow as 3 cm, which was a similar depth to the size of the flow meter. Problems regarding turbulent flow and the impact of vegetation on monitoring are discussed in section 5.4.1.

Site 1:

The first monitored site was at the start of the central swale train (Figure 3-23). Measurements were taken before the weir (Figure 3-24) at the end of the online vegetated pond 1 (Table 3-8). To the west of the site was an offline detention basin, used only when required during large events, however it was not used for the duration of the study.

Figure 3-24 Site 1: Measurement were taken before the weir after the heavily vegetated pond.

Site 2:

Site 2 was after a pipe that conveyed water underneath a path surrounding the large detention basin (Detention basin 1, Table 3-8) (Figure 3-25). Prior to entering the pipe, flow was restricted by Weir 2 (Table 3-9), to ensure the detention basin was utilised.

Measurement point

Figure 3-25 Site 2: Measurements were taken at the start of the rock lined swale.

Site 3

Measurements at site three (Figure 3-23) were taken before weir 3 (Figure 3-26), before a pipe to convey runoff below Brompton Road. Prior to the measurement point was vegetated pond 2, where runoff was detained. There was an inflow pipe from the surrounding housing estate before the vegetated pond.

Figure 3-26 Site 3: Measurement was taken before the weir.

Site 4:

Monitoring at site four was after the outflow pipe that conveyed water under the Brompton Road (Figure 3-23 and Figure 3-27). It was located prior to the fall issues discussed in section 3.7.2.

Figure 3-27 Site 4: Measurements were taken at the start of the narrower ditch. Debris from surrounding building sites was typically present at the site.

Site 5

The fifth set of measurements were taken before weir 4 (Figure 3-28) after two separate inflows from the surrounding housing estates. Erosion highlighted at Site four had stopped, with the channel returning to the designed size. Nonetheless, Swale 5 (Table 3-5) was extremely narrow (50 cm), in comparison with much of the swale train.

Figure 3-28 Site 5: Measurements were taken before the weir, at the end of the narrow channel. Note that the weir plate was stolen before measurements were taken, therefore the weir was not included in the final design in *MicroDrainage®.*

Site 6:

Site six was at the end of swale 7. The swale train narrowed from 3 m prior to entering vegetated pond 3 (Figure 3-29). This section of the swale train was densely vegetated, which reduced flow speeds.

Figure 3-29 Site 6: Measurements were taken before the vegetated pond.

Site 7

Vegetated pond 3 was the largest in the central swale train. It linked to a narrow vegetated swale channel leaving the pond. Measurements were taken at swale 8 (Figure 3-30), before the swale opened up to 3 m wide at rock-lined swale 5. There is an inflow from the surrounding housing site a metre prior to the data collection point.

Figure 3-30 Site 7: Measurements were taken after the final vegetated pond in the management train.

Site 8:

Rock-lined swale 5 was the final measurement, taken prior to a vegetated pond before reaching a stream and wetlands at the outflow of the site (Figure 3-31). The final site provided an overall view of flow management achieved at the site, and enabled comparison with data generated in *MicroDrainage®*.

Measurement point

Figure 3-31 Site 8: Measurements were taken before the rip-rap at the end of the central swale train.

3.7.3.2. Validation Stage 1.2: Modelled data for Hamilton, Leicester

Hamilton required detailed drawing to accurately compare field data with simulations from *MicroDrainage®*. The existing storm sewer system and SuDS layout were drawn in ArcGIS to provide the basemap of the site that was converted to a .DWG file and added to *MicroDrainage®*. Both drainage systems were then designed in *MicroDrainage®* using the site information in section 3.7.2, with a 5 m resolution

LIDAR image. Each observed rainfall event was defined in the program to ensure a comparison could be drawn between the model and field data. Manning's values were estimated based on channel characteristics at each point. Values were determined in *MicroDrainage*® based on the density of vegetation and whether rocks were present, suggested by Chow (1959), ranging from 0.045 for low vegetated rock lined channels, to 0.15 for those that had a greater density of vegetation. As each pipe was concrete, a standard roughness value of 0.6 mm was used (XP Solutions 2016). Adding this information ensured that the design reflected the site and consequently ensured that simulated results closely replicated the response of field data, therefore enabling a validation of *MicroDrainage*®. The addition of Manning's values provided some uncertainty as attributing vegetation levels over a wide area simplified the model, whereas in reality vegetation changed markedly for each device.

Additional uncertainties were associated with scale; previous research on model validation focussed on small scale (typically one unit) devices, as increasing the size of the simulation increased the potential for inaccuracies (Versini *et al*. 2015 & Burszta-Adamiak & Mrowiec 2013). It was also likely that infiltration rates were not consistent over the entire 16 ha site. Whilst the data from Persimmon Homes (2010) defined the underlying geology of Hamilton, as previously discussed (3.6.2.1), *MicroDrainage*® used the WRAP method for infiltration. As this provided only a narrow quantification of the likely infiltration rate at the site, it was possible that it could over or under-estimate infiltration (Boorman, Hollis & Lilly 1995). LIDAR data was used to define flow regimes at the site and runoff contributing areas, but the best freely available for the site was 5 m resolution, which could reduce accuracy.

3.7.3.3 Validation Stage 2: Laboratory Tests

The site at Hamilton, Leicester only consisted of swales, ponds and detention basins, therefore laboratory tests on PPS rigs and filter drains were completed to gain a further understanding of the accuracy of *MicroDrainage*®. Although filter drains were not used in the DST as they are more associated with motorways, demonstrating that *MicroDrainage*® could predict the runoff from the device added further validity to the software.

3.7.3.4 Validation Stage 2.1: Porous pavement Laboratory Tests

80 mm Marshalls PPS blocks over 110 cm x 90 cm were fitted with a laying course and 250 mm sub-base, with an 80 cm x 60 cm rainfall simulator used (Figure 3-32). The laboratory rigs were previously used by Charlesworth *et al*. (2016) as part of an analysis of the water quality implications of the devices for Marshalls, with the rainfall simulator also set up for the project in line with the design specifications of Rodriguez-Hernandez *et al*. (2011). Five tests were run using different rainfall intensities and durations (Table 3-11) with the resulting outflow measured each minute. *MicroDrainage*® was capable of providing outflow data to one decimal point, in l/s, however, the data generated through the PPS rigs seldom achieved flows above 1 l/min, far smaller than measurable in *MicroDrainage*®. For this reason, the data achieved was scaled up from a 0.48 m^2 site to 50 m^2 using the rational method (EQ 3.22). The method used was adapted from Sañudo-Fontaneda *et al.* (2016). This enabled the conversion of the rainfall intensity used in the laboratory to a larger site. A scale factor was then applied to calculate the runoff at the 50 m^2 site. Hydrographs could then be constructed and compared to data generated in *MicroDrainage*®.

$$\mathrm{Q} = 2.78\ \mathrm{ciA} \qquad \text{EQ: 3.22}$$

where

Q = discharge (l/s)

c = the coefficient of runoff where 0 to 1 indicates surface type

i = rainfall intensity (mm/hr)

A = area (ha).

Using laboratory scale data enabled a reduction in the level of potential uncertainties when compared to the Hamilton study. Several variables that influenced the results at Hamilton, such as topography, the unknowns of the pipe system, variation in infiltration and vegetation over a large area were reduced at this scale. Consequently, the methodology adapted the approach taken by Lamera *et al*. (2014) who completed a model validation using a single device (a green roof).

Table 3-11 PPS rig rainfall simulations used.

Test Number	Rainfall simulation
1	150mm/hr for 10mins
2	125mm/hr for 12mins
3	100mm/hr for 16mins
4	75mm/hr for 15mins
5	50mm/hr for 30min

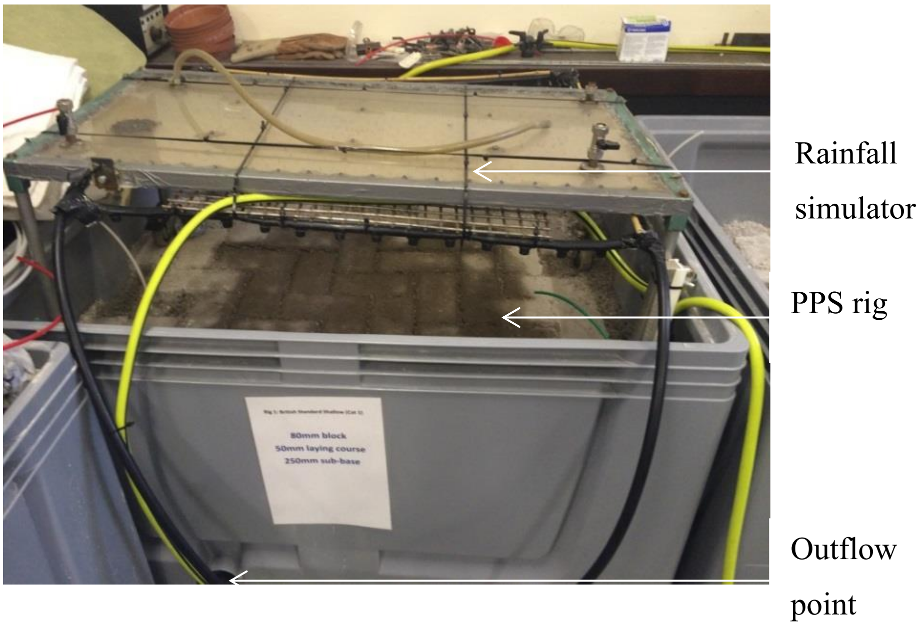


Figure 3-32 Laboratory based PPS Rigs and rainfall simulator.

3.7.3.5 Stage 2.2: Porous pavement modelled data

The simulations were conducted in *MicroDrainage®* for each rainfall event, and compared to the laboratory data. Comparison hydrographs were generated with the values compared using the NSE, which with the field data provided further analysis to the accuracy of *MicroDrainage®* at a smaller scale, with few uncertainties expected and more variables controlled. A further test using filter drains was also completed.

3.7.3.6 Stage 2.3: Filter drain laboratory data

As previously discussed, although filter drains did not form part of the designed SuDS management train from aims 1 or 2, demonstrating the accuracy with which

MicroDrainage® modelled the device adds further validity to the program. A 21.5cm x 21.5cm x 65cm test rig (Figure 3-33) was used with an equally sized rainfall simulator installed to simulate different rainfall events (Table 3-12), as previously used by Coupe *et al.* (2016). The outflow was measured every minute to create a hydrograph that could be compared to data from *MicroDrainage®.* Similar to the approach of the PPS laboratory test, the results were scaled upwards using the Rational Method and the method of Sañudo-Fontaneda *et al.* (2016) to include a 100m long filter drain.

Table 3-12 Filter Drain rainfall simulations.

Test Number	Rainfall simulation
1	200mm/hr for 5mins
2	400mm/hr for 5mins
3	200mm/hr for 10mins
4	400mm/hr for 10mins
5	400mm/hr for 15min

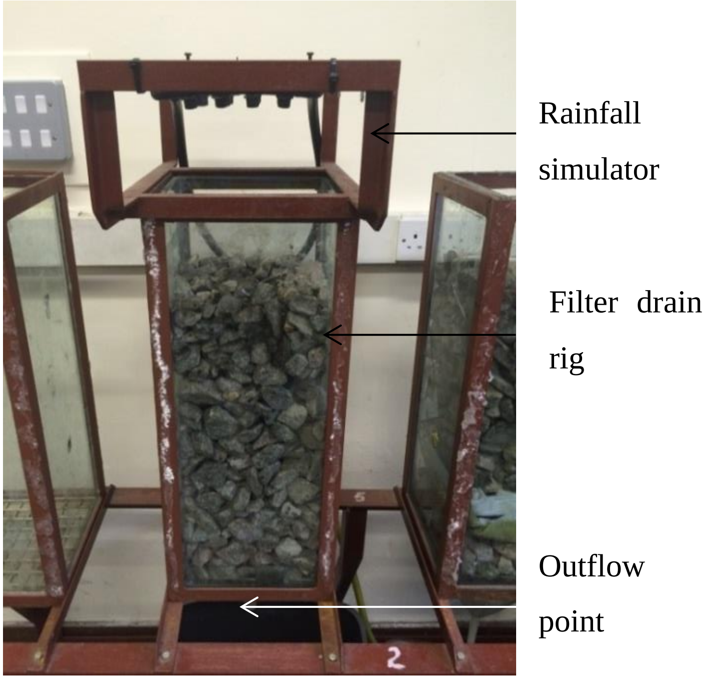


Figure 3-33 Laboratory based filter drain rigs & rainfall simulator.

3.7.3.7: Stage 2.4: Filter drain modelled data

The scaled up laboratory rig was designed in *MicroDrainage*®, with the revised rainfall data simulated. Similar to the method used for the PPS tests, the outflows were compared with the calculated NSE (EQ 2.1). By undertaking field and laboratory methods of validating *MicroDrainage*®, the accuracy of the software was gauged. A high level of accuracy for the software would provide enhanced certainty of the outcomes of aim 1, but also further demonstrate the wider applicability for the DST.

3.8 Summary of the methodology

This chapter outlined how the results for the project were obtained, along with information regarding the site characteristics. The first part of the project involved designing a SuDS management train and a conventional piped system in *MicroDrainage*® based on the site at PDP. The SuDS management train was then deconstructed to determine the effectiveness of each SuDS component based on the 1 in 100 year event at different storm durations for a range of infiltration scenarios. Each component was also analysed to determine the minimum and maximum runoff reduction that could be achieved per m^3 for each device. In addition, the simulations were run for different storm intensities to measure the changing role of each device to different storm intensities and also varying infiltration scenarios.

Determining the role of each device enabled the creation of a DST to assist stakeholders when developing drainage systems. The method that *MicroDrainage*® applied to determine outflow dependent on the site characteristics of rainfall rate, infiltration and site size, were simulated. Assuming a strong correlation between each parameter and runoff enabled a prediction to be made for the likely runoff for each scenario. Each SuDS device was then reduced by 10% in all SuDS management train combinations to determine how runoff alters with different volumes of each device alongside different devices. A regression analysis using a 99% confidence level was then applied to underpin the DST. This enabled users to predict the likely amount of runoff for different site parameters as a result of a specific SuDS configuration. The tool could be used by stakeholders to speed up the design process, as a quick method for determining the volumes of different devices that are required. Furthermore, the ease of determining devices could engage more stakeholders to adopt SuDS into new development design.

The final aspect of the research focussed on validating *MicroDrainage®*. As the program has limited research exposure, no validation of the model was found in the literature. To determine the accuracy of the findings from the first two sections of the research, an understanding of the accuracy of which *MicroDrainage®* predicted runoff was essential. A field based 16 ha assessment using data from Hamilton, Leicester was completed, along with laboratory tests using PPS and filter drains. As well as providing accuracy for the earlier stages of the study, the validation could further engage SuDS specialist and developers with both *MicroDrainage®*, and SuDS, as there has previously been reluctance with practitioners to integrate SuDS due to unknowns around their benefits.

The following chapter will present the findings from the methodology. It will again focus on the three distinct subsections which relate to each aim for the research. As a result of the methodology, Objective 2d was altered as 1 in 100 year rainfall data was unavailable for Lamb Drove (section 3.6.3.1). For this reason, section 4.3.4 focusses on evaluating the DST in the context of the Hamilton Model. This was only possible if the validation (section 4.4.1) of *MicroDrainage®* created a strong correlation between the field and modelled data for the site. As a result, peak flow for the 1 in 100 year 360 minute storm was simulated and compared to the peak flow expected from the DST.

4 Results

4.1 Introduction

The research consisted of three aims which are presented as a flow diagram in

Figure 4-1. Aim 1 (section 4.2) was simulated data generated in *MicroDrainage*®, deconstructing the SuDS management train, analysing the efficiency of different devices at receiving runoff. This focussed on designing and simulating a variety of SuDS management trains to determine their effectiveness. The findings from the simulations identified the differences between conventional drainage and different combinations of SuDS in a management train. The parameters measured were the largest peak flow, which gave an indication of potential runoff, the time to reach the peak and time to reach baseflow which analysed the attenuation potential of the system. The total volume of runoff leaving the site was also quantified to compare the different systems and the overall difference in comparison to conventional drainage to calculate how effective SuDS management trains were in comparison to pipe based drainage.

Aim 2 (section 4.3) involved running models whereby infiltration rates, rainfall and site size were altered to predict runoff for scenarios across England and Wales. This was then combined with a series of model analyses of runoff for different combinations and land take of SuDS. Ensuring a positive correlation between all of the variables enabled the creation of the DST.

Aim 3 was a field and laboratory based validation of the results which analysed the accuracy of *MicroDrainage*®. The field data was obtained from Hamilton, Leicester and compared to the expected flow for the site simulated in *MicroDrainage*®. Similarly, laboratory data using filter drains and PPS rigs were monitored and replicated, to further analyse the software. This gave findings for the first two aims of the research validity, assuming a strong level of accuracy with the software, but also analysed the overall accuracy with which *MicroDrainage*® predicted runoff. This is useful for practitioners by giving them confidence that their designs and simulations are accurately replicated after installation.

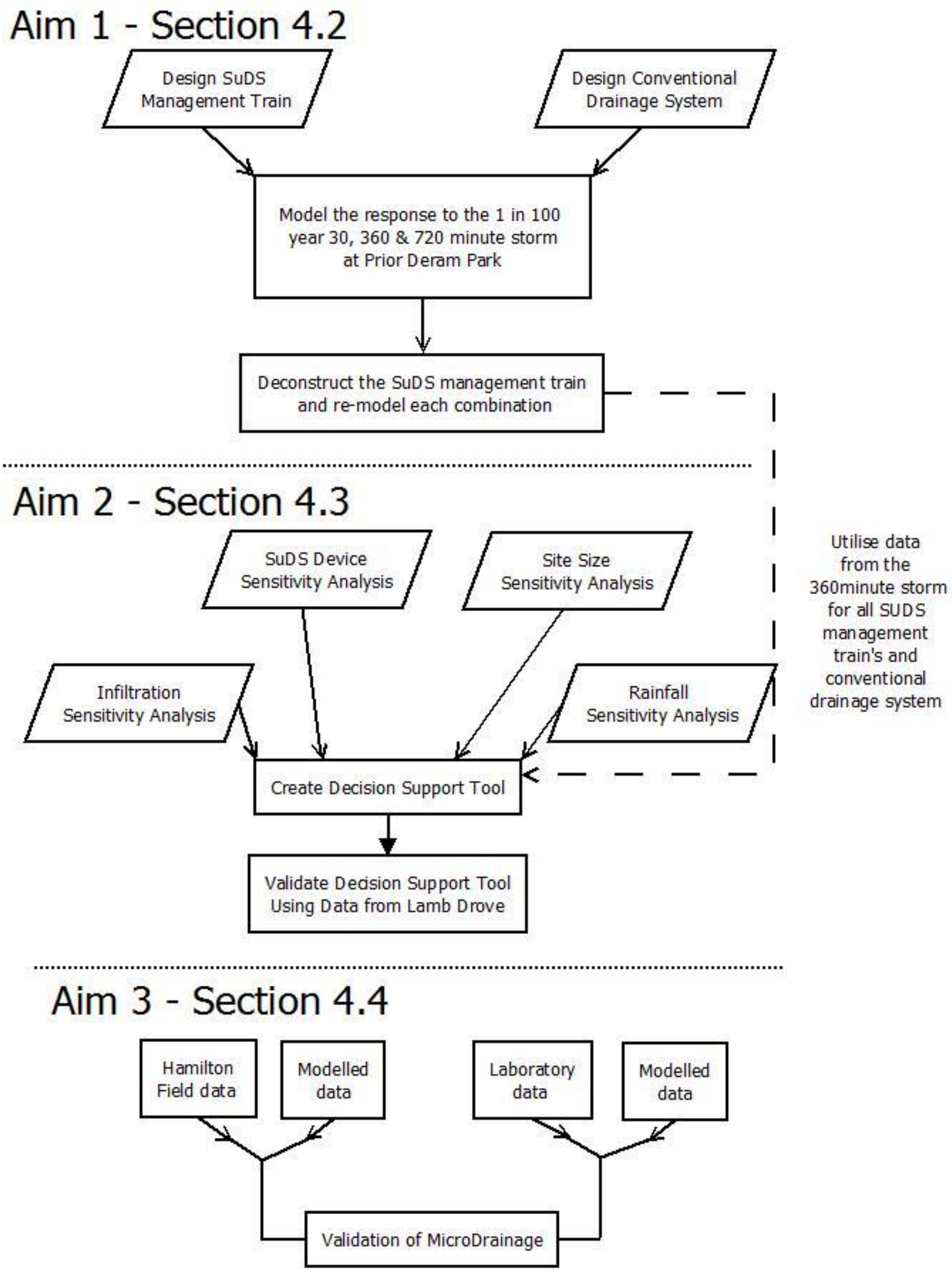


Figure 4-1 Flow diagram of the outline methodology used to generate the results of the research.

4.2 Aim 1: Deconstructing the SuDS management Train

Aim 1 of the project involved simulating different SuDS management trains under changing rainfall intensity and infiltration rates to determine the effectiveness of different devices. The designed test site (section 3.5.1) included detention basins, green roofs, PPS and swales in an area covering 5 ha. A further analysis of the role each device plays in terms of their effectiveness per m^3 is presented in section 4.2.6 to determine the specific impact of each device, as different volumes have been designed at the site. The information from aim 1 will inform stakeholders of the potential 'best-fit' devices, dependent on site conditions, and provide the data to support the development of a DST (aim 2).

4.2.1 Simulated results

As was outlined in section 3.5.3, the 1 in 100 year storm scenario was simulated based on the proposed requirements of The Standards (DEFRA 2015a). Different combinations were simulated to determine the impact on runoff from high intensity short duration (30 minute), medium intensity medium duration (360 minute), and low intensity long duration (720 minute) rainfall. The event of primary concern was the medium duration (360 minute) event as The Standards (DEFRA 2015a) suggest that runoff from a SuDS system after this event should not exceed greenfield runoff values.

4.2.2: 1 in 100 year 360 minute winter storm scenario

The 360 minute storm (11.92 mm/h of rainfall at PDP) was modelled to demonstrate the response of different combinations to a moderate intensity event, evaluating the retention capabilities of the management train. An initial WRAP value of 0.5 was used for the model (section 3.5.5) demonstrating limited potential for infiltration, and further simulations were run using 0.3 and 0.15 WRAP given in section 4.2.5. The resulting hydrographs are presented in Figure 4-2 with more detail in Table 4-1, highlighting the peak runoff, time to peak, the percentage reduction in comparison to conventional drainage, time to baseflow and volume. These factors were discussed by Charlesworth, Harker & Rickard (2003), Semadeni-Davies (2008) and Hamel, Daly & Fletcher (2013) as being critical for evaluating water quantity, and therefore act as determining parameters to consider the more effective SuDS combinations.

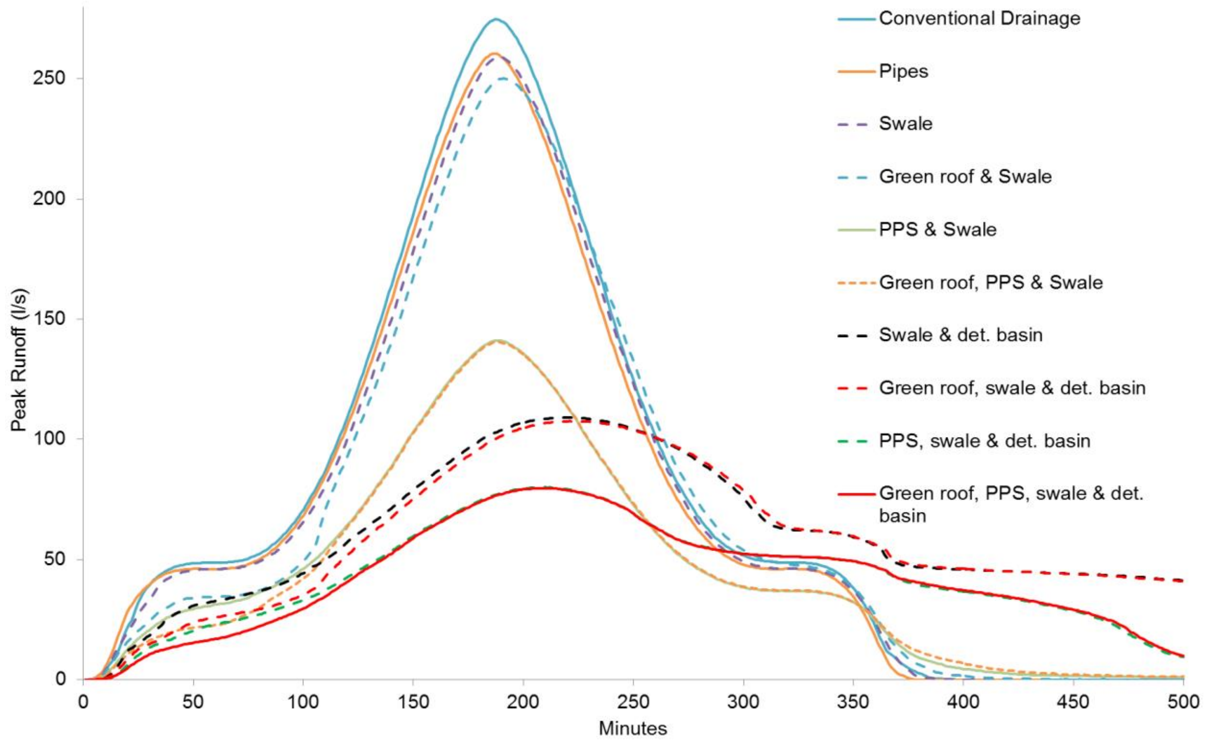


Figure 4-2: Runoff hydrograph for different SuDS combinations as a result of the 1 in 100 year 360 minute winter storm. Note that “pipes” is a conversion of all swales to pipes (section 5.3.4)

Table 4-1 Key runoff characteristics as a result of the 1 in 100 year 360 minute winter storm scenario.

Drainage system	**Peak flow (l/s)**	**% reduction in outflow comparison to conventional drainage**	**Time to peak (mins)**	**Time to baseflow (min)**	**Total volume of runoff (l)**
Conventional Drainage	274.7		186	396	2,361,780
Pipes	260.4		185	377	2,232,216
Swale	259.1	5.7	188	404	2,231,622
Green roof & swale	250.2	8.9	190	464	2,168,436
PPS & swale	141.1	48.6	186	927	1,393,290
Green roof, PPS & swale	140.4	48.9	186	928	1,369,950
Swale & det. basin	109.1	60.3	216	1369	2,233,134
Green roof, swale & det. basin	107.6	60.8	220	1366	2,169,414
PPS, swale & det. basin	80.1	70.8	208	1213	1,391,382
Green roof, PPS, swale & det. basin	79.7	71.0	207	1213	1,368,654

4.2.2.1 Peak flow

Although research has previously attempted to quantify the impact on peak runoff of individual devices, there is limited research that studies the role of different combinations of SuDS in a management train on runoff. Peak flow was the combined amount of runoff leaving the site (in l/s) from each of the three outflow pipes into the receiving watercourse (section 3.5.1). Peak outflow was identified as a critical parameter for measuring the effectiveness of a device, as underlined by Heal *et al*. (2009). The maximum peak outflow identified the potential scale of flooding, as the largest peak runoff generated for each combination was modelled.

Figure 4-2 and Table 4-1 show that the largest simulated runoff, 274.7 l/s, occurred as a result of the conventional drainage system, adding a simple swale train resulted in 259.1 l/s, demonstrating the benefits of utilising SuDS. Moreover, the combination entitled pipes (whereby all swales in the management train were converted to pipes, section 3.5.4) produced a greater flow than the swale system. This gave further evidence that utilising SuDS in any capacity was more effective than pipes.

The difference between peak runoff generated from devices with and without detention basins is demonstrated in Figure 4-2. Table 4-1 further exemplifies this with all devices containing detention basins ranging between 109.1 l/s (swale and detention basin) and 79.7 l/s (green roof, PPS swale and detention basin), in comparison to the lowest peak flow without a detention basin, which was 140.4 l/s (green roof, PPS and swale). Detention basins acted as large stores of runoff controlling how much was released through the rest of the management train and ultimately into the outflow (Ravazzini *et al*. 2014; Wang & Yu 2012). By capturing and storing runoff they were able to reduce total runoff volumes (further discussed in section 5.2).

Another consideration was the impact of PPS, as depending on the devices it worked alongside it produced varying results. PPS was extremely effective at reducing peak flow (a reduction of 118 l/s when added to the swale system) when combined in a management train without detention basins. However their impact reduced when used with detention basins, reducing peak runoff by 29 l/s when added to the combination of swales and detention basin. Nonetheless when compared with green roofs, the other source control device modelled, PPS was the more effective at reducing peak flows. Green roofs reduced runoff by 8.9 l/s when added to the management train consisting of simply swales, compared to the 118 l/s reduction with PPS and swales.

