A GIS WATER BALANCE APPROACH TO SUPPORT SURFACE WATER FLOOD RISK MANAGEMENT

Jacqueline Diaz-Nieto

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ABSTRACT

Concern has arisen as to whether the lack of appropriate consideration to surface water in urban spatial planning is reducing our capacity to manage surface water flood risk. Appropriate tools are required that allow spatial planners to explore opportunities and solutions for surface water flooding at large spatial scales. An urban surface water balance model has been developed that screens large urban areas to identify flooded areas and which allows solutions to be explored. The model hypothesis is that key hydrological characteristics; storage volume and location, flow paths and surface water generation capture the key processes responsible for surface water flooding. The model uses a LiDAR DEM (Light Detection and Ranging Digital Elevation Model) as the basis for determining surface water accumulation in a catchment and has been developed so that it requires minimal inputs and computational resources.

The urban surface water balance approach is applied to Keighley in West Yorkshire where several instances of surface water flooding have been reported. Data for validating surface water flood risk models is sparse because such flooding events are of short duration, very localized and distributed across the catchment. This research used a postal questionnaire, followed up with site visits to collect data on surface water flooding locations in Keighley. The validation exercise confirmed that the major processes responsible for flooding are largely well represented in the model for situations where interaction with the urban sewer network is well represented by the assumptions made in the model. A qualitative analysis based on field visits revealed that the degree of interaction with the sewer network varies spatially, and as the importance of the interaction of the sewer system increases, the accuracy of the model results are lowered. It also highlighted that local detail not present in the DEM, the presence of urban drainage assets and the performance of the sewer system, which are not be represented in the model, can determine the accuracy of model results.

Model results were used as a basis to develop solutions to surface water flooding. A least cost path methodology was developed to identify managed flood routes as a

solution. These were translated into model inputs in the form a modified DEM. It was shown that the simple and fast representation of flood routes and surface storage is of considerable benefit for scenario analysis.

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ABBREVIATIONS

CBMDC	City of Bradford Metropolitan District Council
CSO	Combined Sewer Overflow
DEM	Digital Elevation Model
ESRI	Environmental Systems Research Institute
FEH	Flood Estimation Handbook
GIS	Geographical Information Systems
IUD	Integrated Urban Modelling
LiDAR	Light Detection and Ranging
LU	Land use cost factor
OSMM	Ordnance Survey Master Map
SF	Slope cost factor
SuDS	Sustainable Drainage Systems
SWBM	Surface water balance model

1. Introduction

1.1. Flooding in urban areas

The Oxford English Dictionary defines 'flood' as "an overflowing or influx of water beyond its normal confines" (Allen, 1990). Urban areas can be flooded by water from a number of sources, and these include coastal waters, groundwater, river flows, foul water from sewers, water from burst water mains and rainfall that remains on the urban surface. Flooding has traditionally been classified according to the direct source of water (as listed above) as this has permitted scientists to concentrate on understanding the underlying processes and mechanisms responsible for the water to flow beyond its normal confines, be it the piped sewer system, the river channel, or the infiltration processes that usually drain the land. In reality all flooding is part of the same system; the water cycle. In the current decade, and as a direct consequence of recent flood events, there has been a move towards integrating the research to date in each of the component parts of the system responsible for flooding (although it is recognized that not all parts of the system are always included). Recent flood events in the UK, most notably the flooding in the summer of 2007, acted as a timely reminder that the various processes that lead to different types of flooding, do not always occur in isolation and furthermore interact with each other (Table 1.1). In the summer of 2007, climate conditions led to many UK cities suffering from rivers overtopping their banks as well as a build-up of rainfall on the urban surface (that never entered the sewer system or the fluvial system) and surcharging from overloaded sewers. Since the recent flooding events a new branch of urban flood risk science has taken off and is known as Integrated Urban Drainage (IUD) (Gill, 2008). Whilst there is still much research needed to fully understand and model the processes (both physical and institutional) that lead to flooding from each of the components, IUD modelling aims to integrate current knowledge in each of the fields to better understand the joint consequences.

Table 1.1: Interactions between some of the different sources of urban flooding

Source of flooding	Interactions with other sources of flooding
Fluvial	Raised river levels prevent surface water from discharging into rivers and watercourses and rivers and therefore it remains on the urban surface. Raised river levels also cause backing up of sewers which can lead to surcharging and flooding from the sewer system.
Surface water	Increased surface water makes its way into rivers and increases flow in rivers. Increased runoff production means greater quantities of water enter the sewer system.
Sewer system	Increased flow in sewers leads to increased combined sewer overflow spills into rivers; therefore there is more flow and pollution in rivers. Surcharged assets expel water onto the urban surface aggravating surface water flooding.
Groundwater	Raised water tables can cause direct flooding of basements, tunnels and even at the surface. Groundwater interacts with other potential sources of flooding as raised water tables can reduce soil infiltration and groundwater infiltration into sewers reduces the available conveyance capacity.

1.2. SURFACE WATER FLOODING

The boundaries between the different types of flooding are often blurred. There is a fine line between what is now being termed surface water flooding and sewer flooding. Under normal conditions, rainfall that lands on the urban surface is expected to enter the sewer system and eventually be removed from the urban area (Butler and Davies, 2000). In some cases, rainfall never enters the sewer system for a number of reasons; it could be that the topography means that the flow route of the rainfall falling on a particular spot is never intercepted by a gulley or it could be that the sewer system is full and therefore rainfall cannot enter it. A build-up of surface water in both these cases would be termed surface water flooding. However, it is also possible for rainfall that has entered the sewer system at one point to then leave the sewer system under surcharging conditions at a point further downstream. This water will then proceed to flow on the urban surface and could either be termed sewer flooding or surface water flooding. It is currently the responsibility of each researcher to clearly define the scope of their research.

Several terms are currently in use which can all be interpreted to mean the same type of flooding including; stormwater flooding, pluvial flooding and surface water flooding. A clear consensus on a definition for each of the terms could not be found, and all the terms are used to mean similar types of flooding in the literature. In this research the term surface water flooding is adopted, in line with current practice within organizations in the UK. The definition adopted is that surface water flooding is rainfall that ends up on the urban surface because it does not infiltrate into the ground and neither is it drained by the sewer system. This definition excludes flooding that may arise from sewer surcharges or failures. This runoff, which is termed excess surface water throughout the thesis, either moves across the urban surface as overland flow or remains on the urban surface in the form of puddles and large ponding areas.

Usually puddles in urban areas aren't seen as a problem and therefore they are not referred to as flooding, but when the puddles are large enough to close roads because vehicles cannot drive through, or when the puddles prevent people from getting into their houses, this is a surface water flooding problem. Similarly, very shallow overland flow running along the side of a road does not cause inconvenience, but when the overland flow path is through a property, or is so deep that it prevents vehicles and pedestrians from using the roads, it is classed as a flooding problem. There is now a growing awareness, possibly coupled to a growing frequency of surface water flooding, as illustrated by a quick scan of recent media reports on the internet that refer to surface water flooding incidents as listed below:

- "Some roads were left under several inches of water after an intense rain and hail storm overwhelmed drains on Saturday" (BBC News, 2011)

- "As the road down through the street began to look more like a river, householders were forced to make a mad dash to the fire station to collect sand bags and protect their property" (Harwick News, 2011)

- "...London Assembly's Environment Committee claim some streets could flood from rain within minutes." (EdieWater, 2011)

- "Motorists endured treacherous conditions while driving through flooded roads in Newcastle-upon-Tyne on Saturday – and there is more weather like this to come" (Mail Online, 2011)

- "I watched the water cascading down Feus Road on Wednesday and the drains were clearly no use, again" (Perthshire Advertizer, 2011)

- "The pumping station, to be sited underneath the Corporation Street car park, will pump surface water into the adjacent river during a flood, reducing the risk to central Rotherham" (Yorkshire Post, 2011)

- "We are working with Dundee City Council to investigate the wider issues regarding surface water management across the catchment" (The Courier, 2011)

- "There is obviously a major fault in the system when the drains cannot cope with what has become normal rainfall and we must look again at what has been done and what still needs to be done to ensure that these folk can sleep in their beds at night" (Southern Reporter, 2011)

1.3. MODELLING SURFACE WATER FLOODING AND LIDAR

Up until the last decade surface water flooding (in this case defined as rainfall that is not removed from the urban surface by the sewer system), was modelled and predicted by representations of the piped urban drainage system. These include sewer network models such as Infoworks CS, MOUSE (Model for Urban SEwers) and SWMM (StormWater Management Model) which use mathematical modelling to represent the hydraulics in pipes and manholes (Butler and Davies, 2000). The contributing area of the sewer entry points has traditionally been manually delineated using topographical and land use maps and following expert judgement (MWH Soft, 2011). Runoff from the contributing areas is computed by the Rational Method or one of the empirical percentage runoff coefficients developed by HR Wallingford (DoE, 1983), and is then applied to obtain the volumes of flow entering the system. Surface flooding is predicted at manhole locations where flow exits the sewer system. The volume of flood water exiting the system may then be used to produce an outline of the extent of the flooded area, or an attempt to predict the likely onward overland flow path can be made using topographical data.

LiDAR (Light Detection and Ranging) is a relatively new technology which enables the production of digital elevation models, over large areas and at very high resolutions (Lillesand and Kiefer, 1999). The availability of such data triggered a rebirth in the techniques used to predict surface water flood risk. Existing urban drainage models began to be revised (Allitt et al., 2009) to make use of LiDAR DEMs (Digital Elevation Models), principally to model the onward overland flow route of water leaving the sewer and also re-entering, but also to better predict surface water flood depths and extents. New models have also been developed that exploit the detail in LiDAR DEMs to model overland surface flows using 2D hydrodynamics (Hunter et al., 2008), and LiDAR DEMs have also been used to extract 1D networks representing the urban surface, which are then used to compute channel hydraulics (Maksimović et al., 2009). These on-going developments in urban drainage modelling have also fed into current exercises in integrated urban drainage modelling, whereby sewer network models are coupled to models that represent surface overland flows and in some cases a representation of the fluvial system is also included (Chen et al., 2010).

LiDAR DEMs created much excitement in the urban drainage modelling community because they cover large spatial areas at a relatively low cost (compared to land surveying techniques) and furthermore they represent many of the urban features that dictate water movement, such as buildings and road curbs, which are not always obvious from topographic maps. Whilst LiDAR has generally been accepted as a valuable resource, there are still challenges to be addressed which currently mean that there are inherent limitations in the use of LiDAR for surface water modelling. For example, techniques have been developed to remove vegetation and extract surface heights in its place, but other features such as road bridges and elevated roads continue to pose challenges for hydrological modelling (Evans, 2008). Similarly, depending on the resolution of the data, not all features that dictate surface water movement are captured by LiDAR.