4.2.2.2 Reduction in comparison to conventional drainage

The reduction in peak flow of each combination was compared to conventional drainage to determine the total impact of each management train. This enabled an overall comparison to be drawn between each system to determine the most successful configuration of devices. The initial design for a conventional drainage system was used for comparison (section 3.5.2).

Table 4-1 established that the addition of any of the modelled SuDS devices reduced runoff in comparison with conventional drainage and by just integrating swales into the design, a reduction of 5.7% was possible. Without using detention basins, the model suggested it was possible to obtain a maximum reduction of 48.9% by integrating green roofs, PPS and swales. However each combination that included detention basins generated a reduction in runoff of between 60.3% (swale and detention basin) and 71% (green roof, PPS, swale and detention basin). This had not previously been measured as part of a combination, although SNIFFER (2004) suggested that a standalone swale system reduced runoff more effectively than PPS.

4.2.2.3 Time to peak

Time to peak was defined as the time between the start of rainfall and peak flow (Miller *et al.* 2014) and therefore was another factor in determining the effectiveness of a drainage system. By reducing the time to reach peak flow and ultimately retaining water in the management train, peak runoff would reduce therefore reducing flood risk (Woods Ballard *et al.* 2007).

The time to reach peak flow (Table 4-1) remained reasonably consistent across all configurations without detention basins, with just five minutes between the fastest to peak, 185 minutes for the pipe system, and the slowest to peak, 190 minutes for green roof and swale. Utilising detention basins considerably increased the time to peak as all combinations with detention basins took a minimum of 207 minutes, when all devices were added. It was likely that adding all devices was quicker to reach peak than other combinations with detention basins as both the peak flow and total volume were lower. The role of detention basins reflected research by SNIFFER (2004) who, when measuring standalone systems, suggested that detention basins minimally increased time to peak. They also found that PPS increased lag time in the region of hours, as opposed to the minutes presented in Table 4-1.

4.2.2.4 Time to baseflow

Time to baseflow measured the amount of time water resided in the system, an important consideration for flood alleviation (Hamel, Daly & Fletcher 2013). Conventional drainage collects runoff and rapidly removes it through the storm sewer network into a local watercourse, which can often result in flooding at the outflow (Semadeni-Davies *et al*. 2008). Retaining water in the system enabled infiltration, if the site permitted, and inhibited the flashy peak associated with quickly transferring runoff. When comparing the runoff profile of different drainage systems to the same storm, the more effective devices would take longer for the hydrograph to return to baseflow.

The simulated systems with the slowest return to baseflow were those that included detention basins, increasing the time to between 1213 (all modelled SuDS) and 1369 minutes (swale and detention basin). Of the combinations that included detention basins, modelling all SuDS was the quickest to return to baseflow. This was likely to be a result of the reduced total volume in the system. This supported the findings by Ravazzini *et al*. (2014) who concluded that detention basins can increase the time to return to baseflow. The addition of PPS also increased time to peak, taking nearly double the time of the green roof and swale system, supporting the findings of SNIFFER (2004). The introduction of a management train using more than just swales increased the time to baseflow, as water was retained in the system, compared to conventional drainage. When making a direct comparison between the role of pipes and swales, the pipe system was the fastest of all modelled combinations to return to baseflow, 27 minutes faster than when the arrangement is converted to swales.

4.2.2.5 Volume

The interaction between the role that different combined devices had at reducing volume has not previously been studied. The total amount of runoff leaving the site was calculated to demonstrate the amount of runoff that was “lost” in the system, in comparison to conventional drainage, typically through infiltration or evaporation, before reaching the outflow (Strecker 2002).

The largest total volume of runoff leaving the site was from the conventional drainage system (2,361,780 l), with the addition of swales reducing the volume to 2,231,622 l. All combinations that included PPS produced the lowest total volume leaving the site; a maximum with PPS of 1,393,290 l (PPS and swale) compared to a minimum without PPS of 2,168,436 l (green roof and swale). Although research acknowledged the ability of PPS to reduce runoff (Scholz & Grabowiecki 2007; Gomez-Ullate *et al*. 2010), no research had quantified the impact when combined with different devices. However green roofs, the other source control device simulated, also provided reduction potential. The maximum volume reduction achieved by modelling green roofs in the combination was 63,186 l, when added to the swale system. Stovin (2010) analysed the individual impact of green roofs, suggesting they reduced total runoff by up to 57%, whilst Voyde, Fassman & Simcock (2010) achieved similar results, calculating that three sites in Auckland retained 66% of annual rainfall (1093 mm). Table 4-1 suggested that it was unlikely for the total reduction to be as large as Stovin (2010) presented, however it was still effective.

When detention basins were added to combinations that included PPS, it further decreased the total volume leaving the site by up to 1,908 l, indicating their moderate effectiveness at promoting infiltration during lower flows associated with the SuDS management trains that include PPS (4.2.2.1). However for all other configurations, an increase of up to 1,515 l was identified, therefore suggesting that detention basins were less effective at reducing volumes during larger flows.

4.2.3: 1 in 100 year 30 minute winter storm scenario

The 1 in 100 year 30 minute storm was modelled to assess the response of each combination to a high intensity short duration (73.13 mm/h at PDP) event. Figure 4-3 is the resulting hydrograph which focused on the first fifty minutes after the storm commenced to highlight the primary aspects of the hydrograph, peak and time to peak. Table 4-2 presents a breakdown of each combination based on the parameters discussed in section 4.2. The pipe model flooded in this scenario, therefore no outflow data was presented for this modelled event.

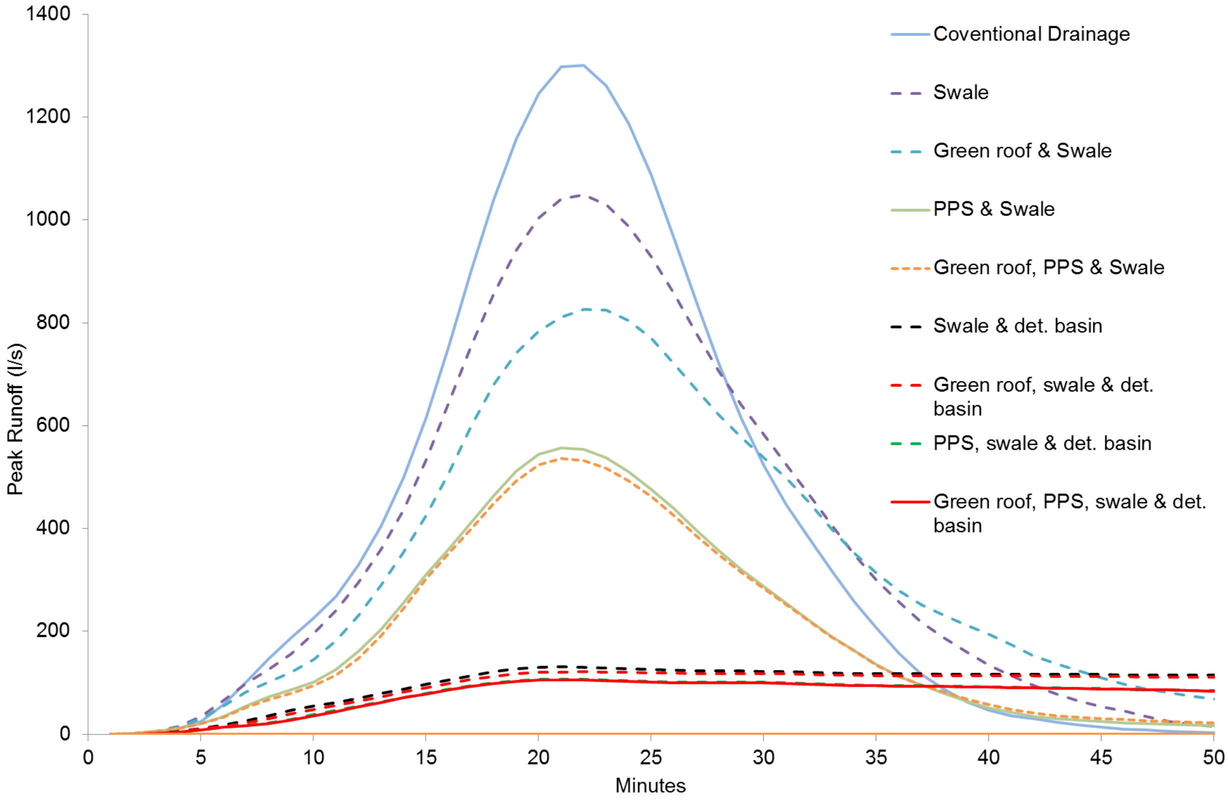


Figure 4-3 Runoff hydrograph for different SuDS combinations as a result of the 1 in 100 year 30 min winter storm; no pipe system as simulation flooded.

Table 4-2 Key runoff characteristics as a result of the 1 in 100 year 30min winter storm scenario.

Drainage system	**Peak flow (l/s)**	**% reduction in outflow comparison to conventional drainage**	**Time to peak (mins)**	**Time to baseflow (min)**	**Total volume of runoff (l)**
Conventional Drainage	1300.0		21	59	1 ,201,224
Pipes	N/A	N/A	N/A	N/A	N/A
Swale	1048.5	19.3	22	85	1,140,696
Green roof & swale	826.1	36.5	22	154	1,086,486
PPS & swale	556.8	57.2	21	620	618,714
Green roof, PPS & swale	536.1	58.8	22	601	652,638
Swale & det. basin	131.5	89.9	21	972	1,140,894
Green roof, swale & det. basin	121.4	90.7	22	963	1,084,980
PPS, swale & det. basin	106.9	91.8	21	832	616,638
Green roof, PPS, swale & det. basin	106.1	91.8	21	848	651,372

4.2.3.1 Peak flow

Figure 4-3 shows that conventional drainage produced a peak flow 251.5 l/s faster than that for a SuDS system. This remained consistent with the potential effectiveness of swales suggested by Woods Ballard *et al.* (2015), with the device primarily used to transport runoff around the site. Comparing different devices at a similar scale, PPS was more effective than green roofs since all configurations including PPS reduced the outflow. This quantified the possible reduction for both source control devices, which was not presented by Woods Ballard *et al.* (2015). However the results agreed with their conclusion that PPS had a ‘high’ runoff reduction potential as opposed to the ‘low’ reduction potential of a green roof. Conversely, Viavattene *et al.* (2010) presented a much closer relationship between the runoff reduction potential of PPS and green roofs, while Stovin (2010) suggested that peak runoff reduction could be as high as 57% by installing green roofs. However, the impact of each device was dependent on the storm intensity.

The most effective devices to reduce peak flow at this scale were the detention basins, reducing it by between 917 l/s and 430 l/s. Like the 1 in 100 year 360 minute winter rainfall scenario (section 4.2.2), they were capable of detaining and slowly releasing runoff to the remainder of the management train.

4.2.3.2 Reduction in comparison to conventional drainage

A 19.3% reduction in peak runoff was achieved by integrating a swale management train, as opposed to conventional drainage. By adding further devices, a reduction of at least 36.5% in peak runoff was accomplished. By using the combination of all measured devices; green roofs, PPS, swales and detention basins, a reduction of 91.8% was possible. This demonstrated the overall effectiveness of a management train containing a range of SuDS devices. By comparing different combinations, Figure 4-3 provided further analysis of the effectiveness of each SuDS device which has not been presented elsewhere in the literature.

4.2.3.3 Time to peak

Three of the simulated management trains that included detention basins had the shortest time to peak at 21 minutes, the same as conventional drainage, which was the opposite of previous research (Astebøl, Hvitved-Jacobsen & Simonsen 2004). However, the peak outflow achieved when modelling detention basins was considerably reduced (section 4.2.2.1) in comparison to the other combinations without the device.

4.2.3.4 Time to baseflow

The conventional system was the quickest to return to base flow, displayed in Table 4-2, 26 minutes faster than swales. Although it had previously been known that a conventional drainage system would rapidly return flow to baseflow (Hamel, Daly & Fletcher 2013; Miller *et al*. 2014; Semadeni-Davies *et al*. 2008), a comparison to SuDS devices had so far not been considered in the literature.

All combinations including more than one SuDS element further increased time of return to baseflow as a result of a high intensity rainfall event. An increase of 69 minutes was achieved by simply adding green roofs to swales. Detention basins also markedly increased the time to return to baseflow by up to 887 minutes which backed up the findings by Zakaria *et al*. (2003) that detention basins retained large volumes of water, therefore increased time to baseflow.

PPS returned different results for return to baseflow, depending on the devices it was combined with. When added to a combination without detention basins, time to baseflow increased by up to 466 minutes, however when added to a management train that included detention basins the time decreased by up to 140 minutes. The reduced time to baseflow when combined with detention basins was because PPS had the capacity to retain runoff, enabling infiltration, which resulted in lower total runoff volumes. However if flow through the device was greater than the infiltration capacity of the underlying soils, water could be retained before being slowly released to the remainder of the management train, therefore increasing the time to return to baseflow (Imran, Akib & Karim *et al*. 2013; Scholz & Grabowiecki 2006; Starke, Göbel, Coldewey 2010).

4.2.3.5 Volume

Table 4-2 established that the maximum total volume to leave the site was as a result of the pipe system, which was in keeping with Swan (2010) who suggested that high flows were typically a result of urbanisation. Total volume was considerably reduced for all management trains containing PPS, with a maximum volume of 652,638 l, in comparison to a minimum of 1,084,908 l for systems without PPS (a minimum of 39.48% decrease). Although Viavattene *et al*. (2010) examined PPS suggesting it was most effective at reducing runoff individually, no research analyses its impact when combined with other devices. Across all scenarios without PPS the addition of green roofs also reduced total volume, with a maximum reduction of 54,483 l (49.95%) when added to the swale and detention basin system. However for the high intensity 30 minute storm, adding green roofs to PPS increased the total volume of runoff leaving the site. This was inconsistent with the results for both the 360 and 720 minute storm analysis.

For this event, a detention basin minimally reduced (a maximum of 2,076 l) the total amount of runoff leaving the site when combined with PPS, and increased the total volume by 198 l when added to swales. This challenged suggestions made by both Woods Ballard *et al*. (2015) and Ravazzini *et al*. (2014) regarding the overall effectiveness of a detention basin.

4.2.4: 1 in 100 year 720 minute winter storm scenario

The final simulation was the low intensity long duration 720 minute event (7.18 mm/h). Simulating the response of each device in the management train to such intensity evaluated the effectiveness of each combination as water backs up and was retained. A greater reliance was placed on retention and ultimately infiltration. The resulting hydrograph for each SuDS combination is presented in Figure 4-4, with more detail provided in Table 4-3.

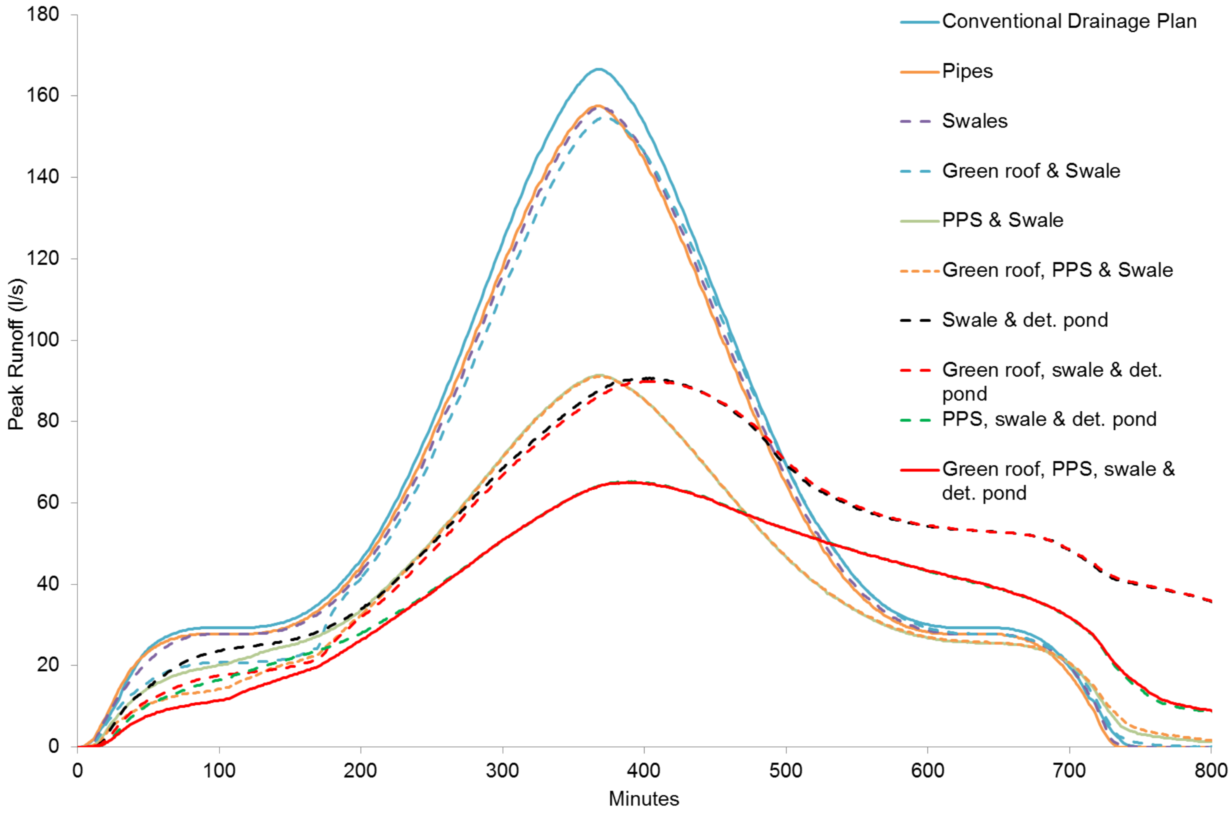


Figure 4-4 Runoff hydrograph for different SuDS combinations as a result of the 1 in 100 year 720 min winter storm scenario.

Table 4-3 Key runoff characteristics as a result of the 1 in 100 year 720min winter storm scenario.

Drainage system	Peak flow (l/s)	% reduction in outflow comparison to conventional drainage	Time to peak (mins)	Time to baseflow (min)	Total volume of runoff (l)
Conventional Drainage	166.6		366	750	2,848,182
Pipes	157.5		365	734	2,690,868
Swale	157.3	5.6	369	759	2,690,478
Green roof & swale	154.8	7.1	370	804	2,624,772
PPS & swale	91.3	45.2	365	1284	1,843,032
Green roof, PPS & swale	91.2	45.3	368	1282	1,803,072
Swale & det. basin	90.6	45.6	400	1618	2,692,548
Green roof, swale & det. basin	89.9	46.0	407	1618	2,626,728
PPS, swale & det. basin	65.2	60.9	381	1488	1,841,754
Green roof, PPS, swale & det. basin	65.1	60.9	388	1489	1,804,416

4.2.4.1. Peak flow

Figure 4-4 again highlights the contrast in runoff between configurations with and without detention basins. Table 4-3 shows that the largest peak flow generated was as a result of conventional pipe based drainage, 166.6 l/s. However the reduction achieved by converting pipes to swales was only 0.2 l/s, much less than the previous scenarios.

For this rainfall intensity, there was little difference between the impact of PPS and detention basins. When adding each device to swales, a reduction of 0.6 l/s was gained by incorporating a detention basin as opposed to PPS, therefore highlighting the increased role of PPS during low intensity events. Combining both devices further increased their impact, by reducing runoff to 65.2 l/ s. The role of detention basins during low intensity long duration events was not as effective as proposed by DEFRA (2005) who suggested they were a critical component and the most effective at reducing runoff peaks for such events.

4.2.4.2 Reduction in comparison to conventional drainage

A minimum 5.6% reduction of peak runoff was achieved by implementing a swale system as opposed to conventional drainage. Without integrating detention basins in the design, a maximum reduction, based on the 1 in 100 year 720 minute winter storm was potentially 45.3% (green roof, PPS and swale). Incorporating green roofs in a design reduced runoff by a maximum of 1.5% when no other source control device was being used. However the addition of PPS reduced the impact of green roofs to 0.1%. This contradicted the findings of Mentens, Raes & Hermy (2006) who suggested that as a result of an extreme low intensity event, green roofs should significantly restrict peak flow. By installing model detention basins, it was possible to achieve a peak runoff reduction of over 45.6%, the most being 60.9% when using green roofs, PPS, swale and detention basin in the model.

4.2.4.3 Time to peak

The time to reach peak flow ranged between 365 minutes (pipes) up to 407 minutes (green roof, swale and detention basin). The inclusion of a detention basin generated increased time to peak, with all four configurations taking between 381 and 407 minutes, adding at least 20 minutes. Including PPS in each of the combination decreased the peak and subsequently shortened the time to reach peak flow.

4.2.4.4 Time to baseflow

Table 4-3 indicated that pipe and conventional systems returned to baseflow values faster than the combinations with SuDS, 25 and 9 minutes faster than swales, respectively. Detention basins had the greatest impact on time to baseflow, increasing the time by up to 859 minutes.

PPS also increased the time it took to return to baseflow, however it was not as effective as detention basins, adding up to 525 minutes when not used with detention basins. The potential of PPS to reduce time to baseflow was highlighted by Scholz and Grabowiecki (2007), however no figures were given to justify exactly how effective they could be, and there was no comparison made to other devices.

The role of green roofs at reducing runoff was variable. When added to the swale system runoff remained for 45 minutes longer than just using swales. However when combined with either or both PPS and detention basins the role was negligible, increasing the time by no more than one minute. The varying ability of green roofs to manage runoff and how effectively the system works with other devices has not previously been identified in the research.

4.2.4.5 Volume

The least effective system at reducing runoff was conventional drainage, which generated a total volume of outflow of 2,848,182 l. This was 157,704 l (5.54%) more than the least effective SuDS system, which was the swale train. Previous research (Heal *et al*. 2009; Swan, 2010; van Woert *et al* 2005) assumed a connection between the large runoff values associated with urbanisation and conventional drainage, however Table 4-3 has quantified the values involved. The four combinations that included PPS reduced the total volume most effectively with a minimum of 821,700 l (31.31%) potentially reduced by including PPS in the model. Green roofs remained consistently effective as a source control device, and although not as effective as PPS, had the potential to reduce total volume by 65,828 l (2.44%) when added to the swale and detention basin system. Including a detention basin had a mainly negative impact on total volume, increasing the amount for models without basins for all combinations apart from when added to PPS and swales. Although the values were negligible (never more than 2,070 l), they demonstrated the ineffectiveness of basins to reduce total flows during low intensity events when runoff was already reduced by other devices.

4.2.5: Comparison between timeframes and infiltration rates

Section 4.2.2 to section 4.2.4 evaluated each rainfall event in turn and the response of each combination of SuDS devices for the 0.5 WRAP scenario. This section will draw comparisons between each SuDS combination to evaluate their overall effectiveness, while also discussing Table 4-4 and Table 4-5, which have simulated runoff for the 0.15 WRAP, high infiltration scenario, and 0.3 WRAP medium infiltration scenario. Each combination was then analysed based on the aforementioned parameters; peak, time to peak, time to baseflow, comparison with conventional drainage and volume. As was the case for the earlier sections, no outflow data for the conventional drainage was possible for the 30 minute event, due to flooding.

Table 4-4 Key runoff characteristics for the 0.15 WRAP scenario: a) 30 minute storm b) 360 minute storm c) 720 minute storm.

a) 30 Minutes *	**Peak flow (l/s)**	**% reduction in outflow comparison to conventional drainage**	**Time to peak (mins)**	**Time to baseflow (min)**	**Total volume of runoff (l)**
Conventional Drainage Pipes	1150.7		21	59	1,059,906
Swale	808.2	29.8	22	85	858,084
Green roof & swale	721.7	37.3	22	151	954,078
PPS & swale	495.3	57.0	21	596	552,456
Green roof, PPS & swale	475.1	58.7	21	612	583,626
Swale & det. basin	124.6	89.2	22	934	1,006,164
Green roof, swale & det. basin	115.0	90.0	22	923	952,032
PPS, swale & det. basin	100.6	91.3	21	806	550,752
Green roof, PPS, swale & det. basin	99.5	91.4	21	821	583,524
b) 360 Minutes *					
Conventional Drainage	242.4		186	396	2,083,878
Pipes	229.8		185	377	1,969,626
Swale	228.6	5.7	187	403	1,968,858
Green roof & swale	220.7	9.0	190	467	1,907,316
PPS & swale	126.1	48.0	187	915	1,256,778
Green roof, PPS & swale	125.5	48.2	188	935	1,231,266
Swale & det. basin	102.5	57.7	217	1312	1,969,836
Green roof, swale & det. basin	101.0	58.3	219	1309	1,907,154
PPS, swale & det. basin	74.7	69.2	206	1176	1,258,644
Green roof, PPS, swale & det. basin	74.3	69.3	207	1175	1,228,188
c) 720 Minutes *					
Conventional Drainage	147.0		366	749	2,513,100
Pipes	138.9		365	733	2,374,500
Swale	138.8	5.6	368	755	2,374,038
Green roof & swale	136.5	7.1	370	815	2,309,976
PPS & swale	82.3	44.0	366	1247	1,667,364
Green roof, PPS & swale	82.1	44.1	368	1276	1,624,404
Swale & det. basin	84.2	42.7	400	1556	2,373,474
Green roof, swale & det. basin	83.6	43.1	405	1557	2,314,830
PPS, swale & det. basin	60.6	58.8	386	1450	1,667,178
Green roof, PPS, swale & det. basin	60.6	58.8	388	1451	1,623,708

Table 4-5 Key runoff characteristics for the 0.3 WRAP scenario:
a) 30 minute storm b) 360 minute storm c) 720 minute storm.

a) 30 Minutes *	**Peak flow (l/s)**	**% reduction in outflow comparison to conventional drainage**	**Time to peak (mins)**	**Time to baseflow (min)**	**Total volume of runoff (l)**
Conventional Drainage	1214.9		21	59	1,120,926
Pipes					
Swale	983.6	19.0	22	92	1,064,454
Green roof & swale	766.0	36.9	22	153	1,012,056
PPS & swale	522.4	57.0	21	612	581,100
Green roof, PPS & swale	501.6	58.7	21	621	614,448
Swale & det. basin	127.5	89.5	22	951	1,065,090
Green roof, swale & det. basin	117.9	90.3	22	941	1,008,846
PPS, swale & det. basin	103.5	91.5	21	817	579,102
Green roof, PPS, swale & det. basin	102.4	91.6	21	833	613,044

b) 360 Minutes *					
Conventional Drainage	256.4		186	396	2,203,800
Pipes	243.1		186	377	2,082,948
Swale	241.8	5.7	188	400	2,082,264
Green roof & swale	233.5	8.9	190	461	2,020,062
PPS & swale	132.5	48.3	187	916	1,317,042
Green roof, PPS & swale	131.7	48.6	187	942	1,291,038
Swale & det. basin	105.4	58.9	215	1338	2,081,844
Green roof, swale & det. basin	103.9	59.5	219	1334	2,019,378
PPS, swale & det. basin	77.0	70.0	207	1192	1,319,190
Green roof, PPS, swale & det. basin	76.8	70.0	207	1192	1,290,918

c) 720 Minutes *					
Conventional Drainage	155.5		367	749	2,657,790
Pipes	147.0		368	733	2,511,336
Swale	146.8	5.6	368	751	2,510,652
Green roof & swale	144.4	7.1	370	812	2,445,996
PPS & swale	86.2	44.6	365	1270	1,744,302
Green roof, PPS & swale	85.9	44.8	365	1256	1,701,864
Swale & det. basin	87.0	44.1	396	1583	2,508,534
Green roof, swale & det. basin	86.4	44.4	403	1583	2,445,612
PPS, swale & det. basin	62.9	59.5	388	1467	1,745,016
Green roof, PPS, swale & det. basin	62.2	60.0	382	1468	1,686,240

4.2.5.1 Peak flow

Overall, the simulated results presented in Table 4-1 to Table 4-5 show the potential reduction in peak flow that could be achieved by integrating any combination of SuDS into the drainage design. Across all scenarios, both the conventional and pipe system provided the largest peak flow. This was further exemplified by the 30 minute storm which flooded the pipe system, irrespective of the infiltration rate modelled. Regardless of the timeframe and potential to infiltrate, by incorporating detention basins into the drainage design a minimum 42.7% reduction in peak flow was achieved. Although detention basins have a high capacity for peak flow reduction, it was possible that the values achieved for each scenario was as a result of the volume of detention basins (6,059 m^3) integrated at the modelled site. A further analysis (section 4.2.6) was therefore undertaken to calculate the role of each device, per m^3 and m^2, to reduce peak flow.

PPS reduced peak runoff by up to 492 l/s (when added to the swale system for the 30 minute event, 0.5 WRAP) and up to 118 l/s for the 360 minute storm with 0.5 WRAP. Although peak flow rates reduced as infiltration rates increased, the impact of each device became marginally less effective. This was likely due to an overall decrease in infiltration at the site, putting more emphasis on the role of SuDS promoting infiltration. The reduction identified through each timeframe with PPS was consistent with Woods Ballard *et al.* (2015) who rated the device as having a ‘High’ runoff reduction potential. However, its effectiveness across all scenarios was dependent upon the devices it was used with, as detention basins consistently produced the lowest flows; when combined with PPS, the impact reduced.

Modelling of green roofs also reduced runoff, and as the substrate was not linked to the site infiltration rate, their impact did not vary throughout the different WRAP scenarios. However when comparing their impacts through each rainfall intensity, the potential peak flows of the systems including green roofs reduced as rainfall intensity decreased. This disagreed with the discussion presented by Mentens, Raes & Hermy (2006) who suggested that as intensity decreased, green roofs would be more effective.

4.2.5.2 Reduction in comparison to conventional drainage

The impact of storm intensity on the effectiveness of a management train has not previously been identified in the literature. The total potential reduction of integrating a SuDS management train to a site as opposed to conventional drainage was entirely dependent on the devices used. Simply integrating swales reduced peak flow by between 29.8% and 19%, but when compared to the “pipe” system, flow only marginally decreased for the 360 and 720 minute scenario; a comparison could not be made for the 30 minute scenario as the pipe system flooded at that intensity. This justified the ‘Low’ potential for reduction by Woods Ballard *et al.* (2015). For the models that incorporated detention basins, the medium and low intensity scenarios resulted in between a 42.7% and 71% reduction with up to 91.8% possible compared to conventional drainage for the high intensity event. This echoed Woods Ballard *et al.* (2015)’s ‘High’ potential to reduce flooding for detention basins. Overall, the total percentage reduction in comparison to the pipe based drainage system reduced as the intensity of the storm decreased and as infiltration increased. The 720 minute 0.15 WRAP event had the smallest amount of reduction, when compared to all other simulations as it was the lowest intensity event with the largest amount of infiltration.

4.2.5.3 Time to peak

The conventional pipe based drainage system was consistently quicker to peak compared to SuDS management trains at low and medium intensity rainfall. The combinations that included PPS, but were without detention basins achieved peak flow either at the same time, or one minute faster for several of the model runs, however their peak flow was considerably reduced. Time to peak increased for every scenario when detention basins were added, due to the increase retention of runoff.

The effect that a modelled green roof had on the management train’s ability to retain water was dependent on the other devices that were also being used. For the majority of scenarios where a green roof was added, time to peak increased as more water resided in the management train. However, when green roofs were added with PPS, swale and detention basin combinations, for both low intensity medium infiltration and medium intensity low infiltration models, time to peak decreased.

4.2.5.5 Volume

Conventional drainage was the least effective at reducing the total volume of runoff compared to other modelled combinations. Although converting pipes to swales reduced the total volume, adding a detention basin to the swale system increased runoff volume for three out of six scenarios. This indicated that although detention basins were extremely effective at attenuating flow and reducing runoff peaks, they were less effective at reducing total volume. However when they were combined with any other device, volume further decreased. All other combinations produced reduced volumes compared to both conventional and piped systems.

Both PPS and green roofs performed well for all three rainfall scenarios, with PPS being the most effective of all the devices measured by a considerable margin, in keeping with the expectations set by Scholz & Grabowiecki (2007). Dependent on the infiltration rate for the site, the volume reduction when using PPS ranged from 712,080 l (36.17%) for the high infiltration site to 838,332 l (37.57%) for the low infiltration site, for the 360 minute event.

4.2.6: Breakdown of the role of each device

Sections 4.2.2 to 4.2.4 modelled the role of each SuDS device in terms of reducing runoff for a specified layout, using a specific coverage of devices. The volume of basins was larger (6,059 m^3) in comparison to the other three devices, therefore an analysis of the impact of each device, per m^3, was completed to see the specific role of each device at reducing runoff. This was supported by an analysis with regards total area to define the role with regards land take (m^2). Detention basins were deeper than all other measured devices, therefore although their total volume is considerably larger, their area (2,189 m^2) is nearly five times smaller than green roofs (10,170 m^2). Table 4-6 to Table 4-8 present the minimum and maximum amount of runoff reduction that could be achieved, and calculate the role each device has for each m^3 and m^2. The data was taken for the 360 minute winter storm, with a focus on peak flows, as was suggested by The Standards (DEFRA 2015a).

Table 4-6 Impact on runoff (l/s) of each device per m3 for 0.5 WRAP 360 minute event.

Devices	**Total volume (m^3)**	**Total Area (m^2)**	**Max reduction (l/s)**	**Min Reduction (l/s)**	**Peak flow ($l/s/m^3$)**	**Peak flow ($l/s/m^2$)**
Detention Basin	6,059	2,189	150.0	61.0	0.025 – 0.010	0.069 – 0.028
Green roof	1,017	10,170	9.0	0.4	0.009 – <0.001	0.001 – <0.001
PPS	1,568	3,380	118.0	28.0	0.075 – 0.018	0.035 – <0.001
Swale	1,323	1.692	11.6	0.4	0.009 – <0.001	0.007 – <0.001

Table 4-7 Impact on runoff (l/s) of each device per m^3 for 0.3 WRAP 360 minute event.

Devices	**Total volume (m^3)**	**Total Area (m^2)**	**Max reduction (l/s)**	**Min Reduction (l/s)**	**Peak flow ($l/s/m^3$)**	**Peak flow ($l/s/m^2$)**
Detention Basin	6,059.00	2,189	136.0	55.0	0.022 – 0.009	0.062 – 0.025
Green roof	1,017.20	10,170	8.0	0.2	0.008 – <0.001	0.001 – <0.001
PPS	1,568.46	3,380	109.0	27.0	0.069 – 0.017	0.032 – 0.008
Swale	1,322.71	1.692	10.5	0.3	0.008 – <0.001	0.006 – <0.001

Table 4-8 Impact on runoff (l/s) of each device per $m^{3\ 3}$ for 0.15 WRAP 360 minute event.

Devices	**Total volume (m^3)**	**Total Area (m^2)**	**Max reduction (l/s)**	**Min Reduction (l/s)**	**Peak flow ($l/s/m^3$)**	**Peak flow ($l/s/m^2$)**
Detention Basin	6,059.00	2,189	126.0	51.0	0.021 – 0.008	0.058 – 0.023
Green roof	1,017.20	10,170	8.0	0.4	0.008 – <0.001	0.001 – <0.001
PPS	1,568.46	3,380	103.0	27.0	0.066 – 0.017	0.030 – 0.008
Swale	1,322.71	1.692	10.0	0.1	0.008 – <0.001	0.006 – <0.001

Sections 4.2.2 to 4.2.5 suggested that detention basins were the most effective method for attenuating peak flow. This was further backed up when analysing the impact with regards the total area of each device (m^2). Detention basins were able to reduce peak flow by a maximum of 0.03 $l/s/m^2$ in comparison to the second most effective device, PPS. However under further analysis, detention basins accounted for nearly four times the amount of volume in comparison with PPS and therefore when calculating the impact of each device on peak flow reduction, per m^3, PPS had the greatest impact on runoff reduction, three times as effective as detention basins.

Figure 4-2 and Table 4-1 proposed that green roofs had little role at reducing peak flow in comparison to detention basins and PPS, which was further supported in Table 4-6 to Table 4-8. A maximum of 0.009 $l/s/m^3$ and 0.001 $l/s/m^2$ was possible, however the devices had only a small storage area of 100 mm (section 3.5.3), compared to the large detention capabilities of the basins. Although green roofs appeared to retain a minimal role at reducing peak flow, their volume was negligible compared to detention basins which could be incorporated in more traditional open space designs, however their total area was considerable: nearly three times more (per m^2) than PPS, the second largest per m^2. As green roofs are not incorporated into traditional open space, this provided a justification for the inclusion of green roofs in a management train, but contradicts Stovin (2010), who suggested that green roofs can have a significant impact when used as a standalone device. Comparing the different infiltration scenarios (Table 4-6 to Table 4-8), there was little change in the role of each device, with PPS being the most effective per m^3 throughout and detention basins per m^2. The performance of each device decreased as infiltration increased, due to the increased amount of runoff entering the devices at the lower infiltration scenario. As the primary purpose of PPS was to promote infiltration, they were able to slightly enhance infiltration in comparison to the green space at the site, which do not actively enhance infiltration.

4.2.7: Aim 1 summary

The findings of aim 1 highlighted the overall importance of integrating detention basins into a SuDS management train. When measured at PDP across the variables presented for each timeframe and infiltration scenario, detention basins were consistently the most effective device at reducing runoff peaks and the time to reach peak flow. PPS was extremely effective at retaining water in the system for longer and reducing total volumes. Although a green roof was an effective source control device, when used with PPS its benefits were reduced because its SuDS functions were taken over by PPS.

However, although the test site is a realistic configuration of SuDS, it did not provide a direct comparison as different numbers of each device were utilised. Table 4-6 to Table 4-8 suggested that although both detention basins were extremely effective at the site, PPS was three times more effective per m^3.

4.3: Aim 2: Decision Support Tool

A DST was created by using a series of model analyses. The creation of a DST enabled:

1. A shorter decision time to determine suitable combinations of SuDS
2. An estimation of the required density of devices to achieve greenfield runoff rates and optimise land take.

Overall, the DST aimed to reduce the time stakeholders spend designing sites, therefore engaging more developers with the benefits of SuDS with regards flood management.

4.3.1: Site parameter model analysis

A relationship between runoff and differing densities of SuDS, varying rainfall, infiltration and site scale, was identified and modelled using *MicroDrainage*®. These relationships enabled a calculation of the estimated runoff under a variety of scenarios. The process explored whether a strong relationship existed between each of the parameters and runoff:

- Rainfall: runoff
- Infiltration: runoff
- Size of the site: runoff
- The number of each SuDS device in each management train: runoff

A model analysis was completed to identify trends with the simulation data for both infiltration and rainfall in *MicroDrainage®*. Determining regression at the 99% confidence level enabled calculation to support the DST.

4.3.1.1: Rainfall

The FEH (Institute of Hydrology 1999) estimated the likely rainfall scenario for catchments across the UK, and is the industry standard tool for modelling rainfall, superseding the FSR (Institute of Hydrology 1975) (section 3.5.5.1). The 1 in 100 year 360 minute storm, as suggested by The Standards (DEFRA 2015a) was modelled, with the predicted rainfall depth being used to classify the site (a key metric generated by the FEH). The rainfall depth could be calculated in the FEH (Institute of Hydrology 1999) for all catchments in the UK for different rainfall intensities. Fifty sites with differing rainfall depths were modelled in *MicroDrainage®* to illustrate the response of the software and are presented in Figure 4-5. A strong positive correlation was found, with an r^2 value of 0.99, therefore as rainfall depth increased, runoff increased, and this enabled the prediction of likely runoff as a result of a specific rainfall event for the DST using the coefficient outputs of the regression analysis.

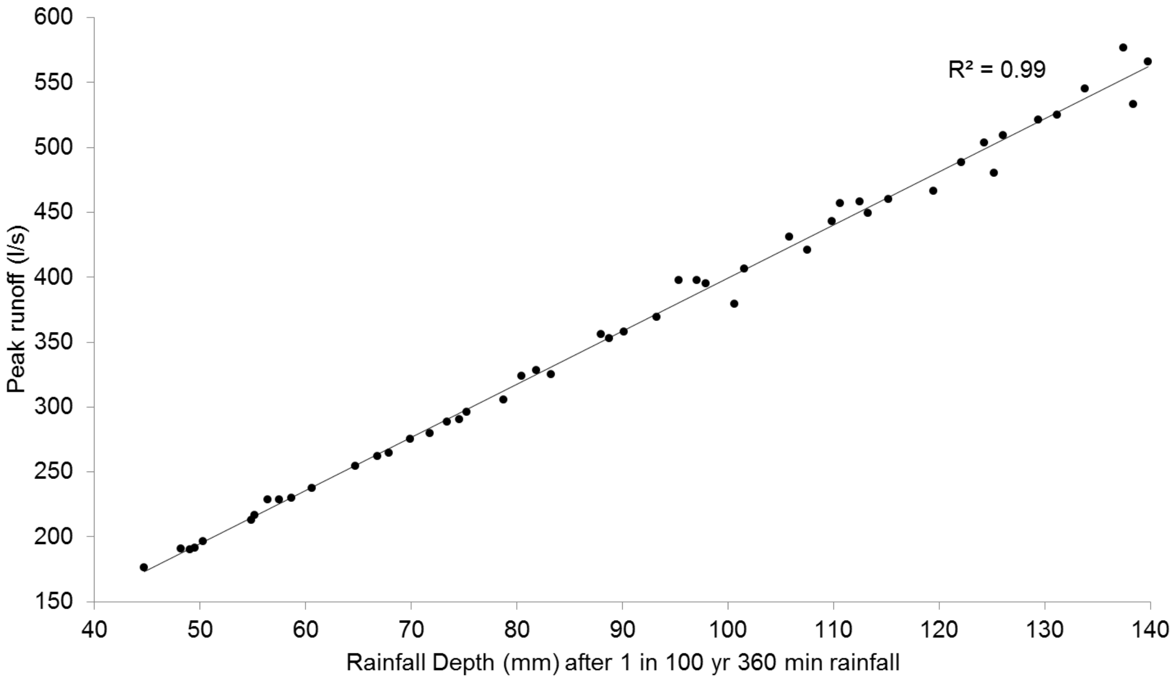


Figure 4-5 Runoff change due to differing rainfall depth (mm) as a result of a 1 in 100 360 minute rainfall event (n=50).

4.3.1.2: Infiltration

MicroDrainage® used the WRAP method to determine the soil conditions of a site. This procedure was developed in the FSR (Institute of Hydrology 1975) and categorised soils into five values. See section 3.5.5.2 for more information on the WRAP characteristics classified in the FSR (Institute of Hydrology 1975).

To determine whether a correlation existed between runoff and the soil value, each site classification was simulated, enabling the data presented in section 4.2.2 to predict the optimal SuDS management train configuration at different WRAP values. Figure 4-6 showed that the simulations generated an r^2 value of 0.99 value (P=<0.01) between different soil conditions and runoff, consequently as the WRAP value increased runoff increased consistently. This was in line with findings presented by Boorman, Hollis & Lilly (1995) who also identified a correlation between WRAP values and runoff.

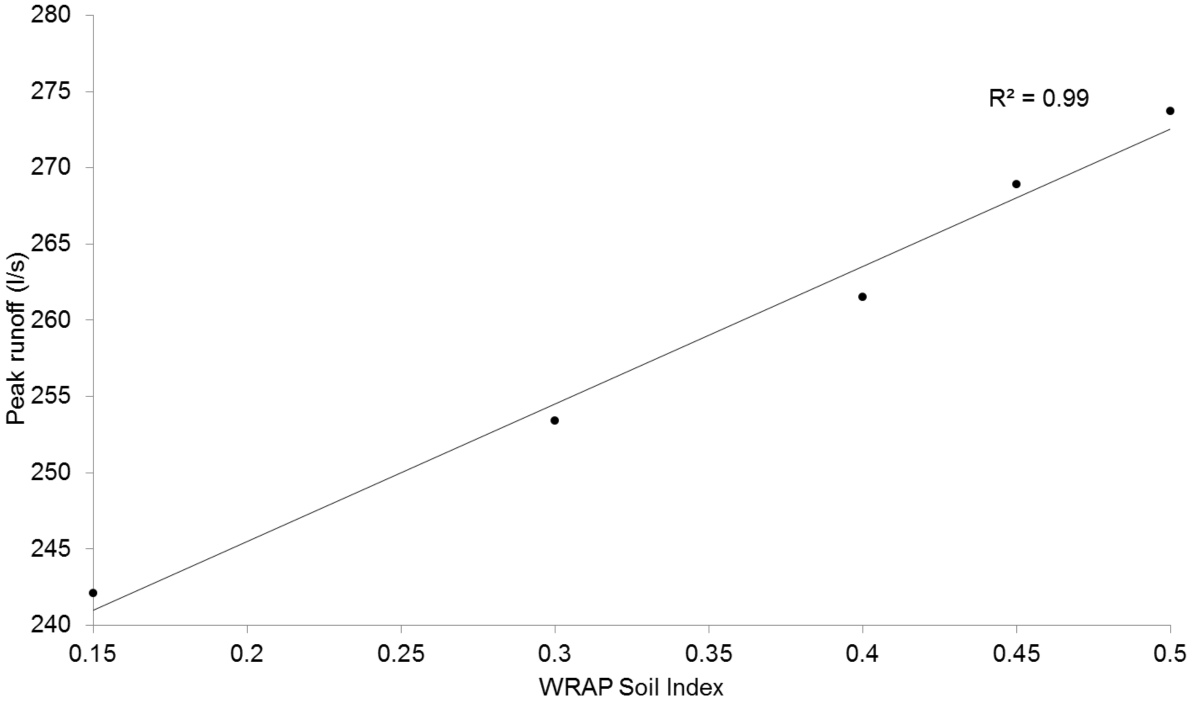


Figure 4-6 WRAP/runoff correlation for the 1 in 100 year storm for modelled conventional drainage (n=5).

4.3.1.3: Scale of Site

To add more detail to the DST, an analysis of how runoff altered with a change in the scale of the site was completed. This enabled the user to input the size of the desired site to estimate likely runoff. Simulated site size ranged from 5 ha up to 50 ha as Kellagher (2012) suggested that processes change after 50 ha (section 2.15).

A simulation in *MicroDrainage®* of a range of sites from 5 ha to 50 ha (Figure 4-7) gave a strong positive correlation: as size of site increased, runoff increased. The r^2 value was strong (0.99) ($p < 0.01$) indicating that estimations could be made with a high level of confidence of likely runoff from differently sized sites.

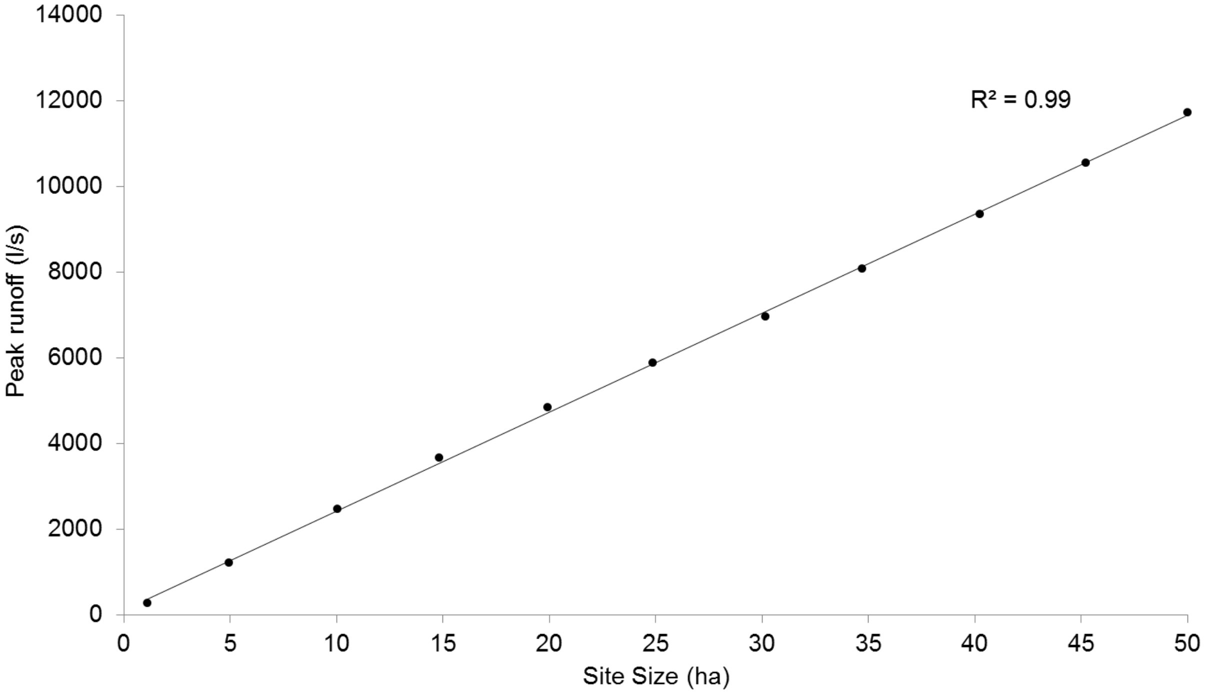


Figure 4-7 Change in runoff as the site size increases (n=11).

Overall, it was determined, based on Figure 4-7 to Figure 4-12, that runoff as a result of varying rainfall, soil index levels and different site size could be predicted with a high confidence level. This suggested that potential runoff as a result of the design presented in section 4.2.1 could be estimated at varying rainfall depths and WRAP index levels.

4.3.2: SuDS model Analysis

The influence of the volume of each SuDS device in each SuDS management train on runoff underpinned the DST. The simulation of how runoff in *MicroDrainage®* altered as the number of devices changed enabled a regression analysis and subsequent coefficient values of the likely runoff as a result of a given a number of each device

(Appendix C). Each device used in the management train was modelled: green roofs, PPS, swales and detention basins.

4.3.2.1: Detention Basins

Each simulated combination including detention basins produced a strong correlation, with a reduction in size of basins resulting in an increase in flow. Table 4-9 showed that an r^2 value of ≥ 0.98 was achieved when reducing the size of modelled detention basins by 10% of the original volume (6059 m^3). It should be noted however that unlike the other model analysis for green roofs (4.3.2.2), PPS (4.3.2.3) and swales (4.3.2.4), detention basins were never entirely removed as by removing detention basins entirely, runoff greatly increased (section 4.2), therefore skewing the data and producing a much weaker correlation. This was the only SuDS combination to record such findings and subsequently the model analysis was completed up to a 99% reduction in size of each basin (combined volume of 60.59 m^3). An adjustment was thus made using the SuDS management train modelled in aim 1 (Section 3.5.3) to calibrate the DST to account for the impact of detention basins on peak runoff.

Table 4-9 Analysis for each combination when reducing the size of detention basins (n=11).

SuDS Management Train	r^2	P-value
PPS, swale & detention basin	0.98	<0.01
Swale & detention basin	0.99	<0.01
Green roof, swale & detention basin	0.99	<0.01
Green roof, PPS, swale & detention basin	0.98	<0.01

4.3.2.2: Green Roofs

A correlation was undertaken between runoff and the percentage coverage of green roofs by simulating 1017 m^3 of green roofs and reducing the area by 10% of the original amount i.e. 1017 m^3 re-simulating and measuring until all green roofs were removed from each combination in Table 4-10. All scenarios demonstrated a strong r^2 value, and only when combined with PPS and swales was it <0.9, with all of the calculations having a p-value of <0.01.With a strong level of confidence in the data, a prediction was made of the likely runoff when used with different devices. This developed research by Stovin (2010) who presented the benefits of utilising green roofs as a tool for runoff management.

Table 4-10 Analysis for each combination when reducing the number of green roofs (n=11).

SuDS Management Train	r^2	P-value
Green roof & swale	0.98	<0.01
Green roof, PPS & swale	0.89	<0.01
Green roof, swale & detention basin	0.94	<0.01
Green roof, PPS, swale & detention basin	0.92	<0.01

4.3.2.3: PPS

Table 4-11 presents the findings for simulation of PPS; each resulted in a strong correlation, $r^2 \geq 0.96$, which therefore enabled a prediction on the likely runoff to leave the site as a result of a user-defined volume of PPS with a high level of certainty.

Table 4-11 Analysis for each combination when reducing the number of PPS (n=11).

SuDS Management Train	r^2	P-value
PPS & swale	0.99	<0.01
PPS, swale & detention basin	0.96	<0.01
Green roof, PPS & swale	0.98	<0.01
Green roof, PPS, swale & detention basin	0.96	<0.01

4.3.2.4: Swale

As swales were involved in each combination for conveyance, eight model analyses were simulated rather than the four undertaken for other devices. All scenarios measured showed that as the number of swales decreased runoff increased, however the strength of the correlation varied from 0.8 to 0.97. The results with a lower r^2 value were simulations whereby runoff changed very slightly e.g. for the green roof, PPS and swale combination, runoff reduced by 0.4 l/s overall. This small level of change was likely to have resulted in the weaker correlations presented in Table 4-12.

Table 4-12 Analysis for each combination when reducing the number of swales (n=11).

SuDS Management Train	r^2	P-value
PPS, swale & detention basin	0.96	<0.01
PPS & swale	0.82	<0.01
Green roof, swale & detention basin	0.87	<0.01
Green roof, PPS & swale	0.80	<0.01
Green roof, PPS, swale & detention basin	0.97	<0.01
Green roof & swale	0.92	<0.01
Swale & detention basin	0.85	<0.01
Swale	0.89	<0.01

4.3.3: Model Analysis summary

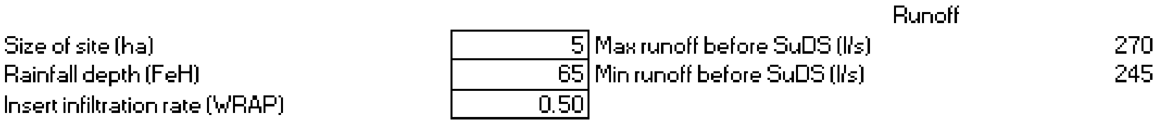
The analysis of each site parameter and each combination of SuDS device provided data for the DST. The support tool was to be used by practitioners prior to the SuDS selection process, giving an indication of the required density of different devices needed to achieve greenfield runoff. Using the formula given by Kellagher (2012) (EQ 3.21), a calculation could be made for the necessary greenfield runoff rate at the site to be developed. The tool therefore presented an opportunity to calculate the potential runoff at a site prior to modelling and design.

4.3.4: Decision Support Tool

A DST using the information generated in section 4.3.1 and section 4.3.2 provided practitioners with the potential peak runoff values dependent on the infiltration, site size, rainfall and chosen SuDS devices (a user guide is available in Appendix C to). Completing a regression analysis from each model analysis in section 4.3 enabled the prediction of the likely runoff as a result of a user-defined amount of rainfall, infiltration and size of site with total number and size of SuDS. By analysing the data at the 99% confidence level, a strong level of confidence could be attributed to the outputs of the tool. The following sections discuss the layout for the tool and the necessary user inputs.

4.3.4.1 User inputs for site parameters

The user initially defined the site conditions, which were the size of the site (ha), the rainfall depth (mm) from FEH and WRAP (section 3.6.2). All cells in MS Excel (Microsoft Corporation 2010) that required the user to input additional data were bordered. EQ 3.1 to EQ 3.6 enabled the calculation of a maximum and minimum likely runoff for conventional drainage, prior to integrating SuDS (Figure 4-8).

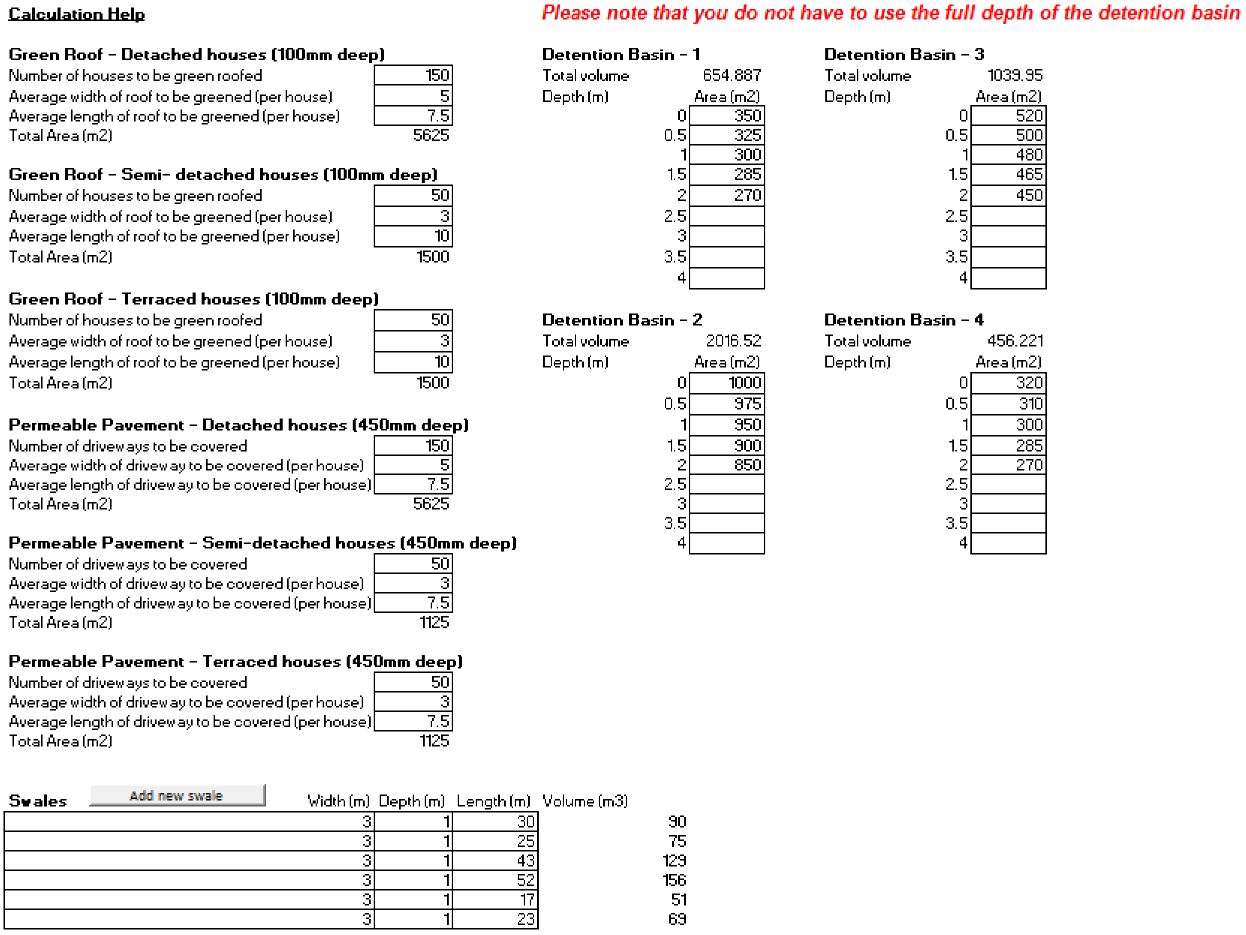


		Runoff	
Size of site (ha)	5	Max runoff before SuDS (l/s)	270
Rainfall depth (FeH)	65	Min runoff before SuDS (l/s)	245
Insert infiltration rate (WRAP)	0.50		

Figure 4-8 User inputs for site parameters in the DST. All cells that require user input are bordered.