1.4. MODELLING WITH GIS

Geographical Information Systems (GIS) are widely used in various disciplines and applications. It is thought that GIS originates from exercises that date back to the 1960s when the first computerized maps were being produced (Longley et al., 2001). Although in many ways GIS are similar to a database, in that various data sets can be linked and queried, and to computer aided design (CAD) in that shapes and geometric properties can be produced and stored, the unique features of GIS are the ability to carry out spatial analyses and queries, and to be able to geo-reference features in relation to the earth's surface. GIS is used as a (spatial) problem solving tool because it allows specific and high resolution information to be combined to produce general patterns which form the basis of the practical output for decision making and problem solving (Longley et al., 2001).

GIS has been widely applied in hydrology (Chen et al., 2004; Jenson, 1991; Maidment, 1993; Maidment, 2002; Singh and Woolhiser, 2002), and GIS software packages include as standard basic tools for hydrologic analysis such as identification of cell flow direction, catchment delineation tools and methods for identifying surface depressions (ESRI, 2010). New algorithms continue to be developed for improving the extraction of hydrological and hydraulic data from DEMs (Freeman, 1991; Metz et al., 2011; Tarboton et al., 1991; Wang and Liu, 2006). GIS has also been used as a modelling platform in itself (Chen et al., 2009), and as a source for extracting or computing parameters as inputs for hydraulic models (Boonya-Aroonnet et al., 2007; Casas et al., 2006; Evans and Ackerman, 2000; Wiles and Levine, 2002). Although GIS has been used to compute river catchment water balances (Arnold et al., 1999), there are few studies that combine standard hydrological tools and GIS capabilities to compute the urban surface water balance with the aim of predicting flood risk locations. The main difference is that catchment scale water balance models are usually based on well-defined and reasonably well understood river channel networks. Water movement across an urban surface is not as straightforward to identify due to small and subtle man-made features which alter natural pathways. A water balance approach that uses a LIDAR DEM in a GIS to dictate locations of surface water accumulation may prove useful in screening for surface water flood risk at large scales. To screen for flood risk over large scales using hydrodynamic modelling, not only requires significant parameterization and calibration but also computational resources. Methods that can screen large areas with minimal resources would therefore be of great value. Similarly, models that facilitate solutions and scenario analysis to be explored over large scales, would be of use. A water balance approach may satisfy these needs.

1.5. SURFACE WATER FLOOD RISK SOLUTIONS AND CLIMATE CHANGE

Much of the UK drainage system, particularly in older towns and cities, dates back to the Victorian era. Since then towns and cities have grown along with connections to the sewer system (Butler and Davies, 2000). This has meant that not only are there more pipes and drains collecting water into the sewer network, but increasing imperviousness and impermeability associated with urbanization also means that more rainfall is converted into runoff. Both of these factors increase the risk of surface water flooding. Coupled to these pressures is the uncertainty surrounding changing rainfall patterns associated with climate change and the need to adapt to an uncertain future (Evans et al., 2004a). Most climate change studies conclude that extreme rainfall events will become more frequent (Hulme, 2002), however translating climate change rainfall scenarios into the temporal resolution required for urban drainage modelling is an area of ongoing research.

Despite calls for a re-think of surface water management (White and Howe, 2004), surface water flood risk only really moved up the research agenda following the flooding in the summer of 2007, with recommendations emerging as a direct result (Pitt, 2008). These are now beginning to be reflected in legislation and The Flood and Water Management Act (2010) is expected to lead to significant changes in the surface water management. For example, the automatic right to connect to the sewer system may be modified and it should become easier to implement sustainable solutions which up until recently were held back by institutional and organizational barriers. SuDS (Sustainable drainage systems and also known as BMPs, Best Management Practices and WSUD, Water Sensitive Urban Design) is a term that describes a collection of man-made features that aim to mimic the natural processes of urban drainage (Woods-Ballard et al., 2007). Although in some cases increasing the capacity of the sewer system or underground assets is still deemed the most viable option, it is now generally accepted that sustainable urban drainage solutions are more desirable and provide greater adaptability to deal with climate change, as well as offering social and ecological benefits (Faram et al., 2010; Wong, 2001).

Recent thinking regarding climate change calls for more emphasis on adapting to climate change, rather than merely stating the impact of climate change (Wilby and Dessai, 2010). Identifying adaption options is a huge challenge as even without climate change, current trends point to the fact that we are in fact reducing our ability to deal with the challenges associated with climate change. Monitoring of the UK's progress in adapting to climate change found that impervious cover increased at the expense of urban green space in six locations in the UK (Committee on Climate Change, 2011), highlighting the reduced adaptive capacity for surface water flood risk management. Faram et al (2010) also make the point that the existing built environment is one of the major constraints in implementing sustainable drainage options. In dealing with surface water flooding, it is not an option to wipe the slate clean and start afresh (Faram et al., 2010), therefore methods are needed to identify viable solutions that can be implemented given the current urban fabric. There has been much progress in this field, in terms of development of decision support tools (Swan, 2003) and guidance (CIRIA, 2011) for identifying opportunities for retrofit SuDS .

1.6. Objectives

The aim of this research is to develop a model for screening for flood risk locations, which is computationally efficient so that it can be used to rapidly evaluate a range of high level surface water flood risk solutions. The overall aim of the thesis is to use the model results to propose surface water management solutions and to evaluate a range of scenarios on their ability to build in capacity to cope with surface water flooding under current and climate change conditions. To achieve the overall thesis aim, three main objectives were set out:

1. **To develop and validate a model to screen for surface water flooding.** A computationally efficient model is required that will represent the main processes responsible for flooding. The research aims to use a LiDAR DEM as a basis on which to develop a model that represents surface water flooding processes, but that requires minimal effort in order to rapidly evaluate solutions and scenarios. The research seeks to test whether conceptually simple approaches that exploit the detail in LiDAR DEMS, are able to form the basis to screen for surface water flooding. The hypothesis that a water balance can represent the main processes that lead to surface water flooding will be tested through the model validation.
2. **To use the model results to propose surface water management solutions over a large scale.** The understanding gained from the modelling exercise, in terms of the general flooding patterns and the processes that lead to surface water flooding, will be used as a basis to propose solutions. The relevant design solutions literature will be reviewed in order to identify a range of options.
3. **To use the surface water model to evaluate a range of solutions in terms of their potential to build in adaptability to climate change.** The solutions identified will be translated into model inputs, in the form of an altered DEM. Climate change scenarios will be created and translated into model inputs in the form of climate change perturbed rainfall. A measure of catchment surface water flooding will be proposed based on model outputs and this will be used to compare and evaluate the solutions.

1.7. THESIS LAYOUT

To achieve the objectives set out above, the research was divided into three major phases which correspond to the three main research activities that were conducted. Each phase of work is covered in a self-contained chapter, which also includes a more detailed introduction and literature review relevant to the research described in the chapter.

The first phase of work involves the development of the model. To complete this phase it was necessary to familiarize myself with the various modelling techniques that were being developed for surface water modelling (e.g. 1D, 2D modelling). The development of an understanding of conventional urban drainage modelling and urban hydrology was also necessary. Based on this understanding I developed a conceptual framework which would then be translated into a GIS modelling tool. Chapter 2 describes current surface water modelling capabilities and developments and against this backdrop of research, a new alternative modelling approach is proposed, fit for the purpose of screening large areas. Chapter 2 is a manuscript submitted and accepted for publication in the ASCE Journal of Hydrologic Engineering.

The second major activity undertaken in order to complete the research was to carry out a validation exercise. It was necessary to discover how emerging models were being evaluated and tested. Appropriate data to validate my model was needed. Chapter 3 describes this model validation. An overview is given of how existing surface water flood risk models are validated, and the methodology, based on questionnaires and local knowledge, which was adopted to validate the model developed in this research is described. The results of the validation exercise are presented and evaluated. Chapter 3 concludes by discussing the insights into the model performance that were gained as a result of the validation exercise. The lessons learnt from the questionnaire exercise, as a means of model validation are also presented.

The final phase of work involved using the model to propose surface water management solutions and evaluate their potential under climate change. This involves interpreting the model results to understand the main processes that lead to flooding in the study catchment. With a greater understanding of the underlying reasons for surface water flooding, appropriate solutions can be sought. A literature review was conducted in order to understand surface water management solutions and design standards. By combining the understanding gained regarding the causes of flooding, and the emerging guidance on surface water solutions, a number of potential scenarios are proposed. It was discovered that there was very little guidance on how to identify managed flood routes and therefore a methodology was developed to find optimal routes through an urban area. Three solutions are selected and represented as new DEMs, which are used as an input for the surface water model developed in this thesis. The results of the scenario analysis are evaluated and discussed.

Finally the overarching conclusions of the research as a whole are presented in Chapter 5 along with future directions for research.

2. Model development

2.1. Introduction

There are serious concerns regarding the potential impacts of climate change and future development on urban flooding (Evans et al., 2004a). Only recently however has surface water flooding received due attention. Surface water flooding arises from rainwater that is not adequately drained naturally or by man-made infrastructure, and therefore accumulates in surface depressions. In the UK it has become commonplace to refer to this type of flooding as surface water flooding. According to the Environment Agency (2007), some two thirds of the flooding that took place across the UK in the summer of 2007 was due to surface water. This rapidly ascended the political agenda and triggered a series of reviews and recommendations (Coulthard et al., 2007; DCLG, 2008; Defra, 2008a; Pitt, 2008). It is now argued that the lack of appropriate consideration of surface water management is reducing our capacity to manage urban flood risk, especially given the uncertainty surrounding climate change (Ashley et al., 2005). Traditional responses to urban flooding relate to development design (Evans et al., 2004b) and high level spatial planning (DCLG, 2006; Defra, 2005). Major changes in urban form result in enormous disruption and cost, making such measures unfeasible. At the same time, enlarging the capacity of urban drainage assets can be costly, given the environmental and economic benefits. As a result of the flooding of 2007, there is a current requirement for UK local planning authorities to develop Surface Water Management Plans (SWMP) (Defra, 2009). Although the development of detailed guidance of what a SWMP should comprise is an ongoing process, locations at risk of surface water flooding need to be identified. There is therefore a need for appropriate tools that will allow local flood authorities to map surface water flood risk for large spatial extents within the resources available to them.

One opportunity for building in capacity to deal with urban flood risk is within pockets of land that become available for redevelopment. The importance of considering surface water flooding in both large scale redevelopment plans as well as individual planning applications is being recognized (DCLG, 2008; Defra, 2008b). In many surface water flooding events the sewer system may operate at capacity with only the major system (i.e. the surface) fully operational. There is therefore a need to better manage urban flood flows at the surface (Balmforth et al., 2006b). Redevelopment should take place in a way that maximises the opportunities for flood risk reduction. Appropriate hydrological tools are required that allow decision makers to explore opportunities and impacts of redevelopment plans at a range of scales.