4.3.4.2 User inputs for SuDS

After defining the site parameters, the user was required to input the chosen density of each available SuDS device to create a management train (Figure 4-9). Housing types were categorised into detached, semi-detached and terraced to ensure the DST was user-friendly and enabled the analysis of a range of different housing types. This supported the calculation for both PPS and green roofs (EQ 3.10 and EQ 3.12). A macro was created that enabled the user to add an unlimited number of new swales to the worksheet, requiring the user to input width, depth and length of each individual swale to calculate the volume. Four detention basins could also be installed at the site with a maximum depth of 4 m, although the user did not have to use the full depth. An area at 0.5 m sections were required to calculate the total volume of each pond (EQ 3.8). After the SuDS were input, the individual impact on runoff of each device was calculated and combined and then subtracted from runoff for conventional drainage to determine the maximum and minimum likely runoff for the SuDS management train (EQ 3.16 to EQ 3.17).



Calculation Help

Please note that you do not have to use the full depth of the detention basin

Green Roof - Detached houses (100mm deep)

Number of houses to be green roofed	150
Average width of roof to be greened (per house)	5
Average length of roof to be greened (per house)	7.5
Total Area (m2)	5625

Green Roof - Semi- detached houses (100mm deep)

Number of houses to be green roofed	50
Average width of roof to be greened (per house)	3
Average length of roof to be greened (per house)	10
Total Area (m2)	1500

Green Roof - Terraced houses (100mm deep)

Number of houses to be green roofed	50
Average width of roof to be greened (per house)	3
Average length of roof to be greened (per house)	10
Total Area (m2)	1500

Permeable Pavement - Detached houses (450mm deep)

Number of driveways to be covered	150
Average width of driveway to be covered (per house)	5
Average length of driveway to be covered (per house)	7.5
Total Area (m2)	5625

Permeable Pavement - Semi-detached houses (450mm deep)

Number of driveways to be covered	50
Average width of driveway to be covered (per house)	3
Average length of driveway to be covered (per house)	7.5
Total Area (m2)	1125

Permeable Pavement - Terraced houses (450mm deep)

Number of driveways to be covered	50
Average width of driveway to be covered (per house)	3
Average length of driveway to be covered (per house)	7.5
Total Area (m2)	1125

Detention Basin - 1

Total volume	654.887
Depth (m)	Area (m2)
0	350
0.5	325
1	300
1.5	285
2	270
2.5	
3	
3.5	
4	

Detention Basin - 3

Total volume	1039.95
Depth (m)	Area (m2)
0	520
0.5	500
1	480
1.5	465
2	450
2.5	
3	
3.5	
4	

Detention Basin - 2

Total volume	2016.52
Depth (m)	Area (m2)
0	1000
0.5	975
1	950
1.5	900
2	850
2.5	
3	
3.5	
4	

Detention Basin - 4

Total volume	456.221
Depth (m)	Area (m2)
0	320
0.5	310
1	300
1.5	285
2	270
2.5	
3	
3.5	
4	

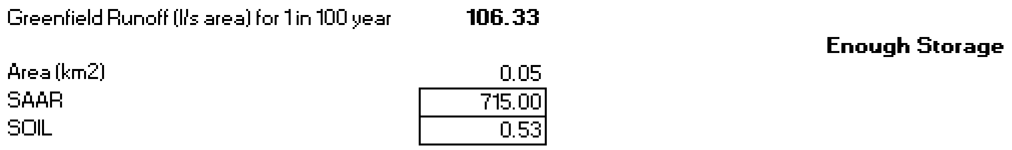
Swales

	Width (m)	Depth (m)	Length (m)	Volume (m3)
	3	1	30	90
	3	1	25	75
	3	1	43	129
	3	1	52	156
	3	1	17	51
	3	1	23	69

Figure 4-9 User inputs for each SuDS device in the DST. All cells that require user input are bordered.

4.3.4.3 User inputs for greenfield runoff calculation

The Standards (DEFRA 2015a) required all new developments to not exceed greenfield runoff, therefore including the formula for greenfield runoff in the DST provided a rapid analysis of the suitability of the management train (Figure 4-10). The calculation for area (km^2) was taken from the size of site input (ha) from section 4.3.4.1, however the user had to define the SAAR and SOIL values from FEH (Institute of Hydrology 1999).



Greenfield Runoff (l/s area) for 1 in 100 year **106.33**

Enough Storage

Area (km2) 0.05
SAAR 715.00
SOIL 0.53

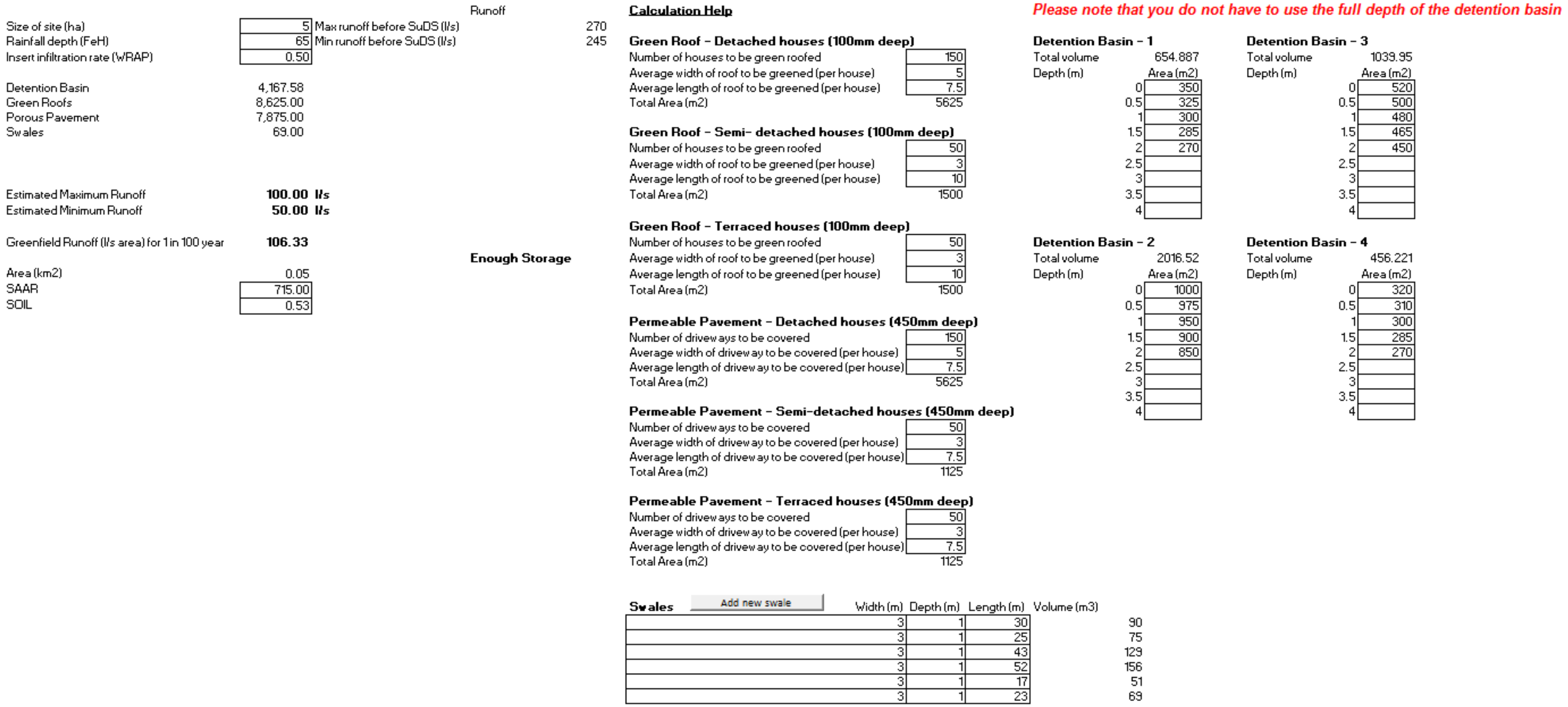
Figure 4-10 User inputs to calculate greenfield runoff for the site. All cells that require user input are bordered.

4.3.4.4 Final decision support tool layout

Figure 4-11 shows the final design of the tool that ran in MS Excel (Microsoft Corporation 2010). The tool was designed to replicate the interface of *MicroDrainage*® by determining the area of green roofs, the volume for each detention basin, and the total coverage of green roofs and swales. A maximum and minimum outflow was given as the output of the tool.

The layout enabled users to input information to all bordered cells, with the remaining information locked. Each green roof simulation was run using 100 mm deep substrate, which is the standard value used in *MicroDrainage*® based on research by Stovin (2010) and 450 mm deep PPS (British Standard Institution 2009). Users were able to add or remove different devices dependent on the number of basins and different area of PPS chosen to integrate into the site.

The estimated peak outflow was the primary output for the tool. Although both lag time and volume change were key variables in determining the success of a SuDS system (Woods Ballard *et al*. 2015), The Standards (DEFRA 2015a) required that peak runoff must not exceed greenfield runoff for the 1 in 100 year 360 minute event. This was calculated in the tool using EQ 4.1. The greenfield runoff provided a comparison with the output of the DST to determine whether the site met requirements, or whether additional SuDS were required.



Size of site (ha)	5	Max runoff before SuDS (l/s)		270
Rainfall depth (FeH)	65	Min runoff before SuDS (l/s)		245
Insert infiltration rate (WRAP)	0.50			

Runoff

Detention Basin	4,167.58
Green Roofs	8,625.00
Porous Pavement	7,875.00
Swales	69.00

Estimated Maximum Runoff	**100.00 l/s**
Estimated Minimum Runoff	**50.00 l/s**
Greenfield Runoff (l/s area) for 1 in 100 year	**106.33**

Enough Storage

Area (km2)	0.05
SAAR	715.00
SOIL	0.53

Calculation Help

Green Roof - Detached houses (100mm deep)

Number of houses to be green roofed	150
Average width of roof to be greened (per house)	5
Average length of roof to be greened (per house)	7.5
Total Area (m2)	5625

Green Roof - Semi- detached houses (100mm deep)

Number of houses to be green roofed	50
Average width of roof to be greened (per house)	3
Average length of roof to be greened (per house)	10
Total Area (m2)	1500

Green Roof - Terraced houses (100mm deep)

Number of houses to be green roofed	50
Average width of roof to be greened (per house)	3
Average length of roof to be greened (per house)	10
Total Area (m2)	1500

Permeable Pavement - Detached houses (450mm deep)

Number of driveways to be covered	150
Average width of driveway to be covered (per house)	5
Average length of driveway to be covered (per house)	7.5
Total Area (m2)	5625

Permeable Pavement - Semi-detached houses (450mm deep)

Number of driveways to be covered	50
Average width of driveway to be covered (per house)	3
Average length of driveway to be covered (per house)	7.5
Total Area (m2)	1125

Permeable Pavement - Terraced houses (450mm deep)

Number of driveways to be covered	50
Average width of driveway to be covered (per house)	3
Average length of driveway to be covered (per house)	7.5
Total Area (m2)	1125

Swales

	Width (m)	Depth (m)	Length (m)	Volume (m3)
	3	1	30	90
	3	1	25	75
	3	1	43	129
	3	1	52	156
	3	1	17	51
	3	1	23	69

Please note that you do not have to use the full depth of the detention basin

Detention Basin - 1

Total volume 654.887

Depth (m)	Area (m2)
0	350
0.5	325
1	300
1.5	285
2	270
2.5	
3	
3.5	
4	

Detention Basin - 3

Total volume 1039.95

Depth (m)	Area (m2)
0	520
0.5	500
1	480
1.5	465
2	450
2.5	
3	
3.5	
4	

Detention Basin - 2

Total volume 2016.52

Depth (m)	Area (m2)
0	1000
0.5	975
1	950
1.5	900
2	850
2.5	
3	
3.5	
4	

Detention Basin - 4

Total volume 456.221

Depth (m)	Area (m2)
0	320
0.5	310
1	300
1.5	285
2	270
2.5	
3	
3.5	
4	

Figure 4-11 Main user-interface of the DST with example data input to demonstrate the outputs of the tool.

4.3.5: DST accuracy

Objective 2c required a validation of the DST to determine its accuracy. Originally, field data for Lamb Drove, Cambridgeshire (Cambridgeshire County Council 2012) was to be used which included rainfall and SuDS data for the site. However as discussed in section 3.6.3.1, after further analysis this was deemed unsuitable as the DST replicated flows for the 1 in 100 year 360 minute storm, but according to the FEH, the flow measured at Lamb Drove was approximately a 1 in 5 year return period and was therefore not comparable.

The simulation at Hamilton for the 1 in 100 year 360 minute storm flooded a small section of the site, therefore the outflow values achieved were less than would be expected using the DST, which modelled channel flow. The suggested outflow for the site from the DST ranged between 570 l/s and 655 l/s, whilst *MicroDrainage®* suggested an outflow of 479.6 l/s with 2421.58 m^3 of flooding. Although this fell outside the range predicted by the DST, it was possible that the DST could have estimated runoff, had the site not flooded. More research is required to further analyse the accuracy of the DST (section 5.3.4)

4.4 Aim 3: Validation

A validation of *MicroDrainage®* was undertaken to determine the wider accuracy of the results from aims 1 and 2. The validation involved the collection of field data (section 4.4.1) at the Hamilton SuDS Management Train, Leicester (section 3.7.2), with the site and rainfall events replicated in *MicroDrainage®*. The management train consisted of swales, detention basins and vegetated ponds, therefore additional laboratory data was collected for PPS which was subsequently modelled to provide additional validation. Further laboratory analysis using filter drains was also completed. Although filter drains were not included in aims 1 or 2 since they typically manage flow from motorways or large roads as opposed to smaller residential developments, nonetheless they provided additional data to support the accuracy of *MicroDrainage®*, demonstrating its validity as a tool for modelling SuDS.

4.4.1: Field Validation: Hamilton SuDS Management Train

An outline of the Hamilton SuDS Management Train and its location was provided in Figure 3-14. Runoff from five rainfall events at different times of the year was measured at eight sections of the site, and compared to the simulated data (Figure 4-12). Table 4-13 presents a proportion of the raw data used for Figure 4-12 (Appendix D for the full dataset). Section 3.7.3.1 outlines the method used to collect the data in Table 4-13 and Figure 4-12, with the field values calculated as a result of the mean of four flow measurements and the cross-sectional area calculated by depth measurements every 5 cm. The NSE was used to determine the validity of the model as the formula was specifically designed to validate hydrological models with field data (Nash & Sutcliffe 1970). The coefficient of determination (r^2) was also used to further validate the model, adopting the approach used by Tramblay *et al*. (2011) (section 3.7).

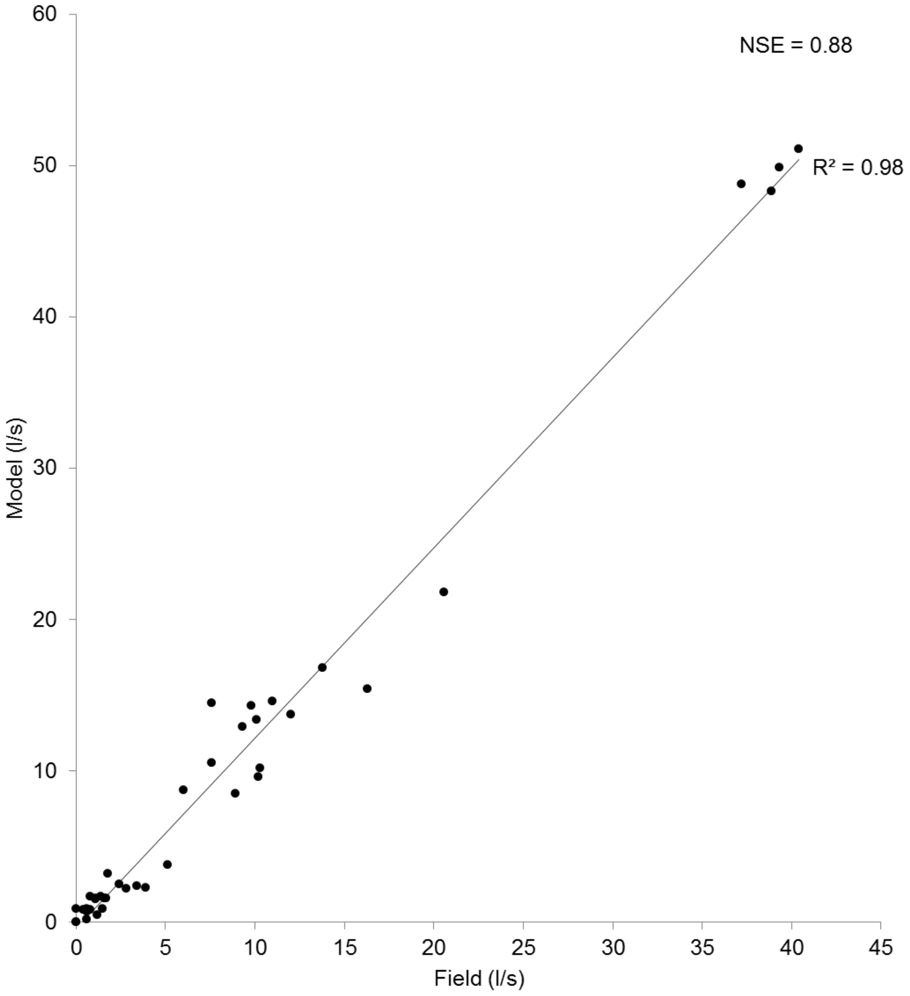


Figure 4-12 Validation of MicroDrainage®, comparing model and field data (n=40).

Table 4-13 Three sets of mean field (n=4) and model (n=1) flow data (l/s) from eight sites taken from the Hamilton SuDS Management Train (Appendix D for remaining data)

Site	**19/02/2015**		**22/02/2015**		**14/05/2015**	
	Field	**Model**	**Field**	**Model**	**Field**	**Model**
Site 1	0.6	0.2	1.4	1.7	0	0
Site 2	1.2	0.5	1.8	3.2	0	0
Site 3	3.4	2.4	6	8.7	0	0.9
Site 4	2.8	2.2	8.9	8.5	0.6	0.9
Site 5	3.9	2.3	12	13.7	0.4	0.8
Site 6	2.4	2.5	9.8	14.3	1.5	0.9
Site 7	1.6	1.6	7.6	14.5	0.6	0.7
Site 8	1.7	1.6	10.1	13.4	0.8	0.8

The NSE calculated a 0.88 level of confidence in *MicroDrainage*® (Figure 4-12). Previous research focussing on modelling green roofs over 23 ha using SWMM produced an NSE of between 0.59 to 0.82 (Petrucci *et al*. 2012). Gaborit *et al*. (2013) focussed on detention basins, using the same software, and achieved a NSE of 0.91 over a 15 ha site. In comparison, Dotto *et al*. (2011) analysed MUSIC over five different sized catchments (105.6 – 10.5 ha) in Australia. They calculated the mean NSE for the model to be 0.61, with the best being 0.8. Therefore an NSE of 0.88 over a complex 16 ha site that integrated two detention basins, four vegetated ponds and swales suggested *MicroDrainage*® performed well, and offers a strong level of confidence in the outputs for both aim 1 and 2. The additional r^2 statistical test calculated an even greater level of confidence in the ability of *MicroDrainage*® to simulate flow, returning a coefficient of 0.98. Although both NSE and coefficient of determination are methods of calculating correlation of a data set, the values vary, with NSE suggesting a reduced level of confidence in *MicroDrainage*® in comparison to the r^2 value. NSE focuses on the link between individual data points; how one field measurement directly links to the corresponding model value, in comparison to the wider dataset. However r^2 focusses more on the overall trends; the mean of both model and field and the standard deviation of the dataset. Therefore NSE provides a more accurate analysis of specific points and is likely to explain why the value is decreased, in comparison to the overall mean analysis provided by the coefficient of determination, which is closer to 1 (a perfect correlation).

4.4.2: Laboratory Validation

Laboratory simulations were conducted using PPS and filter drains to further analyse the accuracy of *MicroDrainage*® (section 3.7.3). Similar to the field method used for Hamilton, different rainfall simulations were measured and then re-created in *MicroDrainage*®. Both the NSE and coefficient of determination were again used.

4.4.2.1: Validation of porous pavement

The PPS block was measured with five different rainfall intensities simulated. The site was scaled up to provide comparison with *MicroDrainage*® as flows from the test rig were considerably smaller than could be achieved in the model (section 3.7.3.5).

Figure 4-13 demonstrates the accuracy with which *MicroDrainage®* predicted outflow for the rigs (a section of the raw data is also presented in Table 4-14 and Appendix D). The recorded laboratory data was the amount of outflow captured during the 1 minute period, compared to the model data for the same period. An NSE of 0.94 was an improvement, in comparison to the Hamilton data, therefore demonstrating the benefits of modelling at the laboratory scale. The results compared favourably with previous research by Principato *et al*. (2015) who modelled runoff from green roofs, calculating an NSE of 0.59 over a 9-month period using SWMM, and Burszta-Adamiak & Mrowiec (2013) who generated a negative NSE, indicating little or no correlation using green roofs and the same software.

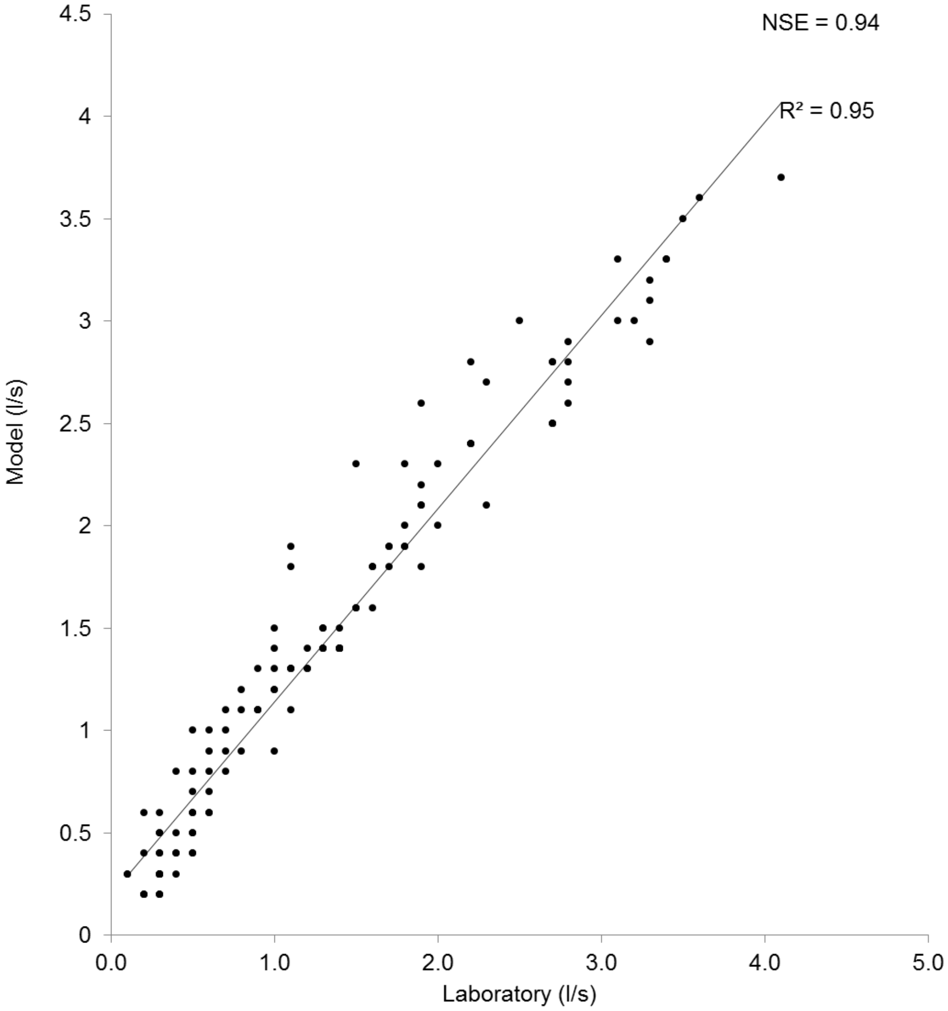


Figure 4-13 Validation of MicroDrainage®, comparing model and PPS laboratory data (n=131).

Table 4-14 One set of laboratory (n=1) and model (n=1) flow data (l/s) for the PPS rigs (Appendix D for full dataset)

	10mins @ 1.2 l/min	
Minutes	**Lab**	**Model**
1	-	-
2	0.6	1
3	1	1.4
4	1.8	1.9
5	2.2	2.4
6	3.3	2.9
7	3.4	3.3
8	3.5	3.5
9	3.6	3.6
10	4.1	3.7
11	3.1	3.3
12	2.5	3
13	1.9	2.6
14	1.5	2.3
15	1.1	1.8
16	0.9	1.3
17	0.6	0.8
18	0.5	0.7
19	0.5	0.6
20	0.3	0.5
21	0.3	0.4
22	0.3	0.2
23	0.2	0.1
24	-	-

4.4.2.2: Filter Drains

Although filter drains were not incorporated into the SuDS management train analysed in aim 1 of the research, a validation using the method provided further evidence of the accuracy of *MicroDrainage®* for predicting runoff. Five events of different storm duration and intensity were measured and replicated in *MicroDrainage®*, with the total outflow from the system captured at minute time-steps (Table 4-15 and Appendix D). The NSE of 0.98 plus an r^2 of 0.99 (Figure 4-14) and with previous data (section 4.4.2.1) demonstrated that *MicroDrainage®* was an extremely accurate tool in this research for predicting flow from both a single SuDS device, as well as when combined as part of a wider management train. Therefore not only are the findings of aim 1 appropriate, but the DST created through aim 2 of the research also has wider applicability.

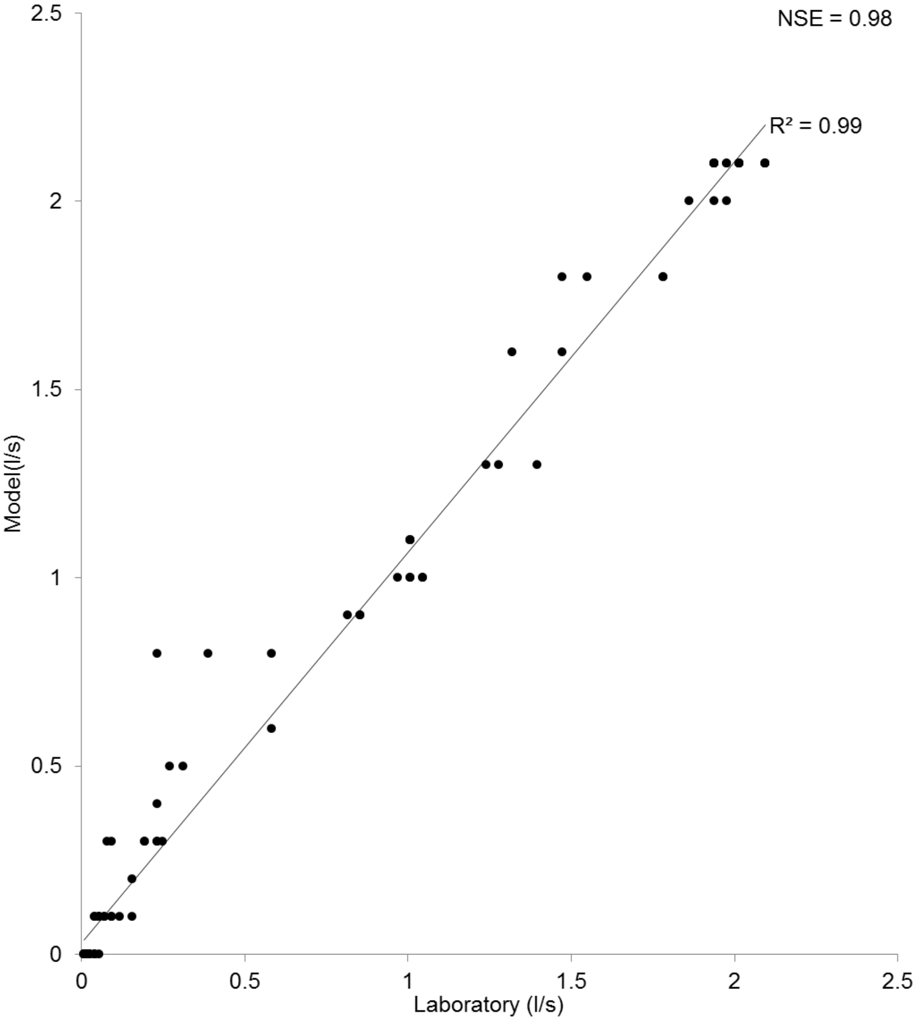


Figure 4-14 Validation comparing model and filter drain laboratory data (n=99).

Table 4-15 One set of laboratory (n=1) and model (n=1) flow data (l/s) for the filter drain rigs (Appendix D for full dataset)

	5mins @ 0.4 l/min	
Minutes	**Lab**	**Model**
0	0	0
1	0.1	0.1
2	0.6	0.6
3	0.9	0.9
4	1	1
5	1	1
6	0.6	0.8
7	0.2	0.3
8	0.1	0.1
9	0.1	0.1
10	-	-

4.5: Conclusion

This chapter has presented the major findings of the research, which were split into three sections: aim 1 related to the effectiveness of different devices to reduce runoff, aim 2 involved creating a DST, whilst aim 3 was a validation of *MicroDrainage*® to determine the accuracy of the results.

The site analysis at all rainfall and infiltration scenarios demonstrated the benefit of detention basins with regards to peak flow reduction. However further analysis of the effect per m^3 led to the conclusion that this was due to the size of the basins used. PPS was more effective per m^3 than all other devices modelled, and was extremely effective at reducing total runoff volume, which was a critical component when evaluating the impact of SuDS. Integrating any SuDS component consistently presented a benefit for the parameters analysed in section 4.2, when compared to both the conventional system and pipes (all swales converted to pipes).

The second part of the research related to the creation of a DST. *MicroDrainage*® was used to complete site and SuDS model parameter analysis, with regression statistics and a prediction based on rainfall depth, infiltration, site size and the number of SuDS. This was possible due to the strong correlations achieved between each site and SuDS parameter and runoff enabling a maximum and minimum prediction of the likely peak flow for these parameters, at the 99% confidence level. The purpose of the DST was to inform stakeholders who integrated SuDS into their design and shorten their decision making time by providing a rapid analysis for the total number of pre-determined devices (using the method provided by Warwick 2013) required to achieve greenfield runoff by evaluating the effectiveness of the water quantity management of each device. These proposals could then be applied in *MicroDrainage®* without the need for designing and simulating several different sites that used multiple combinations and volumes of SuDS to achieve greenfield runoff. An evaluation of the accuracy of the DST was also completed. However, due to lack of compatibility for rainfall data at Lamb Drove, Cambridgeshire (Cambridgeshire County Council 2012) this was not possible, therefore the model created for aim 3 at Hamilton was used. This subsequently also failed as the Hamilton site flooded as a result of the 1 in 100 year 360 minute storm and whilst the simulated runoff in *MicroDrainage®* was short of that suggested by the DST, the flooding skewed the data and provided uncertainty in the results.

The final component of the research was the validation of *MicroDrainage®*. Comparing the model output to field data and laboratory data enabled an analysis of how accurately the model could predict runoff. The NSE was used as the primary method for hydrological model validation, and calculated a correlation between field data at Hamilton and *MicroDrainage®* of 0.88. Previous large scale research (Dotto *et al.* 2011; Gaborit *et al.* 2013; Petrucci *et al.* 2012) produced NSEs ranging from 0.59-0.91, depending on the model used, therefore highlighting the strength of the correlation for *MicroDrainage®*. To further emphasise the accuracy of the program, additional laboratory tests were completed for both PPS and filter drains, as modelling single devices reduced the uncertainties associated with the larger Hamilton site. The PPS validation produced an NSE of 0.94, an improvement on the field data validation, demonstrating the accuracy of *MicroDrainage®*. Furthermore, the filter drain tests also produced an extremely strong NSE of 0.98. Research at a similar scale (Burszta-Adamiak & Mrowiec 2013; Principato *et al.* 2015) produced NSEs ranging from negative values to 0.59. Analysing all three model validation runs suggests that *MicroDrainage®* was an extremely effective tool at predicting runoff, therefore gave a strong level of confidence for both the findings from aim 1 and the DST. Additionally, indicating the accuracy of *MicroDrainage®* to predict runoff would give stakeholders more confidence when designing sites using the UK industry standard model as a validation of *MicroDrainage®* was not widely available in research.

Overall, the findings of the research provided further vindication for using SuDS to reduce excess water quantity. The next chapter puts the findings into a wider context, by analysing the outputs of the research.

5 Discussion

5.1: Introduction

This chapter reviews the results of chapter 4 in the context of the aims and objectives stated in chapter 1. The findings will be discussed, contextualised using the literature, to highlight the benefits of utilising specific devices in a management train (aim 1), the outcome of the DST (aim 2) and the accuracy of the UK industry standard drainage tool; *MicroDrainage®* (aim 3). Objectives 1a, 3a and 3b were addressed in chapter 4. This chapter will discuss the remaining objectives; 1b, 1c, 2a, 2b and 3c, and will address each of the three aims in turn.

5.2 Aim 1: Deconstruct a SuDS management train

Deconstructing the initial SuDS management train that included detention basins, green roofs, porous paving and swales provided an understanding of how different devices worked in *MicroDrainage®* when combined with other SuDS. As land cost is at a premium in urban developments, and the price of installing devices on land that could be used as housing is typically cited as a barrier to further SuDS development (Bastien *et al*. 2010), determining the most effectives devices for runoff reduction is paramount. Water quantity therefore forms a key component of the SuDS square (Figure 2-3). In the context of a changing climate and the stresses placed on existing conventional drainage from urbanisation (section 2.2 and section 2.3), quantifying the most efficient method for sustainable flood management is critical. Although previous research has defined the impact of each device individually (Fach *et al*. 2011; Vollertsen *et al.* 2009; Scholz & Grabowiecki 2007; Berndtsson 2010), this has not been undertaken for water quantity in the context of a whole in-service SuDS management train. As part of STTAT (section 2.17.1), Jefferies *et al*. (2009) defined the relative role of different components, both standalone and combined in a treatment train, regarding their ability to enhance water quality. Comparing the outputs of Jefferies *et al*. (2009) and other similar research (section 2.7), with focus on the remaining components of the SuDS square (Figure 2-3) provides a conclusive assessment of the benefits that can be achieved by using different SuDS.

The devices selected were those deemed highly effective at reducing runoff in the SuDS manual (Woods Ballard *et al*. 2007), therefore dry detention basins were used instead of ponds to provide added runoff reduction as ponds typically contain a volume of standing water, consequently their ability to retain water is reduced. Additionally there is a drowning implication with wet ponds, hence dry detention basins were favoured (Apostolaki, Jefferies & Wild 2006). Analysing the data for SuDS management trains across England and Wales (Table 2-3) gave further information in support of the choice of devices used in the study. Swales were used in the majority of SuDS management trains studied. Of the twenty case studies, only the Bognor Regis Community Centre did not use them for conveyance, choosing infiltration trenches instead. Detention basins were the more common site control device and the second most commonly implemented method overall. PPS was used at twelve of the twenty sites for source control, considerably more than green roofs. Although green roofs only featured on two of the twenty management trains, as they can be installed at all new housing sites with no additional land take, their integration in a management train was seen as necessary to provide additional flood management (Stovin 2010).

Simulating each device in a full management train, then removing different components and deconstructing them enabled an understanding of how they interacted and which ones should be given precedence during the planning and design stage for drainage.

5.2.1 Objective 1b: De-constructing the SuDS management train

Research has established that a SuDS management train has significant potential for improving water quality, so much so that they are often termed *treatment* trains (Jefferies *et al*. 2009) (Section 2.7.1). This was based on the principle that more interlinked devices provided added resilience (Bastien *et al*. 2010). There is limited research on the extent of the benefits in terms of *water quantity* (section 2.5.1). It has been found that detention basins, green roofs, PPS and swales can all contribute to runoff reduction (Del Giudice *et al*. 2014; Fioretti *et al*. 2010; Scholz & Grabowiecki 2007; Woods Ballard *et al.* 2015). Nevertheless, there was a gap in knowledge regarding how effective they can be in combination. Chapter 4 highlighted the benefits that could be achieved in terms of peak flow reduction, time to peak, overall volume reduction and baseflow in comparison to pipe based drainage. The following sections therefore discuss these components in terms of the wider literature and how different SuDS interact, reducing the likelihood of flooding. It will also define how water quantity management fits into the wider components of the SuDS square (Figure 2-3) and links to existing research regarding water quality and amenity.

Each analysis was completed for the 1 in 100 year event, with rainfall durations modelled to analyse how each combination responded to different intensity events. An additional 30% was added to the rainfall simulation to allow for climate change (EA 2009), however new guidance values have subsequently been issued to account for the regional variability of the impact of climate change on rainfall (EA 2016b). Nevertheless, the new central allowance values for events up to 2080 range from 20% - 35%, therefore using 30% still remains a reasonable allowance for climate change.

5.2.1.1 Peak flow & reduction in comparison to conventional drainage

The SuDS square consists of four equally weighted components to represent the role of SuDS in the environment (Woods Ballard *et al*. 2015; Figure 2-3). Nonetheless, both The Standards (DEFRA 2015a) and stakeholders are more concerned about the reduction in runoff that can be generated through using SuDS rather than amenity, biodiversity and water quality implications, likely to be due to the influence of NPPF (DCLG 2012) and the focus on flooding. This was highlighted in The Standards (DEFRA 2015a) whereby the terms “water quality” and “amenity” were not used, with future management trains being measured on their ability to control peak runoff to greenfield values. For this reason analysing peak discharge was seen as a critical factor in determining the benefits of different combinations of SuDS.

Although previous research has discussed the role of individual SuDS and the role that combining devices can have on improving water quality (section 2.7.1), this research demonstrated the ability of a SuDS management train to reduce peak flows in comparison to pipe based drainage. Table 4-1 to Table 4-3 showed that conventional drainage and pipe systems produced the largest peak flows. This was due to the efficiency of conventional drainage by rapidly removing water from the urban environment to the water course and utilising closed channels that prevent both infiltration and evaporation therefore inhibiting runoff reduction (Jones & Macdonald 2007; Semadeni-Davies *et al*. 2008). However through the installation of a simulated SuDS management train consisting of green roofs, PPS, swales and detention basins, modelled peak flow reduced by up to 92% after the 30 minute winter storm and nearly 71% for the critical 360 minute storm (DEFRA 2015a) at a low infiltration scenario. This fell to 70% compared to conventional drainage (79.7 l/s – 76.8 l/s) for a high infiltration scenario, demonstrating the reduced impact of SuDS at high infiltration. For a low infiltration scenario, SuDS stored large volumes of runoff, with infiltration achieved with PPS (Scholz & Grabowiecki 2007). However, for high infiltration areas, the whole site had the possibility for infiltration, therefore peak flows were lower, which marginally reduced the impact of SuDS in comparison to conventional drainage. Ultimately, this suggested that SuDS should be prioritised where the ability to infiltrate is low, as they enhanced the infiltration potential of a site.

All scenarios show that incorporating detention basins into the design had the greatest impact at reducing peak flows, although their influence reduced as rainfall intensity decreased, which had not been explicitly identified previously. Detention basins can store large volumes of runoff and regulate the amount released to the remainder of the management train, controlling high peak flow (Ravazzani *et al*. 2014). 6059 m^3 of detention basins were designed into the test site, nearly four times that of PPS, therefore the volume of modelled detention basins distorted their effectiveness, which was less effective per m^3 than PPS. The detention basins reduced the impact of other devices due to the large volume and storage potential, as the least effective combination including detention basins was with swales which produced 31.3 l/s less runoff than the most effective management train without detention basins. This confirmed the literature (Doubleday *et al.* 2013; Woods Ballard *et al*. 2007) that suggested detention basins were essential for their peak flow reduction benefits. On the other hand, detention basins were typically incorporated into the open land of a site, which was not usually the case for other SuDS devices such as green roofs. As the basins were dry and only filled during large storm events, they could have wider social benefits such as being utilised as a sports pitch, assuming they are maintained correctly (Semadeni-Davies *et al*. 2008; SNIFFER 2006).

Comparing different combined source control devices was novel as previous research has focused on either green roofs or PPS, as opposed to how combining the devices impacted overall runoff (Scholz & Grabowiecki 2007; Berndtsson 2010), however the reduction in peak flow achieved for both source control devices varied considerably. Stovin (2010) showed the benefit of incorporating green roofs into a design, suggesting about 57% reduction in peak runoff could be achieved. The study investigated a single roof only, therefore based on the simulations using *MicroDrainage®* this seemed unrealistic when combining devices in a larger management train. When used simply alongside swales, green roofs reduced peak flow by 9.1 l/s to 8.3 l/s, depending on the infiltration scenario for the 360 minute event. However only a 0.7 l/s to 0.8 l/s reduction was achieved when green roofs were combined with swales and PPS. Although the potential flow reduction from green roofs was minimal, they present additional water quality, amenity and biodiversity benefits for a site (Woods Ballard *et al*. 2015) and were also installed on underutilised space, with runoff in a conventional system entering the housing gutters and being transported into a nearby drain.

Each PPS was 450 mm deep per British Standard Institution (2009) and reduced peak outflow by promoting infiltration and storing a small amount of water. The device had the greatest impact on reducing runoff when not combined with detention basins, when they were the primary method of runoff reduction. Although the findings confirmed the study by Imran, Akib & Karim (2013), who concluded that PPS was an integral component for stormwater management, their impact greatly reduced when combined with detention basins. As detention basins significantly reduced peak flow, their impact negated much of the peak flow benefits achieved by PPS, dampening their effect on runoff reduction. Nonetheless PPS were still effective, reducing peak runoff considerably in comparison with both green roofs and swales. This therefore suggested that PPS should be designated a high priority source control device in a SuDS management train, whilst acknowledging that their relative impacts would be reduced when combined with detention basins. PPS also had multiple site uses, for example, traditional paved driveways and roads can be made permeable (Scholz & Grabowiecki 2007). This therefore added further weight to the benefit of integrating PPS for future management trains to further reduce runoff at the site (Imran, Akib & Karim 2013).

The role of swales for reducing peak flow was also modelled, with Woods Ballard *et al*. (2015) suggesting that swales had a “low” capacity for peak flow reduction and were limited to conveyance. The simulations across each of the rainfall intensities demonstrated that by using just swales, a reduction in peak flows compared to a traditional pipe based system was possible, although not as much as when other devices were added. However when converting all swales to pipes and re-running the simulations, peak outflow decreased, producing only a marginal difference between the two systems. Additionally, the pipe system was the only simulation that resulted in flooding, which occurred as a result of the 30 minute intense storm. As swales promoted some infiltration, they also provide water quality improvements. Swales also provided a much greater amenity and biodiversity benefit. Although the findings further confirmed previous research that demonstrated the relatively limited capability of swales for reducing flooding (Liao *et al*. 2013), it highlighted their importance as a method for linking devices through conveyance. They have traditionally been developed on open land that could potentially take up space for additional housing. However, swales should be used to convey runoff wherever possible, primarily incorporated alongside roads, next to pavements and pathways (Bäckström, Viklander & Malmqvist 2006). Incorporating swales in this way can reduce runoff but also improve water quality and enhance amenity by utilising space that was previously impermeable.

Although peak flow was important in contributing to pluvial flooding, there were a number of additional factors explored in chapter 4. The time runoff took to reach peak flow was also a key element in exploring the level of runoff reduction that was possible.

5.2.1.2 Time to Peak

Although not discussed as a key factor in implementing SuDS in The Standards (DEFRA 2015a), the time to reach peak was a critical component of the storm hydrograph. The purpose of incorporating SuDS into a design was to increase the time to peak in comparison to conventional drainage. Storing water increased the potential for infiltration and evaporation, subsequently reducing total volumes and flows associated with pluvial flooding (Newton *et al*. 2014). This was consistent with Woods Ballard *et al*. (2015) who advocated that detention basins, for example, considerably increased time to peak. Analysing the influence of different combined SuDS as a result of changing rainfall intensities was novel since previous studies had not explored this; it had previously been assumed that for all intensities SuDS would increase time to peak (Jumadar *et al*. 2008; Nawaz, McDonald & Postoyko 2015; SNIFFER 2004).

A primary method for increasing the time to peak was to detain water (Del Giudice *et al*. 2014), which was confirmed by the data presented in section 4.2.2.3. All configurations that incorporated detention basins considerably increased the time to peak in both medium and low intensity rainfall scenarios. Detention basins acted as large tanks that stored water that was slowly released to the remainder of the site, typically limiting flow according to the capabilities of the device (Park *et al*. 2012). The limited impact as a result of high intensity short duration events is a novel finding and was not reflected in the literature which assumed the impact would be consistent for all rainfall scenarios. For events of a similar intensity, Shahpure *et al.* (2011) simulated a likely time to peak consistent with the findings of this research, however the storm duration and site size were not discussed. It was likely that the peak was reached quickly for the high intensity event due to the short duration of rainfall, therefore limiting the potential for variability in time to peak.

The majority of arrangements without detention basins had a similar time to peak as the conventional and pipe systems, although some combinations were quicker or achieved peak flow at the same time as the conventional system. This was inconsistent with much of the literature which suggested that SuDS would always increase the time to reach peak, by retaining runoff (Miller *et al.* 2014; Suriya & Mudgal 2012; Woods Ballard *et al*. 2015). Although time to peak was similar for conventional drainage and the majority of SuDS management trains, the actual peak was considerably reduced, therefore the similar time to peak was likely to be a result of reduced peak flow through integrating SuDS as opposed to conventional drainage. Furthermore, the primary purpose of detention basins was to have a large storage capacity for runoff, unlike the other devices modelled, as both PPS and green roofs had a relatively reduced storage capacity in comparison. Moreover, the primary role of the swales was conveyance hence little was captured and stored in the device.

The findings contradict the perceived understanding of the role that SuDS play in reducing time to peak, as it has previously been assumed that SuDS increased time to peak. Figure 4-2 to Figure 4-4 suggested that a limited increase in the time to peak could be achieved from using combinations without detention basins. However it was shown that although the time to peak increased, more importantly, *peak flow* was greatly decreased in comparison to conventional drainage. Ultimately, it took a similar time to achieve a greatly reduced flow.

5.2.1.3 Time to baseflow

Time to return to baseflow measured the amount of time water was retained in the system and is an under-researched component in flood management. The simulations in chapter 4 demonstrated that all combinations of SuDS increased the time to baseflow, no matter the rainfall intensity or infiltration rate. For the optimum 360 minute event, the time increased by over an hour compared to conventional drainage, for all scenarios with more than one SuDS device. Increasing time to baseflow resulted in a reduced peak flow and potentially a reduced volume, as water was contained in the system for longer, enabling infiltration and/or evaporation (Woods Ballard *et al*. 2015).

Detention basins were the most effective method for increasing the time to return to baseflow, nearly 900 minutes more than conventional drainage. Although they had reduced capacity for infiltration in comparison to PPS, as shown by the larger total volume data (5.2.1.4), they were still capable of holding back large stores of water. Although much of the literature explored the role of detention basins in reducing peak flows, the focus was on detention basins and flood management (Del Giudice *et al*. 2014; Emerson, Welty & Traver 2005; Ravazzini *et al*. 2014), rather than their impact when linked with different SuDS devices.

Time to return to baseflow also increased for all combinations incorporating PPS, which encouraged infiltration as a priority in comparison with the other devices measured. Runoff was retained in the system until it was saturated, forcing it to continue to flow through the remainder of the management train. However the role of both detention basins and PPS together in limiting runoff when combined in a management train has not previously been addressed in the literature (Boogard *et al*. 2014; Hassani, Mohammad & Ghoddusi 2010; Scholz & Grabowiecki 2007). Green roofs were capable of delaying runoff and increasing the time runoff takes to return to baseflow due to their ability to store and capture runoff (Poë, Stovin & Berretta 2015). Nevertheless, like previous characteristics (peak and time to peak) when combined with PPS their impact reduced. As PPS had such a large role in retaining runoff and increasing the time to return to baseflow, it limited the impact of green roofs.

5.2.1.4 Volume

Although not addressed in decision-making processes by The Standards (DEFRA 2015a), the potential total volume reduction that could be achieved by using SuDS was critical in reducing the likelihood of flooding (Ellis & Viavattene 2014; Berndtsson 2010). The literature typically suggested that integrating green infrastructure reduced flow volumes, however an analysis as to what extent has not been undertaken before. The findings of this study also demonstrated the impact on runoff of different linked SuDS, which has previously not been explored.

The benchmark comparison across all scenarios was the performance of conventional drainage systems which, due to the nature of pipes, inhibits infiltration and evaporation, the two main causes of volume reduction (Elliot & Trowsdale 2007). Across all scenarios the total volume of water leaving the management train reduced after the addition of any SuDS device. Including swales in the model reduced runoff by between 130,158 l – 115, 020 l, depending on infiltration scenario, for the 360 minute storm. Therefore when comparing each device in the model, swales were more effective for total volume reduction than both green roofs and detention basins, which contradicted Liao *et al*. (2013), who found that swales had a minimal role in flood management.

It has been shown that the role of green roofs in volume reduction reduced as more devices were added. They consistently reduced the volume of water leaving the site when compared to systems without the device for both medium and low intensity rainfall events as they were able to capture rainfall at the source, which could subsequently evaporate out of the system (Chen 2013). However for the high intensity 30 minute scenario, combining green roofs with PPS increased the total volume leaving the site, which has not previously been analysed in the literature. Although it was likely a result of an increase in intensity increasing runoff, it provided uncertainty with the data and therefore the need to validate *MicroDrainage*®. Stovin (2010) suggested that green roofs could reduce total volume by 57%. The findings of the current study also suggested that green roofs would reduce the volume, so was possible that in a standalone scenario a similar reduction to that attained by Stovin (2010) could be achieved, particularly for the less intense storms. However due to their limited storage capacity and the high return scenario of the modelled storms, it was likely that their capacity was exceeded and their effects overtaken by PPS, which had a much greater potential for storage and infiltration.

The effectiveness of PPS in comparison to other devices was not covered in the literature, however this study showed that PPS consistently reduced total volume for all intensity and infiltration scenarios by storing, detaining and infiltrating runoff. For total volume reduction, arguably a critical component for both on-site and downstream flooding, PPS was fundamental and should be given precedence over other methods. Although all management trains produced substantial runoff reductions in comparison to conventional systems, designs which combined PPS had an increased impact, for example when combined with green roofs, the reduction in volume was further decreased. Green roofs provided additional source control storage, and whilst not as effective as PPS, supported the findings of Stovin (2010) and Voyde, Fassman & Simcock (2010).

In terms of impact on volume, detention basins had the least impact of all SuDS device, for example when not combined with PPS the total volume increased, suggesting that detention basins were ineffective at reducing large flows. This confirmed findings by Emerson *et al*. (2005) and McCuen & Moglen (1988) who suggested that the device had little impact on reducing runoff volumes and under some scenarios actually increased it. Although detention basins performed well for all other measured parameters, reducing the total volume of runoff to leave the site was critical to ensure flood reduction (Woods Ballard *et al*. 2015). This was possibly a result of a small wetted perimeter; the device acted as a tank, allowing less water to infiltrate in comparison with, for example, longer, shallower swales. The large outflows associated with detention basins presented a significant issue for areas downstream, therefore detention basins should not be used alone.

5.2.1.5 Water quantity and the SuDS Square

Water quantity is one aspect of the wider SuDS square (Figure 2-3). As discussed at the start of section 5.2, industry and policy tends to focus on flood management, however ideally all four aspects (water quality, water quantity, amenity and biodiversity) should be of equal importance. The role of SuDS in a treatment train to improve water quality is provided in section 2.7.1.

The outputs of objective 1b demonstrate the influence of SuDS in comparison to conventional drainage, regarding total runoff peaks. This replicated the assessment of water quality by Ellis, Revitt & Lundy (2012) that by integrating any SuDS improved outflow quality and Woods Ballard *et al*. (2015) who defined all of the modelled SuDS as enhancing amenity and biodiversity compared to piped drainage. However the relative effectiveness of different SuDS differs and therefore needs to be fully understood to demonstrate the capabilities in the context of the whole SuDS square. Of the studied runoff characteristics, detention basins were most effective at reducing peak flow, time to peak and time to baseflow, with PPS most effective at reducing volume. However the most effective overall combination was including all modelled devices. Although Bastien *et al*. (2011) modelled different devices, they also concluded that combining the maximum available SuDS was the most effective at reducing TSS, achieving a 95% reduction. Comparing devices modelled as part of this research, swales were capable of reducing 87% of TSS in comparison to 68% by detention basins.

A similar conclusion was drawn by Ellis, Revitt & Lundy (2012) where swales were marginally more effective than detention basins, however PPS was nearly twice as effective for all monitored water quality parameters (TSS, hydrocarbon, organic pollution, heavy metals). They concluded that green roofs were the least effective for all variables, apart from organic pollution mitigation, in comparison to the other devices. This contradicts the findings of Jefferies *et al*. (2009) whereby PPS was given a low classification, similar to that of swales and detention basins (green roofs were not analysed), and a combination of swales and detention basins afforded the same mitigation potential as PPS and detention basins.

Concerning the amenity impact of each of the modelled devices, Woods Ballard *et al.* (2015) states they all enhance amenity and biodiversity in comparison to existing conventional drainage, however the impact of PPS is limited. As PPS are traditionally not green space, their aesthetic potential is reduced in comparison to green roofs, detention basins and swales. Nonetheless, Woods Ballard *et al.* (2015) discuss the potential multi-use space offered by integrating PPS, as they can be used for a range of different purposes. In terms of amenity potential, green roofs are afforded a higher ranking than both detention basins and swales as they have a reduced land take and assuming a reasonable level of maintenance they increase aesthetics. Both swales and detention basins are classified as having “good” amenity potential by Woods Ballard *et al.* 2015. Swales can be incorporated alongside roads to provide increased aesthetics whilst detention basins, assuming they are dry, have several multiple benefits, such as being used for sports pitches (Semadeni-Davies *et al.* 2008; SNIFFER 2006).

Whilst objective 1b defined detention basins and PPS as the most effective devices studied for runoff reduction, they have differing capabilities regarding the wider SuDS square. Ellis, Revitt & Lundy (2012) suggest that PPS is the most effective device for improving water quality and provides a basic level of amenity (Woods Ballard *et al.* 2015). Detention basins have a high level of water quantity reduction and provide several site amenity and biodiversity benefits, assuming the basin is designed for multiple uses, however have only moderate effectiveness at improving water quality (Bastien *et* al. 2011; Jefferies *et al.* 2009). Whilst green roofs and swales provided minimal reduction of runoff, they were both capable of improving water quality, although green roofs were less effective (Ellis, Revitt & Lundy 2012) but both had a high amenity potential. All of the factors need to be quantified to ensure that each aspect of the SuDS square is considered when analysing the relative effectiveness of each device.

5.2.2: Objective 1c: impact per m^3 and m^2 of device on runoff.

Although objective 1b analysed the effectiveness of different SuDS devices in terms of different parameters for flood risk management, it was possible that the results could have been influenced by the number of devices used in the management train. The reduction in runoff per m^3 and m^2 of each device was therefore calculated to further understand the link between devices, and their potential to impact runoff reduction. Previous studies have not standardised the impact on runoff of different linked devices per m^3 and m^2. This also provided practitioners with information regarding the most important devices for future developments, by highlighting the most effective SuDS. Whilst much of the research focused on new-build developments, the prioritisation of space and the impact per m^3 and m^2 of different devices is pertinent for retrofit installations (section 2.8.6). Although space is at a premium in new-build sites, maximising space is even more critical when redesigning urban areas, therefore ensuring the most effective devices are identified is vital (Stovin *et al*. 2013).

The novel analysis calculated that in terms of the potential runoff reduction in m^3/l/s, PPS was the most effective device for each infiltration scenario, even taking into account a slightly reduced effectiveness during high infiltration scenarios (section 5.2.1). Detention basins proved to be the most effective for each measured hydrograph parameter (section 4.2.2 to section 4.2.5), apart from volume reduction, due to their size. Four times as much total space (m^3) was utilised by detention basins compared to PPS, the second most widely used device. However the impact of PPS reduced for the analysis of m^2/l/s as they had larger modelled surface area than all other analysed devices, aside from green roofs. As detention basins were much deeper than other devices modelled, although the volume increased, the land take (m^2) was relatively modest (section 3.5.1). Therefore detention basins were nearly twice as effective per m^2/l/s than PPS. Both analysis shows the need to prioritise PPS and detention basins in addressing runoff, supporting research by Scholz & Grabowiecki (2007) and Woods Ballard *et al*. (2015) who endorsed both as a highly effective flood management tools.