RESEARCH AIMS

Urban topography is a critical factor determining the extent, depth and location of surface water flooding. Changes in topography, e.g. through redevelopment, potentially alter key storage areas and transmit surface water to previously un-flooded locations. Redevelopment alters infiltration characteristics and the amount of excess surface water that is generated. This work is based on the premise that by alteration of these key characteristics urban redevelopment can be exploited to manage surface water flood risk. To explore opportunities for flood risk management, the hydrological connectivity of sites of all sizes across the urban catchment need to be considered.

The hypothesis is that a simple water balance comprised of rainfall inputs, surface storage and pathways is able to represent the main processes that are responsible for surface water flooding. This would avoid the complexities of overland flow modelling coupled with underground drainage, and provide a simple tool with which decision makers can screen a range of scenarios. This can highlight areas which merit the use of more complex modelling tools. Our objectives are (1) to construct a water balance model for urban surfaces, and (2) to test its sensitivity and validity. The model will be used in later studies to explore the opportunities for flood risk management through urban redevelopment.

The model is based on a GIS approach that is widely accessible and capable of analysing raster data: the most common format for Digital Elevation Models (DEMs). GIS is also the standard approach for spatial planning applications and in this study ESRI GIS software was used to manage the data and to assemble the surface water balance model.

CURRENTLY AVAILABLE TOOLS

Traditionally urban drainage is represented using sewer network models. These are principally designed to simulate dry weather flows as well as stormwater flows within a combined system. For this purpose there are many widely used commercially available models; Infoworks CS (Wallingford Software, 2009b) , Microdrainage (Microdrainage, 2009), SWMM (Rossman, 2009), StormNET (Boss international, 2009), MOUSE (DHI, 2009) and others. Most sewer network models have a basic representation of the catchment surface. Empirically derived equations, such as the modified rational method, are used to calculate the runoff volumes that enter the piped system at given entry points. This requires catchment delineation along with an assessment of the pervious and impervious land cover, which has commonly been carried out manually using parcel and contour information from existing maps.

More recently, and as a result of the availability of high resolution DEMs, sophisticated overland flow models are being developed, with the primary aim of better determining surface flood location, depth and in some cases flow velocity. There are two approaches. In the 1D approach, the DEM is used to extract the location and geometry of overland flow paths, which are treated as channels and used to route pre-determined runoff hydrographs. In the 2D approach, the high resolution DEM is used to create the input surface to solve complex shallow water equations. Additionally many of these models are being developed so that they can be fully coupled to existing sewer network models.

Examples of emerging urban overland flow models include:

- the release in 2007 of InfoWorks 2D for integration of overland flow in Infoworks CS v8.5 (Wallingford Software, 2009a) ;
- release in 2007 of the 2D FloodFlow module for use within Microdrainage (Microdrainage, 2007)
- SIPSON (Simulation of Interaction between Pipe flow and Surface Overland flow in Networks) which is a coupled 1D surface and 1D sewer model (Djordjevic et al., 2005);

- a GIS based 1D link and node model for representation of overland flow (Boonya-Aroonnet et al., 2007; Maksimović et al., 2009);
- JFlow, a 2D raster routing model (Bradbrook, 2006) and
- a 2D overland flow urban inundation model (UIM) (Chen et al., 2005; Hsu et al., 2000) and
- a distributed GIS based pluvial inundation model (Chen et al., 2009).

Further reviews of current urban modelling capabilities can be found in (Balmforth et al., 2006a; Elliott and Trowsdale, 2007; Hankin et al., 2008; Leandro et al., 2009; Wheater et al., 2007).

The ability of GIS to process and generate spatially distributed information has meant that GIS have been widely used for hydrological modelling (Whiteaker and Maidment, 2004). Olivera and Maidment (1999) used GIS to identify uniform catchment sub-areas and flow paths and using this information generated catchment hydrographs based on spatially distributed rainfall. Liu et al. (2003) also proposed a method for computing unit hydrographs in GIS using the slope, roughness coefficient and hydraulic radius. This work was developed further to determine the runoff contributions from different land uses within the catchment (Liu et al., 2006).

The advent of high resolution LiDAR DEMs also prompted further investigation and understanding of GIS methods to extract information that act as input for hydrological applications. Barber and Shortridge (2005) compared the GIS derived hydrological outputs (flow direction , basin identification and contributing area) from a standard 30 m USGS DEM and a LiDAR DEM and found the results to be comparable in high relief areas, but greater differences were observed in output for low-relief areas. Erskine et al. (2006) compared five existing algorithms for computing contributing area in GIS and found that when used on DEMs of higher resolutions there are greater differences in the results produced by the algorithms. (Zandbergen, 2006) investigated the occurrence of artificial depressions associated with high resolution LiDAR DEMs and found the number of depressions to be least in DEMs with cell resolutions between 30 and 61 metres. This research is of importance to hydrological modelling since many flow direction algorithms require a depression free surface to generate flow patterns.

Correctly identifying depressions that are artefacts of the data, and then infilling these can be a time consuming task. The standard tool found in most GIS software analyses the surface iteratively several times. Wang and Liu (2006) proposed an alternative and faster method based on least cost analysis. The growing volume of research into GIS methods to create hydrologically correct DEMs is also illustrated by reviews covering issues regarding grid cell resolution and surface modification (Wechsler, 2006).

More recently GIS have been exploited for more specific hydrological applications. Jones et al. (2008) propose a novel technique for identifying the flow patterns of low relief landscapes which in addition to using the D8 flow direction algorithm, is based on facets. In the US where surface storage has been widely incorporated, but where records on the location and characteristics are not always known, a GIS method is proposed to locate and characterize these using LiDAR DEMs (Liu and Wang, 2008). Methods have also been compared for incorporating known piped drainage characteristics (e.g. pipe and gutter elevations) into DEMs for urban hydrological modelling (Gironás et al., 2010). Whilst it was found to be beneficial to incorporate data on known surface drainage for urban flow path modelling, Gironás et al. (2010) noted that varying contributing areas, and therefore catchment characteristics were obtained depending on the method used.

Standard GIS methods such as identifying cell flow directions and determining hydrological flow patterns have been widely used for river catchments. There are fewer studies that extract useful hydrological information relevant to urban catchments. Urban environments pose greater challenges due to modifications by man to the natural surface hydrology (by alternation of the topography) and this is coupled to the greater resolution which is required to accurately identify such features. Similarly few studies have used GIS for modelling urban surface water accumulation based on properties derived from a DEM. Djokic and Maidment (1991) used GIS capabilities to create a network for modelling flows. The piped drainage network was integrated with the known surface drainage and input DEM (which consisted of digitized contours) was used to calculate contributing areas and time of concentration. Due to the acknowledged complexities of identifying flow patterns in urban surfaces, the input DEM was not used to determine the surface flow patterns. This is no longer the case with the availability of high resolution DEMs which capture man-made protruding structures and depressions, that form part of the urban topography dictating flow patterns. Given the freely available existing algorithms to extract key hydrological information from DEMs, and the capabilities of GIS as a hydrological modelling environment it is now also timely to test whether hydrological modelling in GIS is capable of efficiently screening for urban surface water flood risk.

Generally however, hydrodynamic models and those linked to a sewer network may take several hours to simulate a large area. Such models are also complex, often requiring an exact representation of the characteristics of the catchment surface, and the input of a large number of hydraulic and network parameters. These models require expert users. Hence the development and application of a simpler and faster representation of surface water would be of considerable benefit to all those involved in screening for urban flood risk management. This paper describes the development of one such model.

2.2. URBAN SURFACE WATER BALANCE MODEL

Excess surface water is that which remains on the surface after accounting for losses such as infiltration. Water that drains to a surface sink is stored according to the sink volume and any further water is passed downstream. The model assumes that there are no inputs or outputs from the piped sewer system and that there are no further losses, for example as runoff travels across a pervious area.

The water balance is computed as the total water that accumulates and overflows through a series of sinks as presented in Figure 2.1 and Equation 2.1:

$$\underset{P=0 \rightarrow P<0}{P} = \sum P_{j=1,n} + E - V \qquad \textit{(Eq. 2.1)}$$

Where P is the water passed down from sink (m^3), E is the excess surface water from the sink catchment that is not accounted for by smaller nested catchments (m^3), V is the sink volume (m^3) and j is a counter of the nested sinks from 1 to n. Sinks are areas where ponding occurs, making them areas of potential flooding or critical storage. Each sink has a catchment and these are nested, with small catchments nested within larger ones. A nest level of five means that the catchment is nested within and drains to five larger catchments. A value of 1 refers to the major sub catchment from which water drains to a model boundary. Sinks fill up with excess surface water and when a sink is full it overflows and passes water downstream to the catchment in the next nest level. A summary flow chart of the methodology and model processes is presented in Figure 2.2. Box A1 and A2 in Figure 2.2 outline the production of the principal model inputs; an excess surface water layer, a modified DEM and sink polygons. The data and methods used to derive the model inputs are presented followed by a description of the water balance computation.

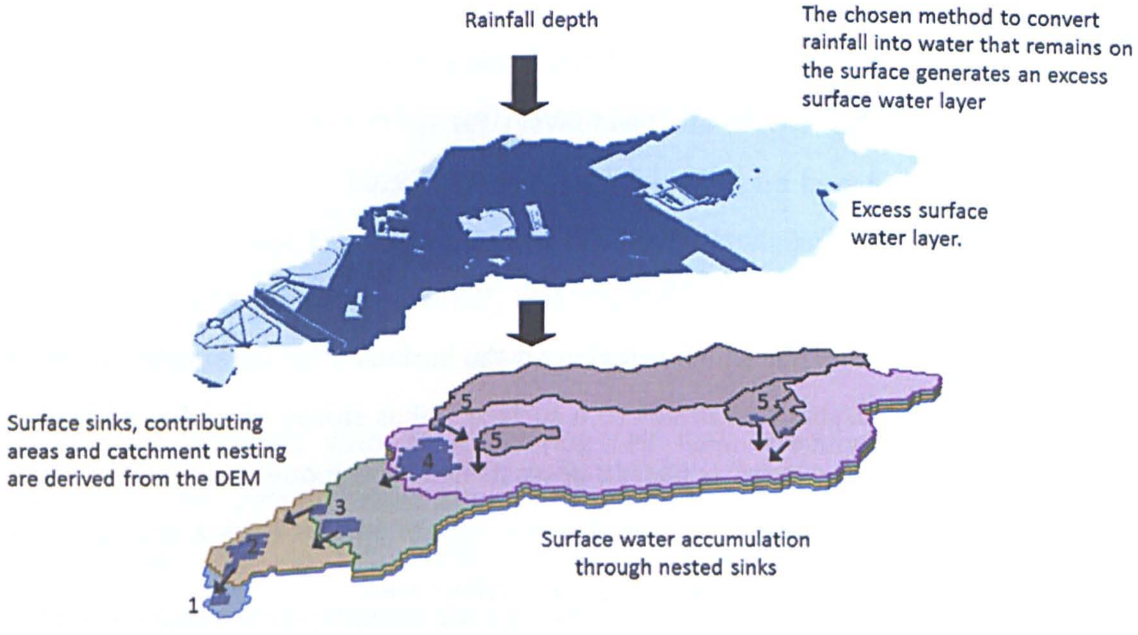

Figure 2.1: Conceptual model of excess surface water accumulation across the urban surface. The contributing areas labelled 5 are nested within 5 other contributing areas. Contributing area 1 is the contributing area of the most downstream sink and its contributing area is equal to the major sub-catchment boundary (and it contains all other contributing areas). Surface water accumulation is calculated by applying Equation 2.1. at the outlet of the contributing areas of nest level 5. The arrows downstream of the number 5 represent the results of the calculation i.e. the water passed down from those sinks. The second iteration applies Equation 2.1. to the contributing areas of nest level 4. In this iteration the contributing areas of nest level 5 are not taken into account, only water passed down from level 5 and contributing area that has not already been accounted for (e.g. for nest level 4 it is shown in purple). The algorithm iterates in this manner until the results for nest level 1 are computed.