As PPS was used instead of traditional impermeable surfaces, it was unlikely to take up potential green space or space for housing, therefore more likely to be adopted by stakeholders as it provides multiple uses, and therefore amenity benefits (Woods Ballard *et al*. 2015). With regards the wider SuDS square, PPS is also capable of greatly improving outflow water quality (Ellis, Revitt & Lundy 2012) therefore further presenting the total potential benefits for integrating PPS in water management. Although not as effective as PPS, detention basins are also capable of improving water quality (Ellis, Revitt & Lundy 2012) and when integrated as an online function, their ability increases further (Jefferies *et al*. 2009). However their role as either an online or offline device influences their amenity potential. Whilst they provide improved aesthetics and green space, their potential increases when designed as an offline tool as they retain multiple benefits, such as sports pitches. This is not as likely if they are an online tool as they will be more regularly utilised (Woods Ballard *et al*. 2015). Incorporating PPS as the primary source control device, and detention basins as the primary site control device enables a high potential for runoff reduction, particularly in relation to land take, but also achieves amenity, biodiversity and water quality benefits.

Although the total volume of green roofs was less than other devices used, their surface area (10,170 m^2) was nearly three times greater than PPS (3,380 m^2), the next largest, enabling more runoff to be captured or passed through the system. Whilst the effectiveness of green roofs was relatively limited, roofs are typically under-utilised in runoff management with developers preferring traditional tiled roofs since green roofs require additional structural reinforcements (Gordon-Walker, Harle & Naismith 2007); this, and their limited impact per m^3 and m^2, makes the device a potentially costly installation for retrofitting at existing sites. Although Stovin (2010) suggested a potential reduction of up to 57%, this was unlikely to be achieved for a high intensity 1 in 100 year return event, as the storage capacity was limited and the ability to retain runoff was determined by the infiltration rate (van Woert *et al*. 2005). For this reason, PPS was a more effective source control system, and should be prioritised over green roofs whose impact was generally limited in larger management trains (Burszta-Adamiak & Mrowiec 2013). Furthermore PPS could be integrated more effectively into existing urban areas as a phased approach to replacing current impermeable paving (Scholz & Uzomah 2013).

However, linking back to the SuDS square (Figure 2-3), although green roofs are less effective as a device for flood management, they can greatly increase the amenity and biodiversity benefits of a site (Woods Ballard *et al*. 2015). Whilst their impact on water quality is also limited (Ellis, Revitt & Lundy 2012), similar to their impact on water quantity, they present a more effective method than the current alternative; a simple tiled roof, which provides no flood management nor does it improve water quality. The wider SuDS rocket (Figure 2-2b) highlights further benefits that can also be achieved through integrating SuDS. Green roofs are capable of cooling urban areas, reducing the impact of the urban heat island effect and providing carbon sequestration (Charlesworth 2010). Therefore, although green roofs are less effective than other SuDS at reducing water quantity and improving water quality, they are capable of achieving wider benefits. For this reason, the site requirements must be scrutinised before integrating green roofs into design.

Green roofs can be considered at new build sites during the early phases of design, with buildings suitably designed to accommodate the increased potential load. This would provide benefits with regards the SuDS square beyond existing tiled methods. Retrofit design presents more problems; there is a cost implication regarding structural reinforcement of buildings to accommodate increased loading from green roofs. Therefore if the desire is to provide flood management or improve water quality, other more cost-effective measured should be considered. However, if the need is for increased amenity or to achieve the factors considered by the SuDs rocket (Figure 2-2b), green roofs are a suitable option for stormwater management.

Swales were marginally more effective than green roofs (0.007 m^2/l/s compared to 0.001 m^2/l/s) in reducing runoff, as shown consistently across all infiltration scenarios. Nevertheless, they were the primary method for conveying runoff and therefore played an integral role in the management train (Allen *et al*. 2015). Although their effectiveness was tied to the infiltration potential of a site (Fach *et al*. 2011), reductions in peak flow, when compared to pipe based systems provided benefits for flood risk management.

Effective design of swales at a site could also maximised space, as swales are often designed in open space that could have additional use, such as housing, or public open space (Dierkes *et al*. 2005). Regarding the impact of swales in relation to the SuDS square (Figure 2-3), designing them alongside roads enables conveyance of runoff and utilises land typically used by impermeable surfaces, therefore increasing the amenity and biodiversity of a site (Bäckström, Viklander & Malmqvist 2006). Although not as effective as other SuDS, swales are capable of slowing down runoff and trapping pollutants, therefore improving outflow quality. Therefore the effective design of swales would not only reduce runoff, but provide amenity, biodiversity and water quality benefits, in line with the SuDS square.

5.2.3 Aim 1: Breaking the barriers for SuDS

SuDS management trains have been used for stormwater management in the UK (Table 2-3) however Table 2-2 lists a number of barriers that exist which inhibit their wider implementation. The outputs from aim 1, discussed in sections 5.2.1 and 5.2.2 reduce the perceived barriers to SuDS and promote their effectiveness at reducing runoff.

Table 2-2 suggests that a typical barrier to SuDS is that they are a relatively untried technology, however examples of case study sites for SuDS management trains were presented in Table 2-3. This research has aimed to further quantify the impact of integrating different SuDS, to ensure that future SuDS developments utilise the most effective devices, whether the requirements are flood management, water quality improvement or overall amenity. This ensures the future success of installations. The outputs of this research show the benefits for installing PPS at source control level, particularly in relation to total volume reduction, and detention basins at the site level, in relation to peak flow reduction. Outlining the relative success of the devices modelled as part of the research provides industry guidance on how to build SuDS and offers initial coordination regarding which devices to use; both of which were defined as further barriers highlighted in Table 2-2.

The outputs of the research have been contextualised using additional supporting literature to demonstrate the role of all four modelled devices with regards each aspect of the SuDS square. This therefore outlines the necessity for SuDS to be better integrated into water management policy in England and Wales. Although green roofs have a high amenity and biodiversity potential (Woods Ballard *et al*. 2015), if water quantity or water quality (Ellis, Revitt & Lundy 2012) are of primary concern, green roofs have limited success, particularly at retrofit locations due to the cost associated with reinforcing buildings to manage load capacity. However assuming swales are designed effectively, they are capable of achieving all four aspects of the SuDS square in comparison to typical conventional drainage. Both PPS and detention basins are capable of effectively reducing runoff quantity and improving water quality, whilst provide some capacity for amenity and biodiversity, although this is reduced for PPS. Therefore the results establish the capabilities of each of the modelled SuDS devices, reducing the barriers for their uptake by demonstrating the benefits that can be achieved when combined in a SuDS management train.

5.2.3 Aim 1 Conclusion

The deconstruction of the management train across a range of key parameters provided insight into the effectiveness of different devices when integrated with others, providing developers with more detail of which devices to use at a site, or which to prioritise. In terms of both peak runoff reduction and volume reduction, green roofs reduced both factors when modelled as the lone source control device. However, PPS was more effective for source control, performing better on all measured variables and per m^3 and m^2 than green roofs. While detention basins reduced peak flows, their role in reducing overall volume was limited and in some scenarios had a detrimental impact on volume. Furthermore, their role per m^3 was lower than PPS, however was better per m^2. Whilst detention basins had wider amenity benefits as recreational land, cost was often a controlling factor, whereas both PPS and green roofs would not take up additional land as driveways could be made permeable and houses built to facilitate green roofs. In addition, PPS was more effective at improving water quality, in comparison to both green roofs and detention basins (Ellis, Revitt & Lundy 2012), therefore making the device potentially more desirable.

To determine the accuracy of the findings, a field validation (aim 3) was completed, as this had never been undertaken for *MicroDrainage*® (section 2.16.5). Validating the model therefore provided a novel approach to this research. Whilst the impact of each device remained relatively consistent through each scenario, the data was only replicable for 5 ha sites under the defined topography. Consequently, to provide greater certainty in the data, a range of site characteristics were analysed in *MicroDrainage*® to ensure the DST had a wider validity.

5.3: Aim 2: Create a Decision Support Tool

Aim 2 focussed on creating a DST to aid practitioners when integrating a SuDS management train at a site. Previous DSTs were analysed such as STTAT (Jefferies *et al*. 2009; section 2.17.1) and provided a framework to determine the role of a flood management based tool. The tool aimed to speed up the decision making process by calculating the number of SuDS needed to achieve the desired greenfield runoff. A range of site and SuDS parameters were analysed in *MicroDrainage*® to provide the calculations for the tool.

5.3.1: Objective 2a: Analyse site parameter influence on runoff in MicroDrainage®

The primary aim of the DST was to enable users to predict the number of SuDS required at a site to achieve greenfield runoff. Although the role of each SuDS device was critical to calculating the final values, the influence of infiltration, rainfall and size of the site also influenced the achievable reduction in runoff. Each parameter demonstrated a positive linear relationship with runoff, as infiltration, rainfall and the size of the site increased, runoff increased.

The relationship between runoff and infiltration has not been widely modelled in *MicroDrainage*® before as previous research has focussed on the accuracy of other models such as SWMM (Jumadar *et al*. 2008). The DrawNet package in *MicroDrainage*® utilised the WRAP formula for quantifying infiltration rates (section 3.5.5.2). The model analysis of the simulated runoff from different WRAP values had an r^2 value of 0.99, an extremely strong correlation, with $p<0.01$ demonstrating the statistical significance.

MicroDrainage® used six parameters from the FEH (Institute of Hydrology 1999) that could be used to calculate rainfall depth (section 3.6.1.1). These were output from the FEH as a result of twenty-five site parameters, including rainfall, aspect, urbanisation of catchment and HOST soil types, therefore the calculation was made using infiltration data. *MicroDrainage*® also required WRAP values to determine the coefficient runoff volume along with the HOST values that were accounted for in the FEH rainfall calculation. Accounting for both HOST values in the rainfall calculation and WRAP values in site infiltration information presented the possibility of double counting the infiltration at the site. However, having the user define the WRAP value in the DST was still necessary, as it was an input required to run the model in *MicroDrainage*®. This demonstrated the necessity of validating *MicroDrainage*®, to determine the accuracy of both aim 1 of the research, and the DST. The rainfall runoff analysis produced an r^2 value of 0.99 and $p<0.01$, representing a high level of certainty of predicting the amount of runoff likely based on a specific rainfall event. The final characteristic measured was the area of the site and its influence on runoff, as the site modelled in aim 1 covered 5 ha. It is logical that as the size of the site increased, runoff increased, this study demonstrates the extent to which the correlation exists in *MicroDrainage*®, and the influence of site size has runoff. Simulating the change in runoff generated by different site scales added further replication to the model. The analysis suggested a strong positive linear relationship in *MicroDrainage*® (r^2 0.99, $p<0.01$) enabling an estimation of the likely runoff for a site of specific size.

Simulating the role of different site specific parameters on runoff enabled an output for the DST. However, there were other parameters that were not modelled as they were site specific. The influence of topography was shown by Ellis & Viavattene (2014) and Cui *et al*. (2014) to determine where runoff flowed and the volume that could be stored. The possible WRAP values were imprecise, using just five classifications (section 3.5.5.2), so it was likely that infiltration would be simplified across the site, impacting total runoff and outflow. To reduce the level of uncertainty, outflow at the 99% confidence margin was used to provide the user with a maximum and minimum amount of likely runoff. Additional information regarding uncertainty is provided in 5.3.3.

5.3.2: Objective 2b: Analyse the influence of SuDS devices in MicroDrainage®

A series of further model analyses were completed to enable prediction of the likely runoff for a specific number of SuDS devices. As aim 1 identified a variable impact on peak runoff for each device dependent on combinations, each modelled SuDS combination was simulated with each component reduced by 10% and re-modelled. Although previous studies have analysed individual SuDS devices (section 2.8), research on the role of different numbers and land-take of combined devices on peak flow is limited.

Previous studies have analysed the role of a single green roof (Stovin 2010) but none quantified the role of changing the number of devices through computer modelling, therefore highlighting the novel approach adopted in this study. Each combination including green roofs produced an r^2 value of >0.89 with a $p < 0.01$. The software simulated a positive linear relationship between increasing runoff and reducing the number of green roofs, as suggested by Getter & Rowe (2006). Similar results were calculated for PPS which produced a stronger r^2 value of 0.96, with $p < 0.01$. A strong correlation and high certainty of the data for both PPS and green roofs confirmed a high level of confidence for the prediction of outflow in the final DST.

Swales presented a more varied and overall slightly weaker correlation when reducing their numbers. All scenarios produced an r^2 value >0.8, while p remained <0.01. All combinations generated an increase in runoff as the number of swales decreased. This was consistent with the findings of Fach *et al.* (2011) and Astebøl, Hvitved-Jacobsen, Simonsen (2004) who indicated the flood management benefits of utilising swales. However, the overall impact on runoff was typically low, with those producing the weakest correlation (PPS and swale, $r^2 = 0.82$, and green roof, PPS and swale, $r^2 = 0.8$) causing an increase of 0.4 l/s - 0.5 l/s when swales were replaced by pipes. The scenario that included all SuDS resulted in an increase of 7 l/s when converting swales to pipes, with combinations including detention basins typically producing lower outputs than when not used. This suggested that swales were more effective at managing the lower controlled flows associated with detention basins, justifying the “low” classification by Woods Ballard *et al.* (2015), as the device became more effective at managing runoff when water was detained. The relationship between the increased effectiveness of swales alongside detention basins, and a reduced impact when managing larger peak flow has not been explored in the literature before.

5.3.3: Objective 2c: Create a DST using the outputs of objective 2a and 2b

The need to create a DST for SuDS selection was identified in section 2.17.1. Each study aimed to simplify the selection method for installing SuDS and ultimately increase their uptake. However none of the methods addressed runoff reduction, focussing on cost estimates, amenity and water quality respectively. Only one component of the SuDS square (Figure 2-3), water quantity, was consistently identified as the key focus, particularly with regards to adoption at new build sites (Hoang & Fenner 2015). Therefore combining decision support with the UK industry standard software *MicroDrainage®* had the potential to reduce the decision making process for SuDS, potentially encouraging more professionals to adopt them and benchmark the devices which could achieve greenfield runoff.

To reduce uncertainty in the DST, each regression analysis from the model simulations was run at the 99% confidence level, with maximum and minimum runoff coefficients calculated (section 3.6.2). Uncertainties were identified in the model and the DST as the data was taken from the adapted PDP site (section 3.6.3), with the design relying on topography for runoff routes, which controls flow, particularly speed, direction and volume. Steep sided slopes increased flow speeds, therefore reducing the potential for infiltration associated with the site.

The tool used four SuDS devices (section 3.6.2), which were reflected in aim 1, either because they were commonly used in England and Wales (Table 2-3) or were effective (Table 2-4). As discussed in section 5.2, green roofs are rarely used in SuDS management trains, but Stovin (2010) suggested they can be highly effective at reducing runoff; therefore integrating them into the DST should demonstrate to stakeholders the potential benefits that can be achieved through their adoption, further engaging users. Detention basins were incorporated as opposed to traditional ponds, as they were more common (Table 2-3), and because they were dry there was a greater storage potential. All runs using the DST were not based on antecedent conditions, as while it was accepted that some water may remain in the system, it was difficult to quantify consistently (section 3.5.2). Although a limited range of SuDS were used, they were representative of existing management trains, by incorporating swales for conveyance, PPS and green roofs for source control and detention basins for both site and regional control, if required.

Both PPS and green roofs had a pre-defined depth in the DST. The depth for green roofs was set as 100 mm as suggested by previous research (Mentens, Raes & Hermy 2006;

Stovin 2010; Uhl & Schiedt 2008), with the user unable to alter the value as it was the depth applied in the sensitivity analysis. Similarly, a depth of 450 mm was applied to the PPS, according to (British Standard Institution 2009). This reduced the flexibility of the tool, but was necessary to ensure consistency between the DST and the sensitivity analysis. The depth for the detention basins was also capped at 4 m which was considerably deeper than traditional detention basins, but provides added flexibility for the user. Previous research (Ravazzani *et al*. 2014; Travis & Mays 2008) has suggested that detention basins can be designed up to 2.5 m and are commonly around 1 m deep.

Although the tool was designed to estimate flow in *MicroDrainage®*, there is the possibility to integrate other aspects of the SuDS square (Figure 2-3) in the future. Previous methods (section 2.17.1), such as Wade & Garcia-Haba (2013) SuDS for Road (Guz *et al*. 2009) and STTAT (Jeferries *et al*. 2009) analyse different aspects with regards to quantifying site suitability, amenity potential and water quality benefits. Although some of the discussed tools do not specifically quantify site benefits that can be achieved through different configurations, nor do they all focus on SuDS management trains, there is the potential to combine the outputs to produce a more all-encompassing approach to decision making. This would enable SuDS to better achieve the specific requirements of the site, for example if the priority is to improve water quality, but flood risk is minimal, different SuDS might be preferred. Therefore integrating the DST created through this research, assuming a successful evaluation using field data similar to that conducted by Jefferies *et al*. (2009) (section 5.3.4), would provide effective decision making, considering all aspects of the SuDS square.

5.3.4: Objective 2d: Re-evaluate the DST using data from Lamb Drove

Previous DSTs for SuDS have predominantly used field or laboratory data to underpin their tools (Nawaz, McDonald & Postoyko 2015; Scholz & Uzomah 2013), and Viavattene & Ellis (2012) created a DST using SUDSLOC to identify flood hotspots and subsequent need for SuDS. Although SUDSLOC was much more complex than the rapid DST created for the purposes of this project, it identified the need to refine the model with future runs to continue its development and overall accuracy to ensure its wider applicability and adoption. Qi & Altinakar (2011) combined ArcGIS with a

Monte Carlo Simulation method to create a decision support for flood management, validating it based on outputs of HEC-FDA, a dam modelling suite, part of the HECRAS package. Both approaches highlight the benefits that can be achieved through validating the DST.

An attempt to compare the outputs from the DST with a study undertaken by Cambridgeshire County Council (2012) at Lamb Drove proved unsuccessful (section 3.6.3.1). After analysing the monitored runoff, it was evident that a comparison with the DST would produce conflicting outputs, as the DST was specific to the 1 in 100 year 360 minute storm. Rainfall simulations from Lamb Drove were found to be a 1 in 5 year event, considerably less than is comparable with the DST.

The objective was subsequently changed to compare with runoff for the Hamilton site (aim 3). As the site was accurately replicated in *MicroDrainage*® (aim 3), total runoff for the site could reasonably be predicted for the 1 in 100 year 360 minute event. Using a model to analyse the DST was unconventional, particularly as the data underpinning the DST was based on *MicroDrainage*®, the program for validation. After running the analysis, the site produced a small level of flooding (2421.58 m^3) from upstream nodes as a result of the modelled storm, therefore the runoff fell short of the prediction for the DST, therefore a greater understanding of its accuracy is needed prior to operational use. Future research is consequently required to complete additional analysis with other sites that do not flood for the 1 in 100 year scenario, refining the approach adopted by Viavattene & Ellis (2012). This can be completed through testing with practitioners, comparing different outputs from *MicroDrainage*® with the predicted peak flow of the DST. This may identify further errors with the tool leading to improvements, providing additional user confidence in the DST.

5.3.5 Aim 2: Breaking the barriers for SuDS

As discussed previously in relation to aim 1, Table 2-2 defines a list of barriers that have typically been regarded as limiting the wider implementation of SuDS. The creation of the DST has aimed to reduce some of these barriers.

A perceived barrier is the number of specialists that are needed and the associated coordination issues to design and integrate SuDS. The tool will assist industry specialists by speeding up the decision making process, providing users with the total number of each modelled device required to achieve greenfield runoff in *MicroDrainage®*. As *MicroDrainage®* is the leading drainage modelling tool in the UK (Hubert, Edwards & Jahromi 2013), simplifying the process is critical. This not only reduces the number of specialists involved, but simplifies the process by providing a benchmark number of necessary devices.

The DST will further impact current industry practice by engaging more practitioners with SuDS, as it will demonstrate how much flood management can be achieved through using such devices and then subsequently speed up the design process for different sites. The need for a DST was highlighted by XP Solutions, who designed *MicroDrainage®* as the next step in supporting the program. XP Solutions have subsequently discussed using the DST to support *MicroDrainage®* in the future.

5.3.6: Aim 2 conclusion

Aim 2 involved the creation and validation of the DST, with 225 simulations from *MicroDrainage®* enabling the prediction of runoff. The simulations were based on user defined site parameters: rainfall depth, WRAP infiltration scenario and site size, as well as the total desired number of SuDS. This could then be compared to greenfield runoff rates, assuming the user knew the site SAAR and SOIL values. The tool had uncertainties associated with the calculations that underpinned it and *MicroDrainage®* (as discussed in section 5.3.3), therefore validation of *MicroDrainage®* was required (aim 3) with an analysis of the outputs from the DST (section 5.4).

As previously discussed (section 5.3.4) Lamb Drove (Cambridgeshire County Council 2012) was abandoned in favour of Hamilton as a validation site. It was imperative to analyse the accuracy of the outputs to enhance user confidence in the tool (Qi & Altinakar 2011; Viavattene & Ellis 2012). Nonetheless, the Hamilton SuDS management train flooded under a 1 in 100 year rainfall and was therefore not comparable with the DST. Validating the DST would provide the user with the confidence of its accuracy and therefore future research would adapt the approach suggested by Viavattene & Ellis (2012) by refining the tool through future real-scenario sites and drainage plans.

5.4: Aim 3: Validate the accuracy of MicroDrainage®

A publically available validation of *MicroDrainage®* using field data is not widely available. By determining the accuracy of the software at predicting different events using both large site scale field data and small scale controlled laboratory tests, the accuracy of the program could be assessed and therefore encourage a wider audience to adopt SuDS. A validation of *MicroDrainage®* has been used to show the wider applicability of the results and demonstrate the overall quality of the model. Models can provide understanding of the likely impacts of an event, in this case rainfall on runoff (Cloke & Pappenberger 2009). Although a number of uncertainties and simplifications are typically made, modelling provides the user with an opportunity to understand flow and therefore implement suitable management.

5.4.1: Objective 3c: Investigate the accuracy of MicroDrainage®.

Both objectives 3a and 3b have been considered in Chapter 4. They focussed on the collection of data from Hamilton, Leicester, and laboratory tests for both PPS and filter drain rigs. Using a similar method to that adopted by Versini *et al.* (2015) and Dotto *et al.* (2011), the NSE and coefficient of determination were calculated to understand the correlation between laboratory or field data and the simulated results in *MicroDrainage®*.

Laboratory-based results showed that *MicroDrainage®* accurately predicted runoff for a small site controlled scenario. Although the filter drain tests were marginally more accurate than PPS, achieving an NSE of 0.98 compared to 0.94 for PPS, they both outperformed other findings offered in the literature. For example, Principato *et al.* (2015) compared field data for a single green roof over a nine month period obtaining an overall NSE of 0.59. It was possible that the reduced NSE was a result of a large dataset as the research compared model data to nine months of continuous field data. When analysing fewer events, Principato *et al.* (2015) achieved an NSE of 0.74 before calibration and 0.97 for 46% of results after calibration.

Uncertainty still existed with the outputs of *MicroDrainage®* as the model did not completely replicate the laboratory findings, however a perfect replication has not previously been achieved in other studies as model assessments simplify conditions (Freni, Mannina & Viviani 2009). Both rigs used for the research had been used previously (section 3.7.3.5 & 3.6.3.6) therefore, it was likely that over time some clogging of the rigs would have occurred increasing the uncertainty with the outflow and ultimately the comparison with *MicroDrainage®*. In addition, while the rainfall simulator for the filter drains covered the surface area of the device, for PPS it was smaller, a 0.48 m^2 rig, with a 0.36 m^2 rainfall simulator. This research modelled the total surface area of the PPS rig, which was smaller than the simulator, however runoff pooled and infiltrated underneath the rainfall simulator and consequently the full extent of the rig was unlikely to have been used. To counter this, a contributing area consistent with the rainfall simulator (0.36 m^2) was added in *MicroDrainage®*, which was still likely to have produced some uncertainty.

As *MicroDrainage®* was designed to replicate flow for a whole site, simulating small laboratory scale systems was not realistic as the lowest flow that could be measured in *MicroDrainage®* was 0.1 l/s, while the fastest outflow for the PPS rig was 0.02 l/s. The site was therefore scaled up using the rational method (EQ 3.22) to enable a comparison with the software. The equation provided a simplistic calculation for scaling up the site, the rainfall intensity and ultimately the outflow. Although this method has previously been used in research for similar purposes, it provided an overly simplistic calculation for predicting flow (Cataño-Lopera, Waratuke & García 2010).

The NSE of 0.88 for Hamilton was less than that achieved in the laboratory (0.94 for PPS and 0.98 for filter drains). Calculating runoff volume over a 16 ha site presented a range of uncertainties, a possible explanation for the limited research undertaken at this scale. However, as *MicroDrainage®* was more suited to simulating runoff at the site scale, highlighted by the need to scale up the laboratory data, it was necessary to further analyse the software.

De Vleeschauwer *et al.* (2014) modelled the impact of source control and end of pipe solutions on river flows for the city of Turnhout in Belgium using InfoWorks for the sewer model and MikeII for the river model. They used a two-phase analysis to ensure model accuracy by using three years of river data for the initial calibration phase (NSE 0.91) and a further three years of river data to validate the model, enabling an overall NSE after calibration of 0.98. Although a calibration and validation approach was suitable for analysing their specific catchment, the validation undertaken in the current research was more focussed on validating *MicroDrainage*®, as opposed to one specific drainage plan. If data had been collected, the model calibrated and then subsequently validated, this would have enhanced the overall effectiveness of the Hamilton model to predict runoff at the site, but would not have critiqued the effectiveness of *MicroDrainage*® to simulate runoff for other model runs. For this reason, five observed rainfall events in the field were taken, and the laboratory tests were conducted using different rainfall intensities to provide an understanding of *MicroDrainage*® as a whole. Gaborit *et al*. (2013) also used an improved and calibrated model, achieving an NSE of 0.91 when using SWMM to study detention basins over a 13 ha site in Quebec. While Gaborit *et al*. (2013) focussed solely on detention basins, and De Vleeschauwer *et al*. (2014) on source control devices, Hamilton included a range of devices from swales to different types of ponds (section 3.7.2), adding further complexity and potential uncertainty to the model.

MicroDrainage® performed consistently with or better than the literature discussed (De Vleeschauwer *et al*. 2014; Gaborit *et al*. 2013; Principato *et al*. 2015), particularly as much of the literature utilised a calibration phase unlike the findings of this research. The reduced NSE for field data was likely to be a result of model uncertainty. As the size of the site increased, the complexity of modelling specific runoff routes and volumes increased (Kellagher 2012). *MicroDrainage*® used a specific WRAP value, which simplified how a site was likely to respond to a storm. Furthermore, each swale was given the same Manning's roughness value, however in reality the vegetation content would vary, therefore providing further uncertainty. Sites 1, 3 and 7 were monitored at the end of vegetated systems and as discussed in section 3.7.2.8, the site was maintained on a three-monthly basis, therefore altering the vegetation density throughout the duration of the research. This is likely to have impacted flow and ultimately the comparison between *MicroDrainage*® and field data. Vegetation additionally creates turbulent flow (Kirby *et al*. 2005) which can result in fluctuations of flow speed that is unlikely to be picked up in *MicroDrainage*®. The Manning's roughness value was used to define rock lined swales, however although a mean calculation was made in section 3.7.2.8, rocks were not homogenous and therefore created an inconsistent roughness value. An estimation was also made of the impact of surrounding houses on runoff, and an assumption that none used rainwater harvesting systems. Finally, further uncertainty was likely through the level of maintenance and general condition at Hamilton. Debris from building work was continually deposited into the channel, and the site often vandalised, which would have disrupted flow and therefore potentially the modelled results. Accounting for each of these factors and the likely generalisation, particularly in relation to vegetation and rock shape and size was likely to have resulted in the reduced NSE of 0.88.

5.4.2: Aim 3: Breaking the Barriers for SuDS

MicroDrainage® is the UK industry drainage modelling tool and incorporates a SuDS function. However other tools are also currently used by different practitioners, such as SWMM and MUSIC (section 2.16). Validating the program will provide industry confidence with regards the outputs of *MicroDrainage®* and therefore engage more practitioners with the accuracy and use of the tool.

Table 2-2 states that an existing barrier to SuDS is that it is often seen as untested technology. The findings of this research show that *MicroDrainage®* is accurately able to predict runoff by comparing field and laboratory data to model data. This will alter existing practice by placing more trust in the role of SuDS and also *MicroDrainage®*, particularly when focussing on flood management.