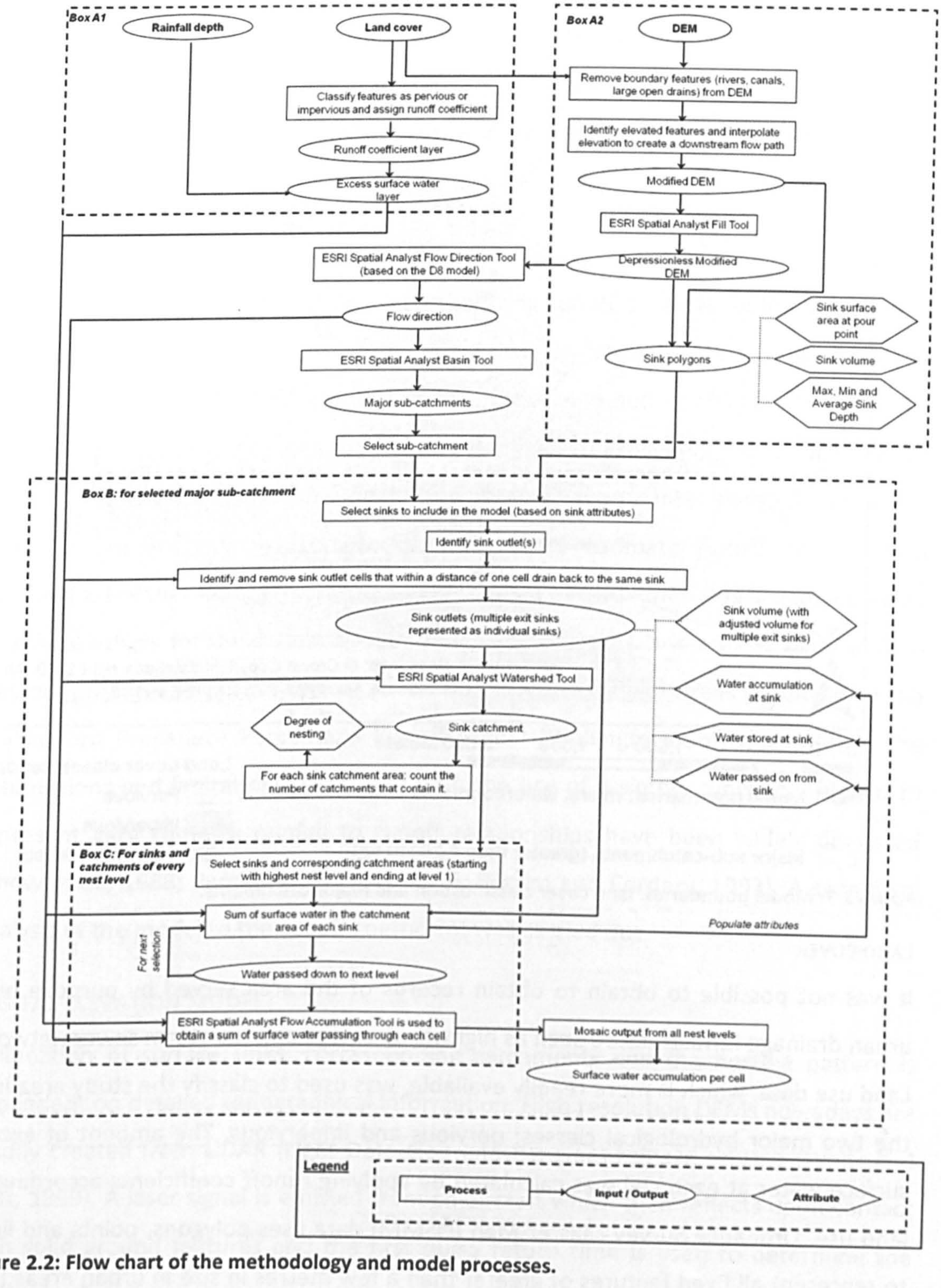

Figure 2.2: Flow chart of the methodology and model processes.

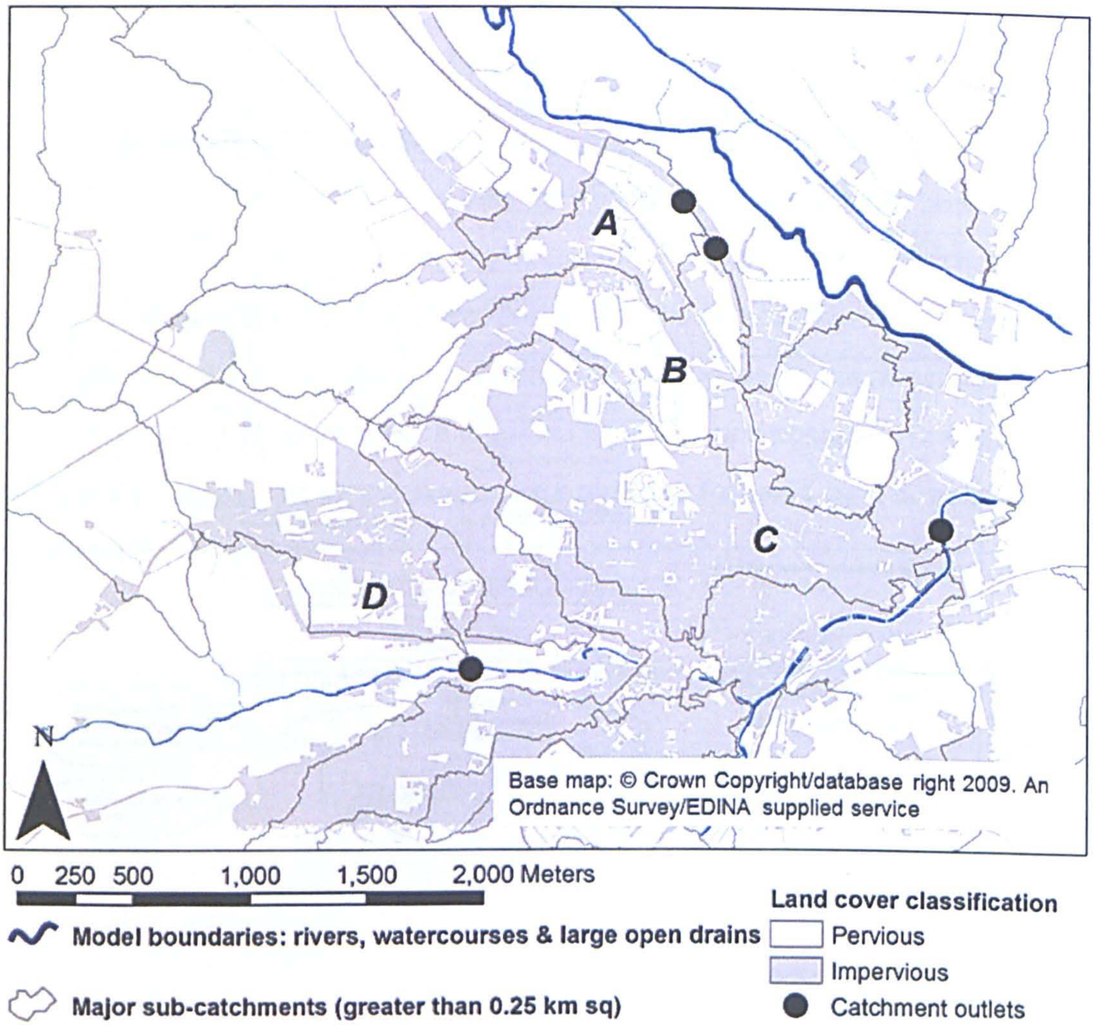

Figure 2.3: Model boundaries, land cover classification and major catchments.

LAND COVER

It was not possible to obtain to obtain records of the area served by purpose built urban drainage infrastructure such as highway drainage and the storm sewer network. Land use data, which is more readily available, was used to classify the study area into the two major hydrological classes; pervious and impervious. The amount of excess surface water at each cell was calculated by applying runoff coefficients according to land use. Ordnance Survey Master Map (OSMM) data uses polygons, points and lines to represent all fixed features of greater than a few metres in size in urban areas (OS, 2008). OSMM data was used to assign runoff coefficients as well as to identify elevated structures and open water features as in Box A1 in Figure 2.2. Since this study is concerned with urban surface water flooding, rivers, watercourses and large open drains are boundaries to the urban drainage system. OSMM represents water features greater than 1 m wide at their true scale and therefore these were used to identify and remove boundary features from the LiDAR DEM (Figure 2.3). Catchment outlets, as identified by the methodology of the surface water balance model lie on the lowest elevation point adjacent to the model boundaries.

RUNOFF COEFFICIENTS

Given the uncertainties associated with allocating runoff coefficients to each specific surface, the study area was divided into only two hydrological classes, pervious and impervious, using attribute information in OSMM. A runoff coefficient of 0.829 for impervious surfaces was adopted from the Wallingford Procedure Percentage Runoff equation, which was based on a limited number of experimental investigations (DoE, 1983). There are numerous methods available to estimate runoff from natural pervious areas that require many parameters. Most of these methods are too complex and data-hungry for the screening tool under development, and a fixed value of 0.25 was adopted based on the typical runoff coefficient for open areas provided by the Wallingford Procedure Percentage Runoff Model (Wallingford Software, 2007). The assumptions and limitations associated with the use of a simple runoff coefficient to represent very complex rainfall to runoff relationships have been widely discussed (Chow et al., 1988; Parak and Pegram, 2006; Pilgrim and Cordery, 1993). A sensitivity analysis of the model to the runoff coefficient was carried out.

DIGITAL ELEVATION MODEL

Delineation of surface sinks, corresponding catchments and the nesting pattern is dependent on detailed topographical information. High resolution DEMs nowadays are readily created from LiDAR (Light Detection and Ranging) remote sensing (Wehr and Lohr, 1999). A laser signal is emitted from an aircraft which then reflects upon contact with solid ground features and the first pulse return time is used to determine the elevation. Building heights are recorded and in some cases roads and pavements can be differentiated, which is important for identifying urban overland flow paths. The last pulse return has vast hydrological significance since it penetrates features that are not entirely solid and permits removal of vegetation features. The LiDAR DEM used in this study was captured and processed by Infoterra in 2004 for The City of Bradford Metropolitan District Council. The survey has a resolution of ~1 m and a quoted vertical accuracy of ±150 mm. Three datasets were provided with varying levels of post-processing;

1. A DEM based on the first pulse return with minimal processing which represents the height of the uppermost surface features including parked vehicles, vegetation and buildings.

2. A building DEM which uses the last pulse return to remove vegetation. Temporary objects such as parked vehicles were also removed and surface heights were interpolated.

3. A bare earth DEM in which buildings (and in some cases elevated roads and tracks) have been removed and ground levels interpolated.

Techniques for processing LiDAR data to produce hydrologically correct DEMs are rapidly evolving (Evans, 2008). The building DEM was used in this study since the presence of buildings is important for flow paths and catchment delineation. A common problem encountered in urban hydrological modelling using LiDAR DEMs is the presence of elevated structures such as bridges and fly-overs. Attempts to create a hydrologically correct DEM typically involve manually interpolating surface heights in order to create a flow path under such structures as in Clarke et al. (2005). In this research these features were further investigated using a combination of OSMM data, Google Earth images and field visits to determine the most likely flow path in each identified case of elevated structures. A visual representation of the modification applied to the DEM to correct for elevated structure is shown in Appendix 1. Figure 2.4 shows the identification of sinks before and after interpolation of surface heights across elevated structures. In Figure 2.4a many deep sinks are identified alongside the elevated features: this is not the case in Figure 2.4b. Problematical features were not restricted to large elevated objects such as fly-overs and bridges, and included smaller features such as elevated walkways between buildings or canopy structures (e.g. for car storage). Evidence of some of these structures is shown in Figure 2.5. No attempt was made to modify such features in the DEM. A further process that is carried out to obtain hydrologically correct DEMs is the identification of surface depressions of which some may be an artefact of the data collection and processing methodologies (Wang and Liu, 2006; Zandbergen, 2006). In this research it was assumed that all depressions in the LiDAR DEM are genuine.

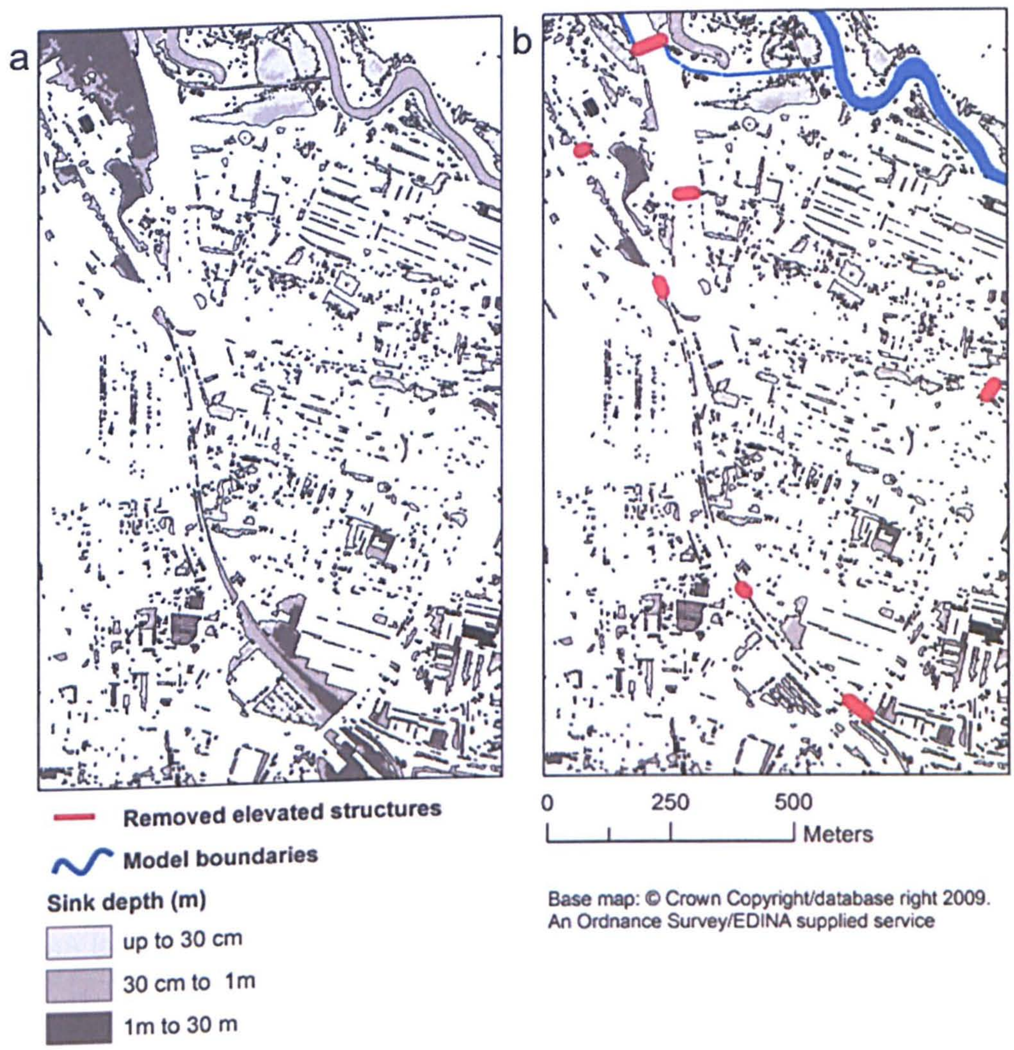

Figure 2.4: Sinks identified (a) prior and (b) post removal of elevated features and inclusion of model boundaries (only sinks with an area greater than 10 m² are shown). Photographs of the removed elevated structures can be found in Appendix 1.


Figure 2.5: Elevated structures that in LiDAR DEMs are represented as barriers to water movement downstream.

LiDAR DEMs have been used extensively in hydrodynamic floodplain inundation modelling (Hunter et al., 2008; Marks and Bates, 2000; Mason et al., 2007; Néelz and Pender, 2007). The LiDAR grid usually has to be reduced in hydrodynamic models due to the permitted maximum number of computational units. For this reason there is much development of methods to optimize the data obtained from LiDAR DEMs whilst at the same time reducing the number of points (Bates et al., 2003; Mandlburger et al., 2008). In this study we have used the LiDAR DEM at the resolution provided without the need for any resampling.

Urban surface water balance computation

The water balance is computed using standard ESRI ArcToolboxes and Spatial Analyst tools which are automated using model builder and organized as toolboxes (further details are provided in Appendix 2 and Appendix 6). The cell flow direction is the starting point for many of the model processes, including the delineation of catchments. The flow direction method used throughout is the D8 algorithm which assigns each cell a single flow direction into one of its eight neighbouring cells, based on the steepest gradient. Using the modified DEM (the output of Box A2 in Figure 2.2) the major surface water catchments were delineated (Figure 2.3). The processes outlined in Box B in Figure 2.2 are applied to the major surface water catchments of interest.

Box B summarises the processes applied to extract the required inputs for the water accumulation model. It is impractical to include every sink in the analysis as many were extremely shallow and therefore would not pose a flood risk. Furthermore shallow or small sinks offer limited potential for storage. Sinks to include were selected based on various combinations of sink attributes. Volume, surface area at maximum extent, maximum depth, minimum depth and average depth were experimented with. The simple criterion of "maximum depth > 0.1 m" was found to greatly reduce the number of very small sinks, whilst not eliminating known flood risk areas. If all surface depressions found in the DEM are genuine, reducing the number of sinks implies that some storage will not be accounted for and there will be some overestimation of surface water accumulation.

The sink extent is the boundary at which it is contained by cells of higher elevation. Sink outlets, where water would flow out of the sink when full, are the lowest cells on the boundary. Water balance calculations in the water accumulation model are made at each outlet. The catchment area of each sink outlet was delineated. The nest level, which states the number of larger catchments in which an individual catchment is contained, was also determined.

Some sinks were found to have more than one outlet cell with the same elevation. These are not necessarily contiguous, resulting in a sink with several outlets (Figure 2.6). These can overflow to different catchments. This causes problems in allocating the excess surface water that should be passed on to each of the downstream catchments. Furthermore this causes problems for catchment nesting since the two downstream catchments may have different nesting levels. The model deals with this by splitting sinks between the outlets, and subdividing their catchments. The adjacent sinks which are in hydraulic continuity in the real world are treated as independent for the purpose of the model. Each outlet is assigned an equal share of the total volume of the sink. A sensitivity analysis was carried out on various methods to model multiple outlet sinks.

The surface water accumulation algorithm (Box C in Figure 2.2) commences by applying Equation 2.1 to each sink in the highest nest level in which there are no nested sinks. The excess surface water from the sink catchment is summed and the volume retained by the sink is subtracted. Any remaining water is passed down as an input to the next nest level. The process is then repeated for every sink, computing all the sinks in one nest level at a time and ending with the water balance calculation for the sinks which then drain out of the major sub-catchment. The attribute table for each outlet is populated with the total water accumulated, amount stored and the volume of water that is passed onto the next nest level. The model also produces a raster layer summarising the total volume of water that passes through each cell, which provides an indication of the major flow paths.