Furthermore, the accuracy with which *MicroDrainage®* was able to replicate runoff suggests that it would be able to predict runoff for a range of different storm intensities for different sites; an existing area of uncertainty highlighted in Table 2-2. Therefore the outputs of the research, combined with those from aim 1, have a bearing on policy. The results show that if designed correctly, SuDS are capable of limiting flooding to the 1 in 100 year scenario and should therefore be further integrated into flood policy in England and Wales.

5.4.3: Aim 3 Conclusion

Aim 3 of the research has focussed on validating the UK industry standard drainage modelling tool, *MicroDrainage*®, as no publically available validation has previously been completed. Field data for five separate rainfall events was captured from the SuDS management train at Hamilton, Leicestershire and compared to modelled outputs from *MicroDrainage*®. The outputs presented a NSE of 0.88, with an r^2 of 0.98, which was marginally less accurate than the outputs for the laboratory validation using porous pavement and filter drains, which achieved an NSE of 0.94 and r^2 of 0.95 and 0.98 and 0.99 r^2 respectively. This compares favourably to other methods, for example Principato *et al*. (2015) which achieved an NSE of 0.74 before calibration. This ensures overall confidence in the outputs of *MicroDrainage*®, and gives further accuracy to support the results produced as part of Aim 1 and Aim 2 of the research.

6 Conclusion

6.1 Introduction

This chapter summarises the limitations of the research and how the aims and objectives (section 1.5) were met. It reviews the main findings of the research, addresses the contribution to knowledge and outlines recommendations for future work.

6.2 Research Limitations

6.2.1. Model

Aim 3 intended to quantify the accuracy of *MicroDrainage*®, and therefore the DST and the outputs of aim 1. As models simplify spatial characteristics to simulate the environment, the outputs are inherently uncertain (Ali, Solomatine & Di Baldassare 2015; Cloke & Pappenberger 2009; Leskens *et al*. 2014). The NSE and coefficient of determination highlighted the accuracy with which the software predicted runoff (section 4.4), however the correlation of all three methods presented some uncertainty. Research regarding model validation occurs at the site or laboratory stage to reduce uncertainty (section 3.7.3), as when the site size increases, the variables that influence runoff rise, resulting in a more complex model. Furthermore, due to the possibility of theft, flow measurements for this research were taken by hand, as opposed to a Doppler based scanner which can measure volume and flow continuously, with a high degree of accuracy (Miller *et al*. 2014). Vegetation density and Manning's values were also generalised, with no change made to account for maintenance plans, adding further uncertainty to the comparison. In addition, several of the sites were monitored after vegetation, which was likely to cause turbulent flow that would alter flow speeds, which is not accounted for in *MicroDrainage*®. Therefore total volume measurements could be incorrect because of the measurement errors above, which would have further contributed to the NSE of 0.88 for the field data.

Nevertheless, the calculated NSE results suggest that *MicroDrainage®* performed well at predicting runoff, and therefore enabled an overall assessment of the level of uncertainty and the subsequent limitations of the research (section 4.4 and 5.4).

6.2.2 Decision Support Tool

The DST was built on assumptions from the outputs of *MicroDrainage®* and whilst all analyses were supported by an r^2 value >0.8, with the majority (70%) >0.9 (section 4.3), the calculations were ultimately underpinned by a small level of uncertainty. Although the validation of *MicroDrainage®* demonstrated the accuracy with which it simulated runoff, the model analysis for each device showed that the relationship between the SuDS devices and runoff in the software was not entirely linear, and therefore simply calculating runoff based on the number of devices presented a level of uncertainty as none produced a perfect fit when measured using r^2. The r^2 values nevertheless suggest that it was possible to estimate with a high level of confidence. The uncertainty of the DST was reduced through the regression analysis, which was completed using the 99% confidence level and enabled calculation of a maximum and minimum range for peak flow.

Regardless of the statistical analysis that had been undertaken to reduce uncertainty, a further analysis of the DST was required to ensure the outputs accurately replicated those of *MicroDrainage®*. This was attempted using Lamb Drove but was unsuccessful due to a difference in rainfall data (section 3.6.3.1). A subsequent analysis using the Hamilton site was also unsuccessful. As the validation suggested that the model could predict runoff with a high level of certainty (section 4.3.4), runoff was modelled for the site based on the 1 in 100 year 360 minute storm, to ensure comparisons could be drawn with the DST. The site however flooded during the event which meant that comparisons could not be made with the DST as the peak values presented in *MicroDrainage®* were less than anticipated (section 5.3.4). This therefore requires future work to continue the development of the tool to demonstrate its future application.

6.3 Review of the Research Objectives

Aim 1 was to model the impact on runoff of multiple SuDS combinations as a result of the 1 in 100 year rainfall event for different infiltration and storm duration scenarios. This provided an overview of the effectiveness of each device, which led to the creation of the DST, aim 2. Aim 3 focussed on determining the accuracy of the results for aim 1, and subsequently the DST in aim 2. Table 6-1 matches the aims and objectives defined in Chapter 1 with the section where they were addressed and discussed.

Table 6-1 Sections where the aims and objective were met.

Aim 1: De-construct a SuDS management train to determine the effectiveness of each component

Objective	**Results section**	**Discussion section**
1a: Create a SuDS management train and a conventional pipe based drainage system at a case study site in *MicroDrainage*® to evaluate runoff from each system.	4.2	
1b: De-construct each component of the SuDS management train to determine the efficiency of each individual component.	4.2.2-4.2.5	5.2.1
1c: Calculate the minimum and maximum impact per $l/s/m^3$ and $l/s/m^2$ of each device on peak flow.	4.2.6	5.2.2

Aim 2: Using the data from aim 1, create a Decision Support Tool (DST) identify the likely number of different SuDS needed to achieve a desired peak runoff.

Objective	**Results section**	**Discussion section**
2a: Analyse how the modelled site parameters of infiltration, rainfall and site scale each influence runoff in MicroDrainage®	4.3.1	5.3.1
2b: Analyse how different coverage of the SuDS devices modelled in aim 1 impact runoff in MicroDrainage®	4.3.2	5.3.2
2c: Using the outcomes of the regression analysis from objectives 2a and 2b, create a decision support tool that estimates maximum	4.3.4	5.3.3

and minimum runoff for site and SuDS parameter		
2d: Re-evaluate the decision support tool using data from the SuDS Management Train at Lamb Drove, Cambridgeshire.	4.3.5	5.3.4
Aim 3: Validate the accuracy of MicroDrainage ® to determine the quality of the data underpinning the Decision support tool		
Objective	**Results section**	**Discussion section**
3a: Capture rainfall and flow field data at the Hamilton SuDS management train, Leicester.	4.4.1	
3b: Run laboratory simulations to determine the response of filter drains and porous paving to designed rainfall events.	4.4.2	
3c: Using the data collected in objectives 3a and 3b, assess the accuracy of MicroDrainage®.	4.4	5.4.1

The following sections review each objective in turn.

6.3.1 Objective 1a

Objective 1a involved creating a SuDS management train in *MicroDrainage*® that included detention basins, green roofs, PPS and swales, and a conventional drainage system. The two scenarios were designed at Prior Deram Park, Coventry, to the current 1 in 100 year and 1 in 30 year standard guidelines, respectively (section 3.5.2 and 3.4.3). The SuDS devices were chosen based on the most commonly implemented in management trains in England and Wales (Table 2-3), and those that Woods Ballard *et al*. (2015) highlighted as highly effective at reducing runoff (Table 2-4). Woods Ballard *et al*. (2015) suggested that green roofs had limited effectiveness at reducing peak flows, and consequently the device is rarely integrated into existing management trains. However, Stovin (2010) highlighted the benefits that could be achieved through integrating green roofs, therefore they were included in this analysis. The results of objective 1a are presented in section 4.2.

6.3.2 Objective 1b

Analysis of the SuDS management train simulated the total impact of the devices on runoff whilst also enabling devices to be removed systematically, revealing the role of individual devices in the management train. The results of this are presented in sections 4.2.2-4.2.5 and discussed in 5.2.1.

6.3.3 Objective 1c

The comparative role of SuDS devices has not previously been studied therefore Objective 1c focussed on further analysing the outputs of Objective 1b. As different volumes and sizes of each device was used in the assessment, quantifying the impact of each device per l/s/m3 and l/s/m2 enabled a direct comparison of the effectiveness of the four modelled SuDS. The results were outlined in section 4.2.6 and discussed in section 5.2.2.

6.3.4 Objective 2a

Objective 2a focussed on the parameters that defined the site in the DST; rainfall, infiltration and size (Section 3.6.1). The tool aimed to predict peak flow for all sites up to and including 50 ha, as stated by Kellagher (2012). The method that *MicroDrainage*® used to quantify each parameter with regards to predicting runoff was analysed, which consequently enabled a prediction to be made with a high level of confidence. The results were presented in section 4.3.1 and discussed in section 5.3.1.

6.3.5 Objective 2b

Objective 2b involved an analysis for each SuDS device, reducing the number of each device in all combinations of the management train to analyse the impact on runoff (Section 3.6.2). The results were presented in section 4.3.21 and discussed in section 5.3.2.

6.3.6 Objective 2c

The outputs of objective 2a and 2b were then successfully combined to create a DST. Although DSTs have previously been created for SuDS, they tend to focus on other aspects, such as amenity and biodiversity (Lerer, Arnbjerg-Nielsen & Mikkelsen 2015), cost-benefit implications (Stovin & Swan 2007), or simply focus on one device (Scholz & Uzomah 2013). The equations that underpin the DST are presented in section 3.6.2 with the final system displayed in 4.3.4 and its use and accuracy discussed in 5.3.3.

6.3.7 Objective 2d

Objective 2d focussed on providing additional user confidence in the tool by undertaking an evaluation based on field data to demonstrate the accuracy with which the tool predicted runoff. The initial focus of the objective was Lamb Drove, Cambridgeshire, as the site report included a SuDS configuration, rainfall and runoff data (Cambridgeshire County Council 2012). However as discussed in sections 3.5.3.1 and 5.3.4 the data were not comparable as the DST predicted runoff for the 1 in 100 year 360 minute storm, but the monitored events at Lamb Drove were 1 in 5 year events. Subsequently, the site analysed in aim 3 was used for comparison. Aim 3 demonstrated that runoff can be predicted with confidence for a SuDS management train in Hamilton, Leicestershire (section 4.3.4). The model was then used to simulate the peak runoff for the site as a result of the 1 in 100 year event, comparable with the DST. However Hamilton flooded as a result of this large rainfall event and subsequently produced inaccurate peak flow data that was not comparable with the DST (section 4.3.4 and 5.3.4). This objective was largely unsuccessful, therefore future research is required to define the accuracy of the DST (section 6.8.3).

6.3.8 Objective 3a

Objective 3a related to monitoring a SuDS management train in Hamilton, Leicester that consisted of swales, detention basins and vegetated ponds (section 3.7). Flow measurements were taken for five rainfall events, and compared to flow data in *MicroDrainage®*, to determine the accuracy with which it predicted runoff. Few studies have undertaken model validation of flow rates at the sub-catchment scale due to the potential uncertainties that are associated with an increase in site size (section 3.6.3). Although there were limitations with the methodology (section 3.7.3.1), the results were demonstrated in section 4.4.1.

6.3.9 Objective 3b

To further understand the accuracy with which *MicroDrainage®* predicted runoff, small scale laboratory tests were used. PPS and filter drains were analysed to determine how accurately the model replicated the response to different rainfall scenarios (section 3.7.3). The results were presented in section 4.4.2 and were discussed with objective 3a in section 5.4.1 and were then evaluated in 5.4.1.

6.3.10 Objective 3c

Objective 3c consisted of the statistical analysis of *MicroDrainage®*, using the outputs of objectives 3a and 3b. Although limitations were presented (section 6.2.1), analysing the site at both the field and laboratory scale provided an understanding of the accuracy with which the software predicted runoff. The results were presented in section 4.4

6.4 Review of Research Findings

The following sections will review the main findings for each of the aims of the research.

6.4.1: Aim 1

The main research findings from the initial site (objectives 1a and 1b) were that detention basins were essential when designing a management train, as they considerably reduced peak flow. Different runoff characteristics were measured (section 4.3) but peak outflow was deemed the most important by The Standards (DEFRA 2015a). However the total impact of detention basin was possibly a result of the increased volume in the design, hence objective 1c was completed. PPS were also effective, particularly at reducing total runoff volume. The introduction of swales to a site automatically reduced peak runoff for all rainfall and infiltration scenarios, with runoff reducing as additional SuDS were added. Green roofs had minimal impact on peak flow, but nonetheless, the combination when all devices were modelled reduced peak flow the most, in comparison to conventional drainage,

When comparing the role of each device, PPS was nearly twice as effective per m^3 as detention basins, but this was reversed per m^2, with detention basins nearly twice as effective as PPS. Although detention basins had an increased volume as they were designed to 2 m deep, they covered over 1,000 m^2 less land than PPS, resulting in the changing value per m^3 and m^2. This therefore shows that per the amount of space used, detention basins are the most effective device. Nonetheless as PPS are developed on land that is traditionally impermeable (Charlesworth, Harker & Rickard 2003) as opposed to detention basins which use space that can be used for wider purposes, their implementation is likely to be increased.

As presented in section 2.5, water quantity forms only one component of the wider site benefits of integrating SuDS yet is typically regarded by practitioners as the most important. In respect of the wider SuDS square, Ellis, Revitt & Lundy (2012) defined PPS as being the most effective device of those modelled at improving water quality, with both detention basins and swales having a reduced impact and green roofs having limited impact. However with regards amenity and biodiversity, the main purpose of PPS is to produce multi-purpose sites. Swales are capable of increasing both amenity and biodiversity, as are detention basins, with their influence being dependant on their use: whether they are online or offline defines if they can be used for other purposes, such as sports pitches. Green roofs have the greatest level of amenity and biodiversity potential in comparison to the other modelled devices as they are designed on land that is previously impermeable tiled surfaces. Each modelled device has different attributes and therefore should be prioritised different depending on the requirements of the site, whether it be to enhance amenity and biodiversity, improve water quality or reduce water quantity. This research therefore aims to inform stakeholders of the most effective devices to ensure that future management trains are successful, and are consequently adopted more widely as opposed to conventional pipe based drainage.

6.4.2: Aim 2

Aim 2 used outputs from aim 1, along with a model analysis for each SuDS combination, to create a SuDS Decision Support Tool for water quantity. Previous research, such as STTAT (Jefferies *et al*. 2009) provided a tool to guide users with the potential water quality improvements that were possible when combining SuDS in sequence to form a treatment train.

The site simulations (section 4.3) concluded that each parameter had an r^2 value >0.98 and $p<0.01$ as each characteristic was altered and runoff simulate. Further simulations in objective 1b for each SuDS device used produced an r^2 of >0.8 and $p<0.01$ with 70% of all measured combinations >0.9 (section 4.3.2). The results consequently enabled a prediction of the amount of runoff, based on differing site and SuDS scenarios, to be made with a high level of confidence. The equations outlined in 3.6.2, using these outputs, were the basis for the DST.

This tool, although acknowledging that there are wider benefits than water quantity, aims to predict the runoff for a site prior to development, based on a user-defined combination of devices. The DST will aim to shorten the decision-making time for developers using *MicroDrainage*®, as the total amount and size of devices required to achieve greenfield runoff can be pre-determined. This will engage additional stakeholders to adopt SuDS by simplifying the decision-making process and demonstrating the benefits compared to conventional drainage.

Further testing is required with users to compare runoff for their *MicroDrainage*® models with the outputs of the DST to determine the accuracy of the tool and make improvements if required. This will provide practitioners with confidence in the DST with regards to predicting runoff, and its use in the decision making process for SuDS selection. Although this was partially completed as part of objective 2c, the results did not provide the necessary assurance, as the initial data for Lamb Drove was not compatible and the model output for Hamilton, Leicester, suggested the site would flood at the 1 in 100 year scenario, therefore providing different outputs to the DST.

6.4.3: Aim 3

The final aim focussed on validating *MicroDrainage*® using laboratory and field data. As *MicroDrainage*® is the industry standard drainage modelling software in the UK, the accuracy with which it predicts runoff is paramount. Previous studies have utilised the software with limited quantification of its accuracy, therefore this research has analysed the software demonstrating the accuracy with which it predicted the outflow for aim 1 and also the DST (aim 2). Furthermore, validating the program provided additional confidence in its outputs for SuDS functionality and will provide future users with enhanced confidence when using *MicroDrainage*® and further engage users with the runoff reduction possibilities that can be achieved through implementing SuDS.

The analysis of field data concluded a NSE of 0.88 and an r^2 of 0.98 (section 4.4.1), suggesting a strong correlation between field and model data far greater than several studies that have focussed on small scale individual devices (Principato *et al.* 2015) (section 5.4.1). The model also returned r^2 of 0.96 and 0.99 for both laboratory scenarios, and an NSE of 0.94 and 0.98 respectively. Overall, the findings demonstrate that *MicroDrainage*® replicated flows with a high degree of certainty.

6.5 Implications of the Research Findings

Table 2-2 outlined the barriers that exist with regard to the implementation of SuDS. Although some of the barriers are outside the scope of the research, the findings have a range of implications on existing practice.

Aim 1 focussed on providing guidance on which devices should be prioritised, highlighted as an existing barrier by Table 2-2. Both detention basins and PPS provide a high level of flood management in comparison to the other modelled devices and should therefore be prioritised, particularly at source control where PPS was consistently more effective than green roofs. A further implication of the findings is that practitioners often assume that SuDS are only suitable at high infiltration sites; this research has found that as infiltration capacity decreases, the impact of SuDS increases. This implication, if accepted, will therefore further engage practitioners with SuDS.

Engagement will also be increased through the creation of the DST. The implications of the DST are that, assuming a successful validation (section 6.8.3), designing SuDS in *MicroDrainage®* will be a simpler and quicker process as the tool is able to define exactly how many of each device are required to achieve greenfield runoff. Table 2-2 suggested that the planning and design processes need better coordination, therefore this DST could further align them by simplifying decision making. Table 2-2 proposed that the difficulty to predict runoff for SuDS has traditionally been a barrier to their wider installation. The main implication of aim 3 was that *MicroDrainage®*, the industry standard drainage modelling tool, was an extremely effective method for modelling runoff, therefore providing users with confidence in the tool to design SuDS at future developments. The subsequent recommendations for industry and policy, as a result of these implications, are presented in section 6.8.

6.6 Contributions to the Body of Knowledge

This research has contributed to the wider understanding of the ability of SuDS to reduce flooding, particularly when combined in a management train (Charlesworth *et al*. 2013; Lashford *et al*. 2014). As flood management is typically cited as the most important determinant for implementing SuDS, highlighting the impact that SuDS can have in a management train (section 2.5.1) will engage stakeholders with the most suitable device to utilise in future drainage plans. This will ensure that future developments are more likely to be successful and increase stakeholder confidence in SuDS. This study also demonstrated how integrating a swale train can be more effective at reducing peak runoff than pipes, therefore whilst it has simulated the considerable benefits of PPS, it has also highlighted how effective other devices are. Although detention basins take up a relatively large amount of open space in new developments, they are extremely effective at reducing peak flow (section 4.2.2) and should be integrated into future management plans whenever possible.

The outputs have also produced a water quantity focussed DST (section 4.3). Past research has advocated the need for reducing the decision making time in the SuDS selection process, however past methods have focussed on factors other than water quantity (section 2.17.1). It is a straightforward method that can rapidly predict the likely outflow of a site, based on the rainfall depth for the 1 in 100 year 360 minute storm, WRAP value, site size and the SuDS to be installed. This outflow can then be compared with the greenfield runoff for the site, a requirement of The Standards (DEFRA 2015a) to determine the suitability of the proposed devices. SuDS can be added or removed, according to requirements, which will provide a benchmark for designing a site in *MicroDrainage*®, ultimately reducing the simulation time for testing different combinations of SuDS.

The final contribution made by the research is focussed on the validation of *MicroDrainage*®. The program is used by both industry and research with limited validation of its accuracy of predicting runoff when integrating SuDS. Section 4.4 and 5.4 concluded that the software has a high level of confidence, based on field and laboratory data, for simulating flow. This firstly provides context to the outputs of aim 1, and assurance of the accuracy of the DST, and secondly gives some context to the accuracy of *MicroDrainage*®.

6.7 Conclusions

The research has provided a novel approach to analysing the ability of different SuDS devices in a management train at new build sites in relation to flood management. However if the research were to be extended in a future project, more focus would be given to the retrofit environment. Whilst the role of devices for retrofit was considered in Figure 3-1, it was decided that the focus would be designing to maximum capacity and therefore using the new build environment. Although the findings from new build can be applied to retrofit, for example PPS can effectively reduce peak flow in new build sites and would continue to do so in the retrofit environment, there is less possibility for detention basins due to potential land take. More factors of the SuDS square (Figure 2-3) could also be considered, such as amenity, carbon sequestration and reducing the urban heat island effect as these are often equally as important at retrofit than at a new build site (Charlesworth 2010). Furthermore a more structured approach should be taken to validating the DST. This provides scope for further research (section 6.8.3) and is a necessary pre-requisite to ensure the successful take-up of the DST. Although there are complexities associated with using field data to undertake the validation, as identified by using the data from Lamb Drove (section 6.3.7), it remains a critical aspect, as identified by Jefferies *et al*. (2009). Nevertheless, the results of the research provide new insight and therefore recommendations for industry and policy and provide avenues for future research.

6.8 Recommendations

The research outputs have provided a number of recommendations. The following paragraphs discuss the recommendations in the context of industry, policymakers and future research.

6.8.1 Recommendations for Industry

The research defined the relative effectiveness of different SuDS (section 4.2 & section 5.2) to ensure that the most effective methods of sustainable flood management are integrated in the future. Section 5.2.1 concluded that detention basins were most effective at the site scale. Further analysis of the role of potential reduction per l/s/m^3 suggested that PPS was more effective, as opposed to detention basins per l/s/m^2. This therefore provides industry with an outline of devices that should be prioritised in a SuDS management train, when focussing on flood management.

The development of the DST to support site design further engages practitioners with SuDS. The tool enables users to pre-define the number of green roofs, PPS, detention basins and swales necessary at a site to achieve greenfield runoff. This will simplify the process by shortening the decision making time spent determining the required number of each device in *MicroDrainage*®, therefore engaging additional practitioners with the benefits of SuDS with regards flood management and *MicroDrainage*®.

Although *MicroDrainage*® is the UK industry standard drainage modelling tool, the lack of prior validation not only provided uncertainty about the accuracy of findings of this research, but also when the software is used by industry. The production of strong NSE values, backed up by even stronger r^2 values provide practitioners with confidence in the accuracy of the software and encourages engagement of a wider audience with the model and subsequently benefits to SuDS.

6.8.2 Recommendations for Policymakers

As discussed in section 2.4 and 2.5, in the context of a changing climate and the push for sustainable approaches, SuDS demonstrate sustainable runoff management (Woods Ballard *et al*. 2015). The Standards (DEFRA 2015a) required sites to be flood resistant up to and including the 1 in 100 year 360 minute storm, therefore their wider implementation is essential. Sites have begun implementing SuDS, however resistance to the approach is still prevalent (Hoang & Fenner 2015), hence the results of the present study are important by further outlining their effectiveness. Calculating the comparative role of different SuDS combinations with conventional drainage demonstrates their success as a method of flood management. The findings show that policymakers should prioritise both PPS and detention basins at new build sites, but also further utilise the capabilities of combining SuDS, as opposed to stand-alone methods. When also combined with research to demonstrate the effectiveness of SuDS management train with regards water quality (Jefferies *et al*. 2009), policymakers should ensure that all future SuDS developments are incorporated into a train to ensure maximum effectiveness. Demonstrating their potential for flood management would likely further engage practitioners to utilise them at future developments.

6.8.3 Recommendations for Future Research

Objective 1c: Calculate the minimum and maximum impact per m^3 *and* m^2 *of each device on runoff.*

As discussed in section 2.5.1, water quantity reduction has typically been regarded as a key factor to explain whether SuDS were implemented (Hoang & Fenner 2015). This was further justified by the focus on runoff volume in The Standards (DEFRA 2015a). Although research has quantified the ability by which different individual devices enhance water quality, similar to that of water quantity, no research has quantified how this changes as part of a management train. The same is the case for both amenity and biodiversity.

This research has demonstrated that by combining multiple individual devices, some have a reduced impact on total runoff volumes, compared to the expected values in the literature, for examples green roofs in comparison to the findings suggested by Stovin (2010) and Voyde, Fassman & Simcock (2010). Therefore quantifying how effective different devices were in combination at enhancing water quantity and quality, amenity and biodiversity will further support the value of SuDS. Creating a tool that quantified the impacts of integrating a SuDS management train at a site would encourage a wider audience to engage with their benefits. This is extremely pertinent in light of a changing climate, and the push for more sustainable measures, however whilst a direct improvement can be made in comparison to conventional drainage for water quantity, demonstrating additional benefits will further support the adoption of SuDS.

In addition to understanding wider benefits, more research is required on the long term cost-benefit of implementing SuDS. As well as land take and total runoff, the cost element is regularly cited as a barrier to installing SuDS (Duffy *et al*. 2008). The EA (2007b) calculated the cost of implementing individual SuDS, but the overall benefits are further enhanced by using a management train, thus understanding of the overall costs is necessary. There are a range of uncertainties when calculating these costs, which has resulted in a lack of conclusive research on the topic, for example, the cost of materials, maintenance and ownership, insurance implications, short and long term costs. Nonetheless, providing a tool that could estimate cost, would, with quantifying all other aspects of the SuDS square, demonstrate all benefits for integrating SuDS and provide a compelling case for their use at new sites across the UK, and for retrofit installation.

Objective 2d: Re-evaluate the DST using data from the SuDS Management Train at Lamb Drove, Cambridgeshire.

Section 5.3.4 discussed the evaluation of the DST using data generated from *MicroDrainage*® for Hamilton, using the 1 in 100 year 360 minute storm. The DST predicted runoff to be greater than the *MicroDrainage*® model, but a comparison was not possible due to the site flooding. Therefore, further calibration and validation should be undertaken to determine the overall accuracy of the DST. This should be undertaken, as suggested by Viavattene & Ellis (2012), by stakeholders using the tool, through a two phase process: calibrate the DST using data for different new developments in England and Wales, then validate the system using other new developments. This would ensure the tool worked more closely with *MicroDrainage*®, therefore providing users with further confidence.

Objective 3a: Capture rainfall and flow field data at the Hamilton SuDS management train, Leicester.

Although The Standards (DEFRA 2015a) suggested that SuDS should be effective at managing runoff up to and including the 1 in 100 year event, there was limited field research on the ability of SuDS management trains to manage smaller flows. This research has analysed five events, for the purpose of validating *MicroDrainage*®, at Hamilton, Leicester. However, future research regarding the role of the site over a longer, more permanent period would further develop understanding. As discussed in section 5.4, models presented a number of uncertainties with regards to predicting large sites. Therefore field data would provide an opportunity to quantify the effectiveness of different devices combined in a management train and the role of maintenance and vegetation growth on the system. This would provide additional evidence to support the role of combining SuDS to manage flooding.

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Appendices

Summary of appendices

Appendix	Content
A	Summary of presentations and peer reviewed publications in approximate date order
B	Ethical Approval
C	Decision Support Tool and User Guide
D	Field data for Hamilton and laboratory data for PPS and Filter drains

Appendix A: Summary of presentations and peer reviewed publications in approximate date order

Lashford, C., Charlesworth, S., Warwick, F. (2016) 'Water Quantity: Attenuation of the Storm Peak'. in *Sustainable Surface Water Management Systems: A Handbook for SuDS*, ed. by Charlesworth, S. and Booth, C. Wiley Blackwell: London, 59-74

Lashford, C., Charlesworth, S., Warwick, F. (2016) 'Modelling for Design'. in *Sustainable Surface Water Management Systems: A Handbook for SuDS*, ed. by Charlesworth, S. and Booth, C. Wiley Blackwell: London, 270-281

Lashford, C. Charlesworth, S. Warwick, F. Blackett, M. (2016) 'Using catchment scale field data to validate MicroDrainage: Results from the North Hamilton, Leicestershire, SuDS Management Train'. *The Water Efficiency in Buildings Network Conference*. held 5th – 7th September 2016 at Coventry University

Charlesworth, S., Warwick, F. and Lashford, C. (2016) 'Decision-making and sustainable drainage: design and scale'. *Sustainability,* 8. 782

Lashford, C. Charlesworth, S. Warwick, F. Blackett, M. (2016) 'Creating a Sustainable Drainage Flood Risk Decision Support Tool'. *Faculty of Engineering, Environment & Computing Internal Research Symposium*. held 24th February 2016 at Coventry University

Sañudo-Fontaneda, L., Jato-Espino , D., Lashford, C., and Coupe, S.(2016) 'Investigation of the design considerations for Highway Filter Drains through the comparison of stormwater management tools with laboratory simulation experiments' *Novatech 2016*. held 28th June- 1st July 2016 at INSA, Lyon

Lashford, C. Charlesworth, S. Warwick, F. Blackett, M. (2015) 'The implementation of a sustainable drainage flood management decision support tool' *SUDSNET.* held 3rd - 4th September 2015 at Coventry University

Lashford, C. Charlesworth, S. Warwick, F. Blackett, M. (2015) 'Creating a Sustainable Drainage Flood Management Decision Support Tool'. in Maere, T. Tik, S. Duchesne, S. Vanrollegham, P. in *Proceedings of the 10th International Conference on Urban Drainage Modelling: Poster Presentations,* 'Urban Drainage Modelling 2015' held 20-23 September 2015 at Mont-Sainte-Anne, Québec, Canada

Charlesworth, S. Booth,C. Warwick, F. Lashford, C. Lade, O. (2014) 'Rainwater Harvesting – Reaping a Free and Plentiful Supply of Water' *in* Booth, C. Charlesworth, S. (editors) Water Resources in the Built Environment: Management Issues and Solutions

Charlesworth, S. Lashford, C. (2014) *Hard SUDS infrastructure in the urban environment,* Review of Current Knowledge: Foundation of Water Research

Lashford, C., Charlesworth, S., Warwick, F., and Blackett, M. (2014) ‘Deconstructing the Sustainable Drainage Management Train in Terms of Water Quantity – Preliminary Results for Coventry, UK’. *CLEAN: Soil, Air, Water* 42 (2), 187-192

Charlesworth, S., Perales-Momparler, S., Lashford, C., and Warwick, F. (2013) 'The sustainable management of surface water at the building scale: preliminary results of case studies in the UK and Spain'. *Journal of Water Supply: Research and Technology – AQUA* 62 (8), 534-544

Charlesworth, S., Perales-Momparler, S., Lashford, C., and Warwick, F. (2013) 'The sustainable management of surface water at the building scale: UK and Spanish case studies’. *The Water Efficiency in Buildings Network Conference*. held 25-27 March 2013, in Oxford, UK.