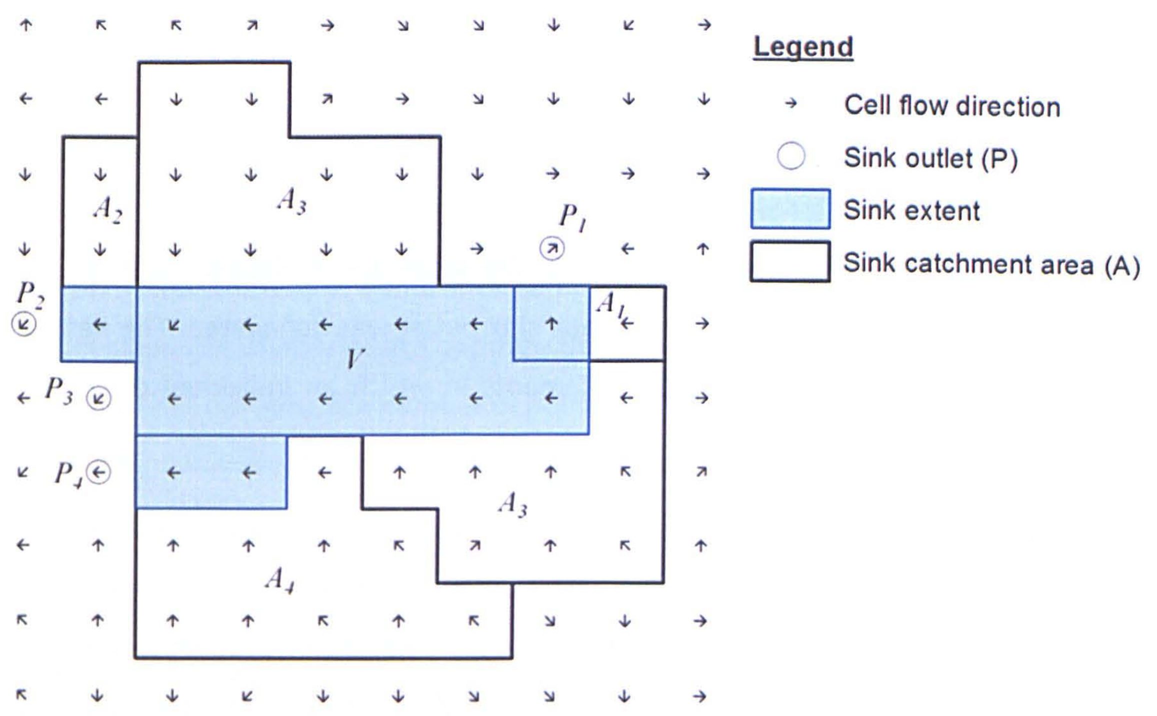

Figure 2.6: An illustrative sink and its catchment and cell flow directions (in this example a multiple outlet sink is shown).

Application of the model

This research uses the town of Keighley in West Yorkshire to develop the model (Figure 2.7). Keighley sits in a hilly depression formed by the confluence of the River Aire with the River Worth. The River Aire and its functional floodplain border the north east end of the town. The River Worth and its tributary, the North Beck, both incorporate culverted sections, and flow into the town from a south west direction. Upslope the town is surrounded by rolling moorland and grassland. Keighley's sewer network is predominantly a combined system that drains by gravity from the southwest to the northeast. Marley wastewater treatment works is located at the downstream end and discharges treated effluents into the River Aire.

Keighley has suffered from frequent surface water flooding, notably in 2002 and 2003. In the summer of 2003, rainfall events led to localized flooding on three separate occasions in a four week period (CBMDC, 2005). Some of the flooded areas had no record of having flooded before.

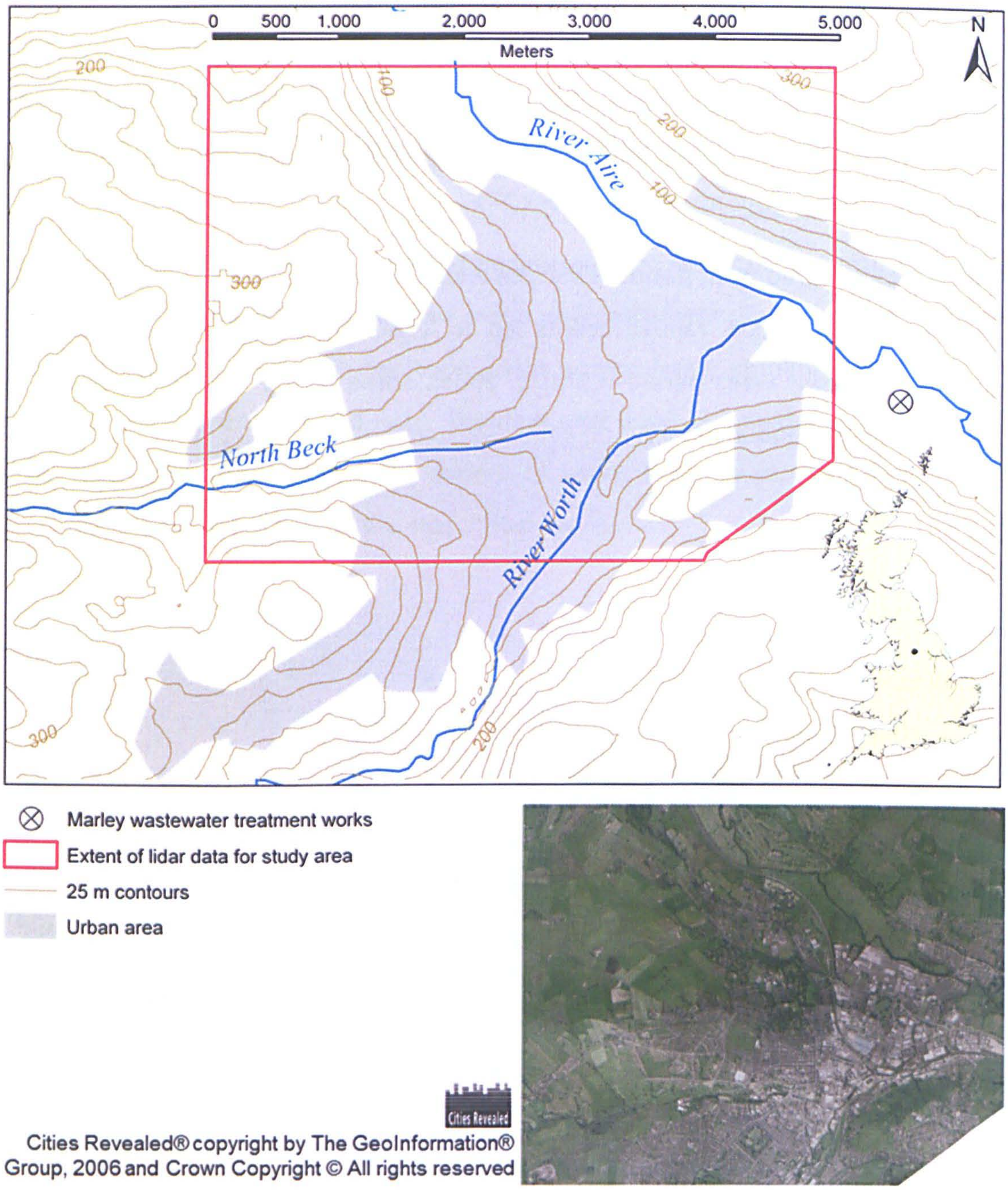

Figure 2.7: Map and aerial photography of case study location.

2.3. MODEL RESULTS

SENSITIVITY ANALYSIS

The assumptions made in the model are tested with a sensitivity analysis. The purpose of the sensitivity analysis was to determine the most appropriate representation of significant processes and parameters in the model. Sensitivity analyses were performed for:

- the method used for processing multiple outlet sinks,
- the criteria used to select sinks to be represented in the model, and
- the runoff coefficient values used to generate the excess surface water.

The assumptions made regarding the impact of the performance of urban drainage infrastructure due to backflows from the river were not tested. This was explored as part of the model validation in section 3.3 and the implications are discussed in section 5.4.

TREATMENT OF MULTIPLE OUTLET SINKS

The aim of this test is to determine model sensitivity to the representation of the processes occurring at multiple outlet sinks. The model algorithm does not allow for a fully realistic apportionment of outflow from a sink with more than one outlet. Three simple methods of apportioning outflow from multiple exit sinks are proposed and compared in terms of the water balance results and the predicted locations of surface water flooding. The sensitivity analysis consists of determining whether the methods produce results (water balance and patterns of flooding locations) that are arguably different from each other. This would indicate that selection of an appropriately simple representation of these processes is critical to the model results and would therefore warrant further investigation and development.

A multiple outlet sink is illustrated in Figure 2.6. The most logical option, given a lack of knowledge of the hydraulic behaviour of the various outlets, is to deal with multiple outlet sinks by finding out the total volume entering the sink, take into account the sink's storage and then pass on any remaining water equally through each of the outlets. In this method the sink is indeed treated as a single entity:

Single sink method $P_i = \dfrac{W - V}{n}$ *(Eq. 2.2)*

Where *P* is the volume leaving each sink outlet (m^3), *V* is the sink volume (m^3), *W* is the surface water that accumulates at the sink (m^3) and *i* is a counter of the outlets from 1 to *n*. The water accumulation algorithm does not accommodate this method and an alternative approach was required. Two alternatives were tested whereby the sink is split into parts related to each outlet, with each part treated independently. Equation 2.3 assigns an equal share of the sink volume to each outlet, while Equation 2.4 shares the sink volume in proportion to the catchment area (m^2) (A) of each outlet

Split sink method 1 $P_i = W_i - \left(\frac{V}{n}\right)$ *(Eq. 2.3)*

Split sink method 2 $P_i = W_i - V\left(\frac{A_i}{\sum A_{i-n}}\right)$ *(Eq. 2.4)*

Neither is representative of reality but both allow multiple outlet sinks to be processed using the water accumulation algorithm. The split sink methods were compared to the single sink method. The major catchment labelled *A* in Figure 2.3 was used with a 10 mm rainfall event. The single sink method was processed manually for 19 of the nest levels accounting for 67% of the catchment area and 389 of the 938 sinks. Table 2.1 shows that in terms of total water stored, the split sink methods produce results that are within 2% of the results obtained with the single sink method. There are small differences in the number of full sinks (-4.0 to +5.1%) and their surface area (up to 3.6%).

Table 2.1: Water balance results using the various methods for computing the water passed down through the multiple outlet sinks.

	Single sinks method	Split sink method 1	Split sink method 2
Water stored in sinks	1168 m^3	-1.7%	0.4%
Number of sinks full to pour point	176	-4.0%	5.1%
Area of sinks full to pour point	2782 m^2	3.6%	2.5%
Water stored in sinks full to pour point	621 m3	-1.6%	2.0%

These results show that the split sink approaches differ in the distribution of water across the catchment but, in terms of urban flood risk prediction, these differences are relatively small. All three methods produce a very similar pattern. Most of the single outlet sinks store approximately the same volume of water under the three methods, and the differences are principally explained by larger changes in the multiple outlet sinks. The split sink approaches sometimes classify part of a multiple outlet sink as full, whereas the single approach classes the entire sink.

A Kappa statistic is the percentage correctly classified minus the correct classifications that could have occurred by chance (Longley et al., 2001). Sinks were classified into full or not full. Table 2.2 shows that the split sink methods produce similar results in terms of classifying sinks as full or not full with Kappa statistics of 84% and 91%. Most of the differences using split sinks method 1 are due to the smaller number of sinks that are reported as full.

Table 2.2: Contingency matrix comparing the sink results of method 1 and 2 with the single sink method.

		Method 1		Method 2	
		Not full	Full	Not full	Full
Single sink method	Not full	201	12	200	13
	Full	19	157	4	172
Percentage correctly classified			92.03		95.63
Kappa statistic			83.63		91.22

To further compare the differences between the split sinks and the single sink methods, the spatial changes in accumulated volume were assessed. The accumulated volume along many of the major flow paths remains the same. Most of the large changes (i.e. greater than 25%, positive or negative) are not along the main flow paths. The largest changes occur immediately downstream of the multiple outlet sinks and in both split sink methods the changes diminish to between 0 and ± 4% by up to 100 metres downstream. It can therefore be concluded that the changes do not accumulate downstream but rather become less significant.