Lashford, C., Owen, O. (2013) ‘Exploring the social aspects and perceptions of sustainable drainage systems: a qualitative pilot study using a mobile focus group’. *RGS Postgraduate Mid-Term Conference.* held 25th – 27th March 2013 at Birmingham University

Lashford, C. (2012) ‘Sustainable drainage management train: A sustainable flood management strategy’ *SUDSnet.* held 4th – 6th September 2012 at Coventry University

Lashford, C. (2012) ‘Sustainable Drainage Management Train: A sustainable flood management strategy?’. *Faculty of Business Environment & Society Internal Research Conference*. held 25th June 2012 at Coventry University

Lashford, C., Charlesworth, S., Blackett, M., Warwick, F. (2012) ‘Investigation of the use of a SuDS Management Train to reduce flooding in an urban environment’. *GISRUK Conference*. held 11th-13th April 2012 at Lancaster University

Lashford, C., Charlesworth, S., Blackett, M., Warwick, F. (2012)‘Sustainable Drainage Management Train: A sustainable flood management strategy?’ *RGS Postgraduate Mid-Term Conference*. held 20th - 22nd April 2012 at Nottingham University

A copy of all publications and papers that have been submitted to a conference proceeding can be found in the Appendix A folder of the attached CD.

Appendix B: Ethical approval

Ethical approval was granted on three occasions for the research to reflect the desk based study (Appendix B1), the field data form Hamilton, (Appendix B2) and the laboratory tests (Appendix B3).

Appendix B1: Ethical approval for desk based research

Name of applicant: Craig Lashford ....

Faculty/School/Department: [Business, Environment and Society] Geography, Environment & Disaster Management

Research project title: Deconstructing the sustainable drainage management train in terms of water quantity; preliminary results for Coventry, UK

Comments by the reviewer

1. Evaluation of the ethics of the proposal:	
2. Evaluation of the participant information sheet and consent form:	
3. Recommendation: (Please indicate as appropriate and advise on any conditions. If there any conditions, the applicant will be required to resubmit his/her application and this will be sent to the same reviewer).	
	Approved - no conditions attached
	Approved with minor conditions (no need to re-submit)
	Conditional upon the following – please use additional sheets if necessary (please re-submit application)
	Rejected for the following reason(s) – please use other side if necessary
X	Not required

Name of reviewer: Anonymous **Date:** 05/08/2013

....

Appendix B2: Ethical approval for collection of field data at Hamilton, Leicestershire

Name of applicant: Craig Lashford ....

Faculty/School/Department: [Business, Environment and Society] Geography, Environment & Disaster Management ....

Research project title: Deconstructing the Sustainable Drainage Management Train to Reduce Flood Risk

Comments by the reviewer

4. Evaluation of the ethics of the proposal:

5. Evaluation of the participant information sheet and consent form:

6. Recommendation:

(Please indicate as appropriate and advise on any conditions. If there any conditions, the applicant will be required to resubmit his/her application and this will be sent to the same reviewer).

☐ Approved - no conditions attached

☐ Approved with minor conditions (no need to re-submit)

☐ Conditional upon the following – please use additional sheets if necessary (please re-submit application)

☐ Rejected for the following reason(s) – please use other side if necessary

☒ Not required

Name of reviewer: Anonymous **Date:** 26/08/2014

....

Appendix B3: Ethical approval for collection of laboratory data

Certificate of Ethical Approval

Applicant:

Craig Lashford

Project Title:

Deconstructing the Sustainable Drainage Management Train to Reduce Flood Risk; laboratory data

This is to certify that the above named applicant has completed the Coventry University Ethical Approval process and their project has been confirmed and approved as Low Risk

Date of approval:

29 February 2016

Project Reference Number:

P42003

Appendix C: Decision Support Tool and User Guide

Appendix C provides the coefficient values from the regression analysis that supports the DST, a copy of the DST (found in the folder titled Decision Support Tool.xls) and a user guide for the tool.

C 1.1: Coefficient values

The coefficient values were calculated as a result of the regression analysis for each model analysis (Section 4.2) and support the equations that underpin the DST (Section 3.5.2). Table E-1 is the coefficients for rainfall (also provided in EQ 3.1 and EQ 3.1) and Table E-2 are the maximum and minimum regression values for each SuDS device for each combination.

Table E-1 The coefficient values that were calculated from the regression analysis at a 99% confidence value for rainfall

Rainfall coefficient (Max)	Rainfall coefficient (Min)
4.15288139	3.765292974

Table E-2 The coefficient values that were calculated from the regression analysis at a 99% confidence value for each SuDS device

Maximum				
Combination	**Swale**	**Green roof**	**PPS**	**Detention basin**
Swale	0.001355759			
Green roof & swale	0.000919805	0.0099273		
PPS & swale	0.000408266		0.039693	
Green roof, PPS & swale	0.000512048	0.0012524	0.037399	
Swale & Detention basin	0.01268974			0.019507
Green roof, swale & detention basin	0.013202998	0.0018095		0.019081
PPS, swale & detention basin	0.007407172		0.009749	0.010462
Green roof, PPS, swale & detention basin	0.007268281	0.0005989	0.009616	0.010453

Minimum

Combination	**Swale**	**Green roof**	**PPS**	**Detention basin**
Swale	0.000620426			
Green roof & swale	0.000463621	0.0075354		
PPS & swale	0.000128632		0.030674	
Green roof, PPS & swale	0.000149301	0.000554	0.028417	
Swale & Detention basin	0.004810601			0.016497
Green roof, swale & detention basin	0.005637847	0.0010531		0.015146
PPS, swale & detention basin	0.004323551		0.006311	0.007633
Green roof, PPS, swale & detention basin	0.004823442	0.0003137	0.006246	0.00754

C 1.1: Decision Support Tool User Guide

The SuDS Decision Support Tool for Flood Management: User Guide

Introduction

The SuDS decision support tool assists users with developing a SuDS management train in *MicroDrainage®*. Before you begin using the tool, you will need the following information for your site (most can be found in the Flood Estimation Handbook):

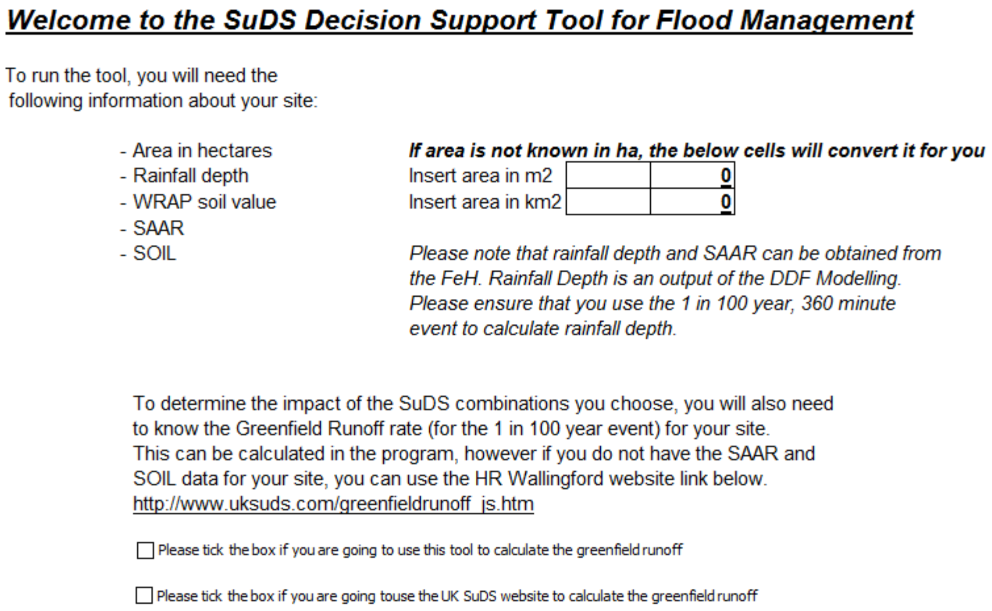
- Area of the site (ha) *note the tool can convert from km^2 or m^2 to ha*
- Rainfal depth (mm)
- WRAP soil value
- SAAR (Standard Average Annual Rainfall)
- SOIL
- Number and size of houses to be integrated at the site

Decision Support Tool Introduction Screen

Once the SuDS Decision Support Tool (DST) is open you will be prompted with Figure E-1. If you are unaware of the area of your site (ha), use the m^2 or km^2 conversion as appropriate.

The SuDS DST can be used to calculate the greenfield runoff. The recent Non-Statutory Standards for SuDS (DEFRA 2015) requires new site developments to not exceed greenfield runoff. However, if you would prefer to use the UK SuDS website (a link is provided), please feel free. You can progress by ticking the appropriate box:

- Use the tool to calculate the greenfield runoff
- Use the UK SuDS site to calculate greenfield runoff.



Welcome to the SuDS Decision Support Tool for Flood Management

To run the tool, you will need the following information about your site:

- Area in hectares
- Rainfall depth
- WRAP soil value
- SAAR
- SOIL

If area is not known in ha, the below cells will convert it for you

Insert area in m2		0
Insert area in km2		0

Please note that rainfall depth and SAAR can be obtained from the FeH. Rainfall Depth is an output of the DDF Modelling. Please ensure that you use the 1 in 100 year, 360 minute event to calculate rainfall depth.

To determine the impact of the SuDS combinations you choose, you will also need to know the Greenfield Runoff rate (for the 1 in 100 year event) for your site. This can be calculated in the program, however if you do not have the SAAR and SOIL data for your site, you can use the HR Wallingford website link below.
http://www.uksuds.com/greenfieldrunoff_js.htm

☐ Please tick the box if you are going to use this tool to calculate the greenfield runoff

☐ Please tick the box if you are going touse the UK SuDS website to calculate the greenfield runoff

Figure E-1 SuDS DST opening page

Decision Support Tool Introduction Screen

Please see Figure C-2 for a visual demonstration for the following sections.

Part 1: Site information

All boxes that are bordered in Figure E-2 enable the user to input the necessary data. At this stage, you will need to add in the following information for your site:

- Site size (ha)
- Rainfall depth (mm) from the FEH
- WRAP value

This will provide you with the maximum and minimum likely runoff in *MicroDrainage®* based on using conventional drainage (l/s).

The tool is for projects up to and including 50ha, for bigger projects this tool is unlikely to be suitable.

Part 2: SuDS information

You are now able to start adding in SuDS. Each device will be explained in turn. The only device that is integral to the DST is swales, all other devices do not need entering, if you do not wish to use them.

Detention Basins

You are to add the area (m^2) for each 0.5 m depth of the detention basin, in line with the method in *MicroDrainage®*. You are unable to change the depth and will therefore have to work with 0.5 m increments. The DST will calculate the combined volume in the corresponding box below **Part 1**.

Please note that although the detention basins are drawn in the tool to be up to 4 m deep, you do not have to use the full depth.

Green Roofs

The DST allows for the classification of three different housing types in *MicroDrainage®*; detached, semi-detached and terraced. This provides you with flexibility when calculating the amount of space available for green roofs. All green roofs are 100mm deep. This cannot be altered. Please insert the following values into the correct bordered boxes:

- Number of houses of each housing classification
- Average width of the house (m)
- Average length of the house (m)

Similar to detention basins, the total volume will be added to the corresponding cell below **Part 1**.

Porous Pavement

The calculation for porous pavement is similar to that used for greenfield runoff. It is again classified into the three different housing types and the depth for all porous paving is 450mm deep. This cannot be altered. The following information is required:

- Number of driveways of each housing classification
- Average width of the driveway (m)
- Average length of the driveway (m)

The volume will again be calculated and added to the corresponding cell under Part 1.

Swales

Swales are used for conveying runoff around the site. You are able to define the total number of swales that you want to use by clicking on the “Add New Swales” button. Once you have the desired number of swales, you will need to add in the following information:

- Average depth (m)
- Average width (m)
- Length (m)

The calculated volume for all swales will be added to the cell below Part 1.

Total runoff for your site

A maximum and minimum likely runoff will be rapidly calculated once you have input information for each of your desired SuDS devices. If you have used the UKSuDS site to calculate greenfield runoff, please not the difference between values. If your designed site produces a higher runoff than greenfield, you can add or remove SuDS or alter the existing number as you wish. If you are using the DST to calculate greenfield runoff, continue to **Part 3.**

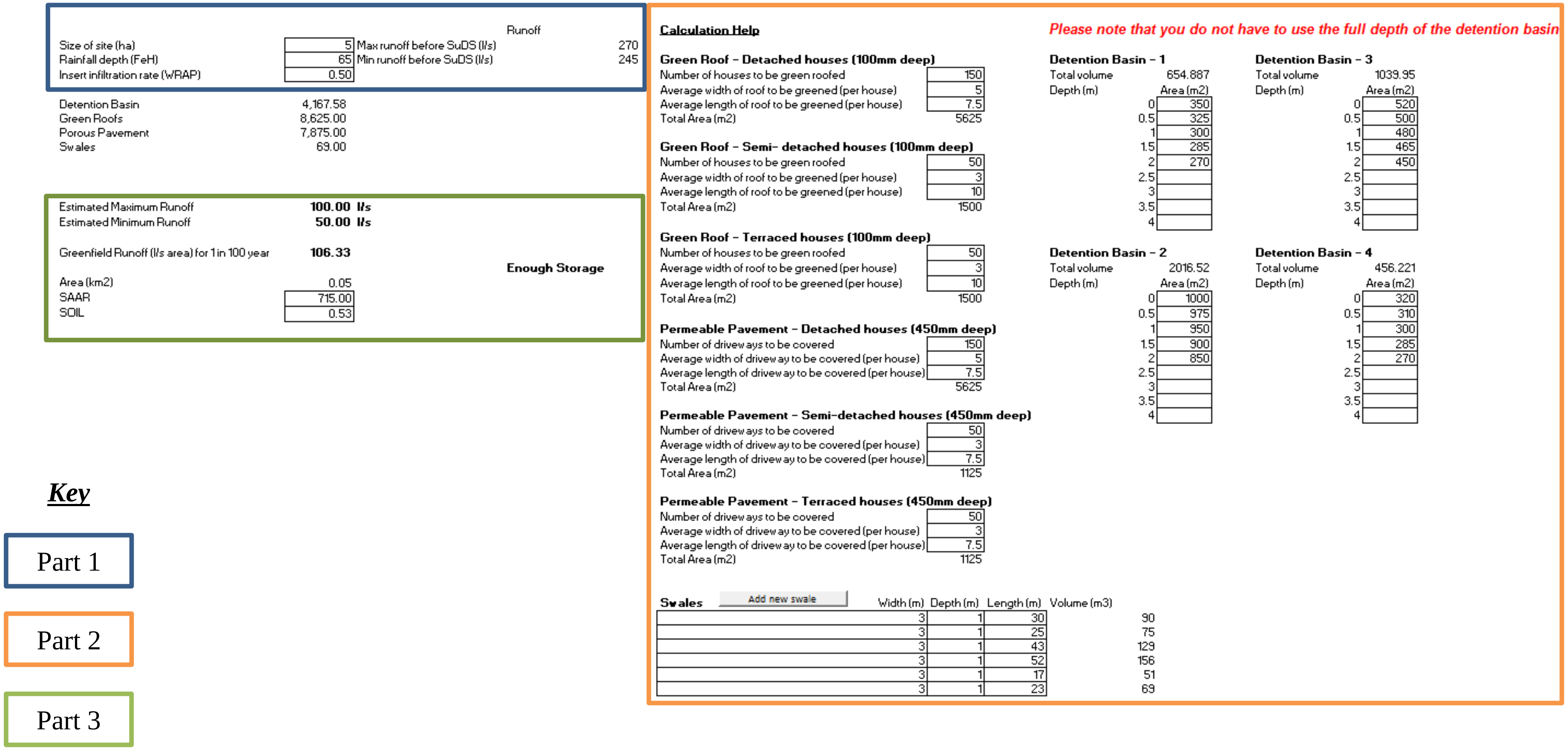
Part 3: Greenfield runoff

The final aspect of the tool involves calculating the greenfield runoff and comparing it to the likely maximum and minimum runoff for your designed site. Please add the following values to the corresponding boxes (note that the area is already calculated based on the value given in ***Part 1***:

- SAAR
- SOIL

This will calculate the greenfield runoff for the site and provide you with information on how to proceed: either the site does not exceed greenfield runoff and you can use the values to create the site in *MicroDrainage*®, or additional SuDS are required.

This tool only works in combination with MicroDrainage® and should only be used as a guidelines as to the number of devices needed to model the site in the program.



			Runoff
Size of site (ha)	5	Max runoff before SuDS (l/s)	270
Rainfall depth (FeH)	65	Min runoff before SuDS (l/s)	245
Insert infiltration rate (WRAP)	0.50		

Detention Basin	4,167.58
Green Roofs	8,625.00
Porous Pavement	7,875.00
Swales	69.00

Estimated Maximum Runoff	**100.00 l/s**	
Estimated Minimum Runoff	**50.00 l/s**	
Greenfield Runoff (l/s area) for 1 in 100 year	**106.33**	
		Enough Storage
Area (km2)	0.05	
SAAR	715.00	
SOIL	0.53	

Calculation Help

Please note that you do not have to use the full depth of the detention basin

Green Roof – Detached houses (100mm deep)

Number of houses to be green roofed	150
Average width of roof to be greened (per house)	5
Average length of roof to be greened (per house)	7.5
Total Area (m2)	5625

Green Roof – Semi- detached houses (100mm deep)

Number of houses to be green roofed	50
Average width of roof to be greened (per house)	3
Average length of roof to be greened (per house)	10
Total Area (m2)	1500

Green Roof – Terraced houses (100mm deep)

Number of houses to be green roofed	50
Average width of roof to be greened (per house)	3
Average length of roof to be greened (per house)	10
Total Area (m2)	1500

Permeable Pavement – Detached houses (450mm deep)

Number of driveways to be covered	150
Average width of driveway to be covered (per house)	5
Average length of driveway to be covered (per house)	7.5
Total Area (m2)	5625

Permeable Pavement – Semi-detached houses (450mm deep)

Number of driveways to be covered	50
Average width of driveway to be covered (per house)	3
Average length of driveway to be covered (per house)	7.5
Total Area (m2)	1125

Permeable Pavement – Terraced houses (450mm deep)

Number of driveways to be covered	50
Average width of driveway to be covered (per house)	3
Average length of driveway to be covered (per house)	7.5
Total Area (m2)	1125

Detention Basin – 1

Total volume	654.887
Depth (m)	Area (m2)
0	350
0.5	325
1	300
1.5	285
2	270
2.5	
3	
3.5	
4	

Detention Basin – 2

Total volume	2016.52
Depth (m)	Area (m2)
0	1000
0.5	975
1	950
1.5	900
2	850
2.5	
3	
3.5	
4	

Detention Basin – 3

Total volume	1039.95
Depth (m)	Area (m2)
0	520
0.5	500
1	480
1.5	465
2	450
2.5	
3	
3.5	
4	

Detention Basin – 4

Total volume	456.221
Depth (m)	Area (m2)
0	320
0.5	310
1	300
1.5	285
2	270
2.5	
3	
3.5	
4	

Swales Add new swale

	Width (m)	Depth (m)	Length (m)	Volume (m3)
	3	1	30	90
	3	1	25	75
	3	1	43	129
	3	1	52	156
	3	1	17	51
	3	1	23	69

Key

Part 1

Part 2

Part 3

Figure C-2: Main decision making page

8 Appendix D: Field data for Hamilton and laboratory data for PPS and Filter drains

Appendix D contains the raw data that enabled the validation of *MicroDrainage*® in Aim 3. Table D-1 is the field and model data for Hamilton, Table D-2 is the laboratory and model data for PPS and Table D-3 is the laboratory and model data for filter drains.

Table D-1 Field and model data for Hamilton, Leicester for five separate rainfall events. All flow data is in l/s.

Site	**19/02/2015**		**22/02/2015**		**14/05/2015**		**26/08/2015**		**03/12/2015**	
	Field	**Model**	**Field**	**Model**	**Field**	**Model**	**Field**	**Model**	**Field**	**Model**
Site 1	0.6	0.2	1.4	1.7	0	0	1.1	1.5	1.1	1.6
Site 2	1.2	0.5	1.8	3.2	0	0	5.1	3.8	0.8	1.7
Site 3	3.4	2.4	6	8.7	0	0.9	10.2	9.6	10.3	10.2
Site 4	2.8	2.2	8.9	8.5	0.6	0.9	7.6	10.5	9.3	12.9
Site 5	3.9	2.3	12	13.7	0.4	0.8	13.8	16.8	39.3	49.9
Site 6	2.4	2.5	9.8	14.3	1.5	0.9	16.3	15.4	37.2	48.8
Site 7	1.6	1.6	7.6	14.5	0.6	0.7	20.6	21.8	38.9	48.3
Site 8	1.7	1.6	10.1	13.4	0.8	0.8	11	14.6	40.4	51.1

Table D-2 Laboratory and model data for PPS. All flow data is in l/s.

	10mins @ 1.2 l/min		**12mins @ 1 l/min**		**16mins @ 0.8 l/min**		**15mins @ 0.6 l/min**		**25mins @ 0.4 l/min**	
Minutes	**Lab**	**Model**	**Lab**	**Model**	**Lab**	**Model**	**Lab**	**Model**	**Lab**	**Model**
1	-	-	-	-	-	-	-	-	-	-
2	0.6	1	0.4	0.8	0.2	0.6	0.1	0.3	-	-
3	1	1.4	0.8	1.2	0.5	1	0.3	0.5	0.1	0.3
4	1.8	1.9	1.5	1.6	1	1.3	0.6	0.9	0.2	0.4
5	2.2	2.4	2	2	1.6	1.6	0.9	1.1	0.3	0.6
6	3.3	2.9	2.2	2.4	1.8	1.9	1.1	1.3	0.5	0.8
7	3.4	3.3	2.2	2.8	1.9	2.2	1.3	1.5	0.7	1
8	3.5	3.5	2.8	2.9	2	2.3	1.4	1.5	0.8	1.1
9	3.6	3.6	3.2	3	2.2	2.4	1.6	1.8	0.9	1.1
10	4.1	3.7	3.3	3.1	2.7	2.5	1.6	1.8	1	1.2
11	3.1	3.3	3.3	3.2	2.7	2.5	1.7	1.9	1.1	1.3
12	2.5	3	3.4	3.3	2.8	2.6	1.7	1.9	1.1	1.3
13	1.9	2.6	3.1	3	2.8	2.7	1.8	2	1.2	1.3
14	1.5	2.3	2.3	2.7	2.8	2.8	1.9	2.1	1.2	1.4
15	1.1	1.8	1.8	2.3	2.7	2.8	1.9	2.1	1.3	1.4
16	0.9	1.3	1.1	1.9	2.7	2.8	1.9	1.8	1.3	1.4
17	0.6	0.8	1	1.5	2.7	2.5	1.5	1.6	1.3	1.4
18	0.5	0.7	0.7	1.1	2.3	2.1	1.2	1.3	1.4	1.4
19	0.5	0.6	0.6	0.7	1.7	1.8	0.9	1.1	1.4	1.4
20	0.3	0.5	0.5	0.6	1.3	1.5	0.7	0.9	1.4	1.4
21	0.3	0.4	0.4	0.5	1	1.2	0.5	0.5	1.4	1.4
22	0.3	0.2	0.3	0.4	0.8	0.9	0.4	0.4	1.4	1.4
23	0.2	0.1	0.3	0.3	0.6	0.6	0.3	0.3	1.4	1.4
24	-	-	0.3	0.3	0.5	0.5	0.3	0.3	1.4	1.4

	10mins @ 1.2 l/min		12mins @ 1 l/min		16mins @ 0.8 l/min		15mins @ 0.6 l/min		25mins @ 0.4 l/min	
Minutes	**Lab**	**Model**	**Lab**	**Model**	**Lab**	**Model**	**Lab**	**Model**	**Lab**	**Model**
25	-	-	-	-	0.5	0.4	0.2	0.2	1.4	1.4
26	-	-	-	-	0.4	0.3	0.2	0.2	1.4	1.4
27	-	-	-	-	0.3	0.2	-	-	1.1	1.1
28	-	-	-	-	0.3	0.2	-	-	1	0.9
29	-	-	-	-	-	-	-	-	0.7	0.8
30	-	-	-	-	-	-	-	-	0.6	0.6
31	-	-	-	-	-	-	-	-	0.5	0.4
32	-	-	-	-	-	-	-	-	0.4	0.4
33	-	-	-	-	-	-	-	-	0.3	0.3
34	-	-	-	-	-	-	-	-	0.3	0.3
35	-	-	-	-	-	-	-	-	0.3	0.3
36	-	-	-	-	-	-	-	-	0.2	0.2

Table D-3 Laboratory and model data for filter drains. All flow data is in l/s

	5mins @ 0.4 l/min		**5mins @ 0.8 l/min**		**10mins @ 0.4 l/mins**		**10mins @ 0.8 l/mins**		**15mins @ 0.8 l/min**	
Minutes	**Lab**	**Model**	**Lab**	**Model**	**Lab**	**Model**	**Lab**	**Model**	**Lab**	**Model**
0	0	0	0	0	0	0	0	0	0	0
1	0.093	0.1	0.2326	0.3	0.155	0.2	0.2326	0.3	0.2481	0.3
2	0.5814	0.6	1.2791	1.3	0.3101	0.5	1.3953	1.3	1.2403	1.3
3	0.8527	0.9	1.7829	1.8	0.814	0.9	1.7829	1.8	1.5504	1.8
4	0.969	1	1.9767	2	1.0465	1	1.938	2	1.8605	2
5	1.0465	1	1.9767	2.1	1.0078	1	1.938	2.1	1.938	2.1
6	0.5814	0.8	1.3178	1.6	1.0078	1	1.938	2.1	2.0155	2.1
7	0.1938	0.3	0.2713	0.5	1.0078	1.1	1.938	2.1	2.0155	2.1
8	0.093	0.1	0.0775	0.3	1.0078	1.1	1.938	2.1	2.0155	2.1
9	0.0543	0.1	0.0698	0.1	1.0078	1.1	1.938	2.1	2.0155	2.1
10	0.0388	-	0.0388	0.1	1.0078	1.1	1.938	2.1	2.0155	2.1
11	0.0233	-	0.0233	-	0.8527	0.9	1.4729	1.6	2.093	2.1
12	0.0233	-	0.0233	-	0.2326	0.4	0.2326	0.8	1.9767	2.1
13	0.0233	-	0.0155	-	0.155	0.1	0.093	0.3	2.093	2.1
14	0.0233	-	0.0155	-	0.0543	0.1	0.0543	0.1	2.093	2.1
15	0.0155	-	0.0155	-	0.0388	-	0.0388	0.1	2.093	2.1
16	0.0155	-	0.0078	-	0.0233	-	0.0233	-	1.4729	1.8
17	0.0155	-	0.0078	-	0.0233	-	0.0233	-	0.3876	0.8
18	0.0155	-	0.0078	-	0.0233	-	0.0233	-	0.1938	0.3
19	-	-	-	-	0.0155	-	0.0155	-	0.1163	0.1
20	-	-	-	-	0.0155	-	0.0155	-	0.0698	0.1
21	-	-	-	-	-	-	-	-	0.0543	-