Although there are subtle differences in the surface water accumulation patterns achieved with the different methods for processing multiple outlet sinks, most of the noticeable changes occur at similar locations for both split sink methods and these are generally downstream of the multiple outlet sinks. The single sink method for multiple outlet sinks cannot be processed automatically by the nesting algorithm. Nesting levels are assigned based on the catchment area of sink outlets and multiple outlet sinks produce catchments with different nest levels which cannot be processed simultaneously. It is possible to add further complexity to better describe the flow processes at multiple outlet sinks in a more realistic and representative manner but based on the results of the sensitivity analysis, this is not justified given the small differences that are observed when the alternative approaches are used. Furthermore this is primarily a screening tool to allow high level scenarios to be explored, and it is considered beyond the scope of the model to accurately capture local detail. Both alternative approaches reproduce the overall catchment patterns and are therefore appropriate for the model purpose. Equation 2.4 requires the computation of the fictional catchment area of the various sink parts, therefore the more straightforward Equation 2.3 has been adopted in this study.

SINK SELECTION CRITERIA

This sensitivity analysis explores the changes observed in water balance results as sinks are excluded from the model. The aim of the test was to find an acceptable compromise between excluding sinks from the model in order to speed up model execution, and inclusion of all identified surface sinks. A solution was sought that maximised the number of eliminated small sinks, but that minimised the change in the overall surface storage represented in the model.

This sensitivity analysis explored different selection criteria for inclusion of sinks in the model. A comparison was made with the situation where all 7245 identified sinks were included and when only sinks with a maximum depth of >10 cm and >20cm were considered. The results are presented in Figure 2.8 and Table 2.3. A >10 cm maximum depth threshold eliminated circa 90% of sinks, equivalent to a 10% reduction in storage volume from a 10 mm event (assuming all these sinks would fill). A >20 cm maximum depth threshold removed only slightly more sinks (~95%), but resulted in a 20% reduction in storage capacity. As detailed in Table 2.3, there is ~20% more water leaving the catchment with the 20 cm threshold than with the 10 cm threshold. This illustrates how this reduction in storage capacity translates through the model to produce the large differences in the results.

The >10 cm maximum sink depth is considered an appropriate compromise between reducing the number of sinks represented and the number of calculations, whilst not removing an excessively large proportion of the potential storage capacity. It is recommended that field surveys and a validation exercise are completed to reveal appropriate sink selection criteria in the future.

Table 2.3: Water balance using a 10 cm and 20 cm threshold for sinks selected to be represented in the model.

	Greater than 10 cm	*Greater than 20 cm*
Number of sinks in model	645	311
Eliminated storage capacity (m^3)	382	769
Volume stored in sinks in a 10 mm event (m^3)	3036	2852
Volume leaving catchment for a 10 mm event (m^3)	867	1049

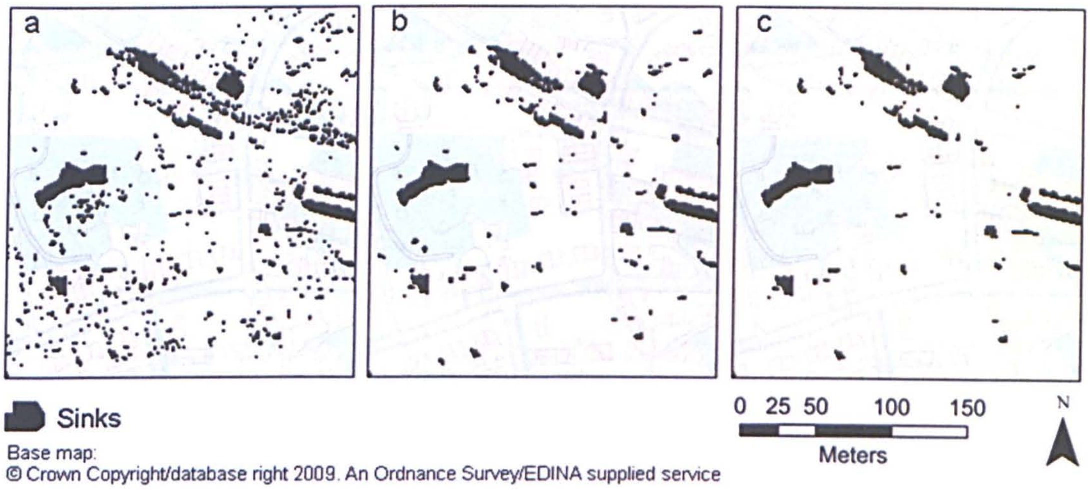

Figure 2.8: Sinks present with (a) no selection criteria, (b) sinks with maximum depth > 10 cm and (c) those with maximum depth > 20 cm.

RUNOFF COEFFICIENT

This test explores the sensitivity of the volume of water stored and passed down at individual sinks to changes in the runoff coefficients. The model behaviour should reproduce the changes in in water accumulation across the catchment to changes in runoff coefficient, but this cannot be tested because no such data exists at similar scales from the real world. This sensitivity analysis was conducted to learn about model behaviour and to quantify the unit changes experienced in model output (water balance at individual sinks and total water accumulated at grid cells) for a given unit change in the runoff coefficients.

Two catchments labelled *A* and *B* in Figure 2.3, with differing proportions of pervious and impervious land cover, were used in the analysis (Table 2.4). Figure 2.9 summarizes the changes in the water balance that are observed when the pervious and impervious runoff coefficients are varied by 25%. Smaller changes in the total excess water produced are observed when the pervious runoff coefficient is varied since the low runoff coefficients mean that excess water originating from pervious land cover is always a small proportion of the total. This is particularly the case in catchment B where only 20% of the land cover is pervious and therefore the excess water produced from the pervious land cover is always a very small proportion of the total excess water; less than 7% in the baseline analysis. Catchment B is therefore not sensitive to changes in the pervious runoff coefficient.

Table 2.4: Characteristics and water balance computation for a 10 mm excess surface water event.

	Catchment A			Catchment B		
Area (m^2)	948000			1126000		
Pervious land cover (%)	72			20		
Number of sinks	936			2375		
Total sink volume (m^3)	60500			65400		
Total sink area (m^2)	17200			32700		
Rainfall depths (mm)	5	10	50	5	10	50
Excess surface water (m^3)	1951	3903	19514	4027	8054	40269
Water stored in sinks (% of total)	100	78	33	65	50	25
Water leaving catchment (% of total)	0	22	67	35	50	75
Overflowing sinks (% of total)	28	43	74	25	39	71

The changes in the impervious runoff coefficient in catchment B result in almost a proportional reduction in the total excess water produced. The changes observed in the water stored in the sinks and water exiting the catchment are not proportional (Figure 2.9). The position and storage capacity of sinks in relation to the distribution land cover within the catchment determine whether the storage capacity freed up by a reduction in water produced from one type of land cover means that water originating from the other land cover type can therefore be stored.

Despite catchment A having a large proportion of pervious land cover (72%), sensitivity to changes in both the impervious and pervious runoff coefficient is comparable (Figure 2.9a). Reducing the runoff coefficient for the 5 mm events lead to reductions in water stored across the catchment that are directly proportional to the reduction in total excess water produced. Figure 2.10 however shows how the sensitivity varies greatly between sinks and very few sinks pass on a volume of water relative to the reduction in excess surface water. Sinks with a 0% change are those that do not pass any water downstream and therefore store 100% of incoming water across all the scenarios tested. It is a different distribution of water across catchment sinks that leads to an overall proportional change. Similar patterns of individual sink behaviour were found for both catchments and for changes in the pervious runoff coefficient.

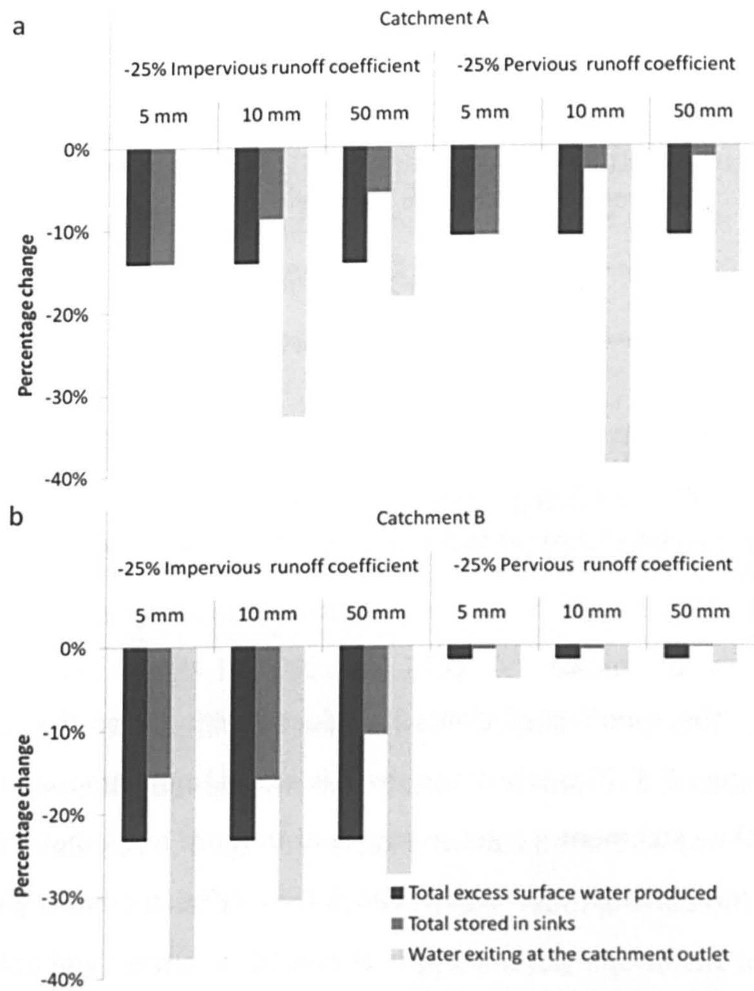

Figure 2.9: Percentage change in total excess surface water produced, total water stored in surface sinks and total water exiting the catchment for a -25% change in the runoff coefficients in (a) catchment A and (b) catchment B.

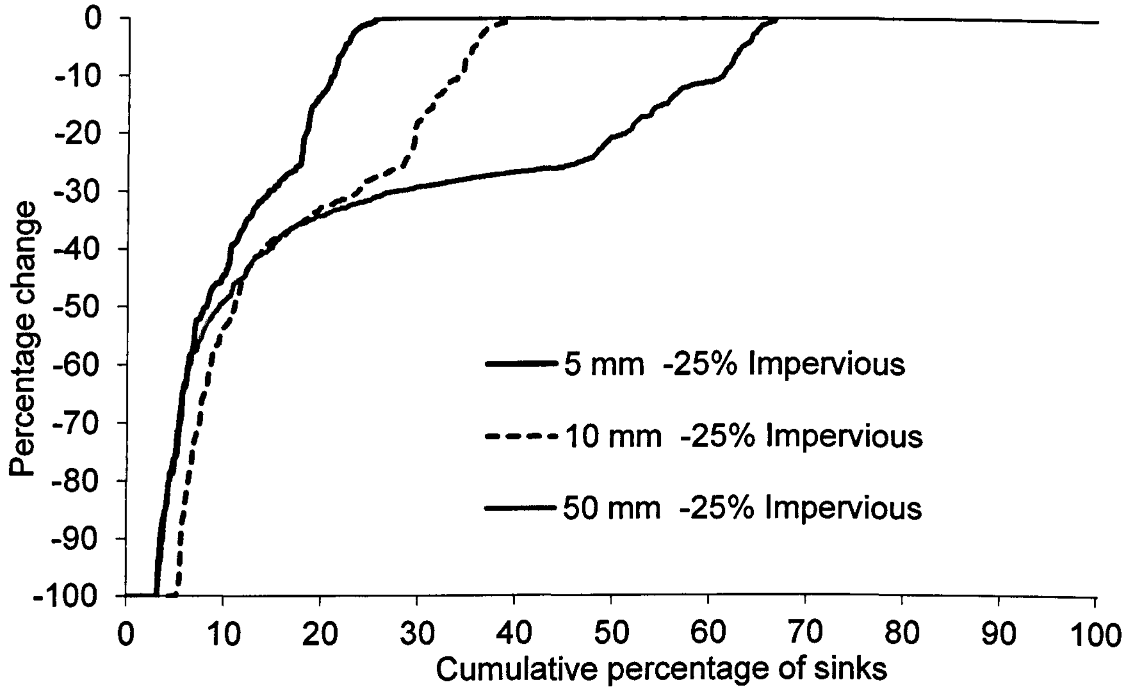

Figure 2.10: Percentage change in water passed down at each sink shown as a cumulative percentage of total number of sinks in Catchment A.

The sensitivity to changes in the runoff coefficients is reduced with larger rainfall events in both catchments (Figure 2.9). This is because there is a limit to the amount of water that can be stored in the catchment. Larger events lead to more sinks that are full in all scenarios and therefore there is limited scope for changes to the stored volumes.

The above assessment does not expose changes to the flow paths. The changes in water volume accumulated at each cell were examined. Most cells exhibited changes that were approximately relative to the change in the runoff coefficient and similar patterns were produced for the various event volumes. A small number of cells representing major flow paths, most of which were intercepted by sinks, resulted in greater changes. In catchment A the main flow path with an accumulated volume of over 1500 m^3 in a 10 mm event exhibits greater changes downstream whereas the opposite is true in a 50 mm event. Although the principal catchment flow paths prevail, changes in runoff coefficients lead to significant localized alterations in flow paths as expected.

The sensitivity analysis revealed that the responses are catchment specific and depend on a combination of factors, making it difficult to predict the cumulative changes that will take place. Some of the factors that influence the catchment response to changes in the runoff coefficients are the proportion and distribution of pervious and impervious land cover in relation to sink storage and location and the size of the rainfall event. This illustrates that the methodology has the potential to help understand complex interactions such as the relationships between catchment characteristics, land cover, sink location and volume and sensitivity to the runoff coefficients for different event volumes.

MODEL VALIDATION

To validate the model, a 10 mm event was applied to four major catchments where flooding was known to occur (*A*, *B*, *C* and *D* on Figure 2.3). Sparse data on flood location was available from the City of Bradford Metropolitan District Council. Many of the known flooding locations shown in Figure 2.11 became apparent during the flooding events in 2002 and 2003. An example of a rainfall event responsible for significant flooding in Keighley is that of the 3rd of July 2003. The recorded rainfall depth one hour into the storm was 20.20 mm and at the end of the storm 8 hours later was 28.4 mm. Model runs using rainfall depths of 5 mm, 10 mm, 20 mm and 50 mm were carried out and the 10 mm event depth provided the closest match to the known flooding locations. 10 mm is approximately equivalent to the remaining rainfall after making an allowance for the sewerage system by subtracting the average rainfall intensity from the hydrograph of a typical 60 minute 20 year return period rainfall event over Keighley. This assumes that the sewerage system has the capacity to carry the average rainfall intensity of such a storm.

Sinks that are within 6 metres of a building or road, with a surface area greater than 4 m^2 and that were overflowing were classified as posing a flood risk. Figure 2.11 compares model sinks that can be classified as posing a flood risk and those areas that are known to have surface water flooding problems. In general there is excellent agreement in the location of the predicted filled sinks and the observed flood locations. In some cases the outlines are approximate and merely summarize a group of properties, of which some have suffered from flooding but the exact location is not known. This initial and informal validation exercise indicates that the model produces very conservative results and is probably overestimating the number of sinks that fill, and therefore the flood risk. This is likely to be partly due to the exclusion of the drainage system which is responsible for draining many of the areas highlighted at risk of flooding. It may also be the case that the model is correctly depicting areas that flood, but these locations have not been made aware to the local authority. Despite this, it is reassuring to see that most of the known locations subject to surface water flooding have been highlighted by the model. It is much harder to identify any false positive model results since the local authority representatives could not confirm the locations that do not flood.

The model has also identified some key aspects of the flooding performance of the catchment. For example the area labelled *a* in Figure 2.11 is at the lower end of the catchment adjacent to the River Aire floodplain and it is therefore highly likely that water will naturally pond there prior to discharging to the River Aire. Discussions with local authority representatives also confirmed that under rainy conditions this area is waterlogged and OSMM data highlights the presence of an open drain at that location. Several properties within the area labelled *b* have reported flooding and the model also shows this. The catchment area of these sinks is largely composed of grassland (which is unlikely to be served by urban drainage infrastructure).

In some instances the exact properties that have experienced flooding have not been identified by the model, but a location nearby has been flagged. This may be the result of small local variations which may displace water, such as a lowered curb or raised structures (such as a wall) and that have not been captured by the LiDAR DEM. There were also two locations (*c* and *d*) that reported severe flooding and although the model highlights the presence of an overflowing sink, the sink is small compared to the reported flooding extent. The flooding at area *c*, however may be explained by a major flow path that the model identifies in this area. Hence surface flows may have caused some local flooding en route. Area *d* is more difficult to explain. The model has identified a very small sink (a surface area when full of 6 m^2 and a volume of 0.5 m^3)

with a small catchment (61 m^2). Local speculation about flooding in the area is that the flooding is caused by runoff from a large non-urban upstream area. Therefore if local accounts are correct the model has failed to pick up a larger sink within the area and catchment delineation is also incorrect. The model identifies a sink the width of the road at location *e*. Local authority representatives could confirm that when other parts of the catchment are flooding, this part of the road does not flood in this manner. This suggests that the model has either incorrectly delineated the sink, which could be a result of local variations or the location is well served by the drainage system. If the latter is true, then the model has highlighted a potential flood risk area should the drainage system fail at that location.

One of the greatest assets of LiDAR DEMs is the huge amount of detail that is captured. For example in many cases it is possible to distinguish between the road and the pavement and features such as driveways can sometimes be detected. This scale of detail may be exploited to better determine the exact path and ponding of surface water since it is recognized that urban flow paths may not follow the lie of the land due to manmade features such as buildings and walls. Small variations between the actual and model topography may result in significant differences to the resultant flow paths and flooding extent, hence, a formal validation exercise is recommended in order to test model validity with greater confidence.

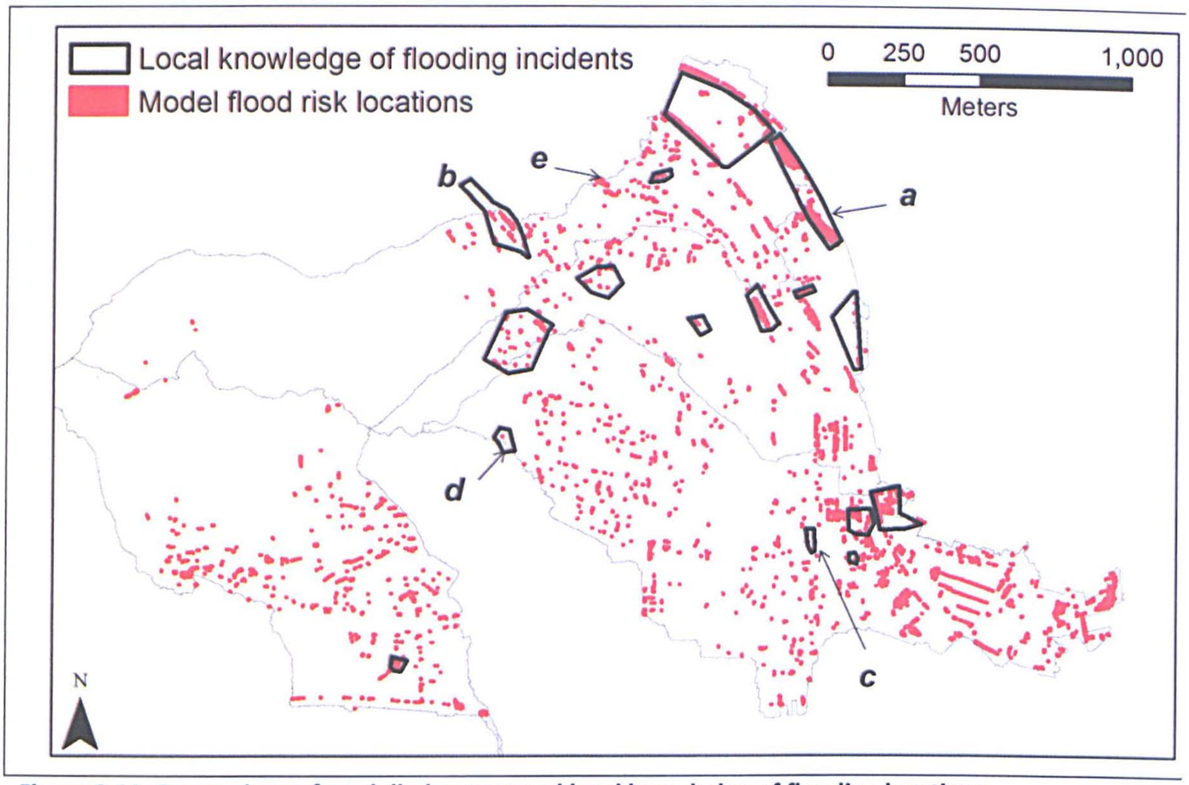

Figure 2.11: Comparison of modelled output and local knowledge of flooding locations.

2.4. Discussion

The water balance model is not proposed as an alternative to detailed hydrologic and hydraulic modelling, but as an additional evaluation tool to assist in high level spatial planning and decision making. It also serves as a process to identify areas of interest that require further analysis, and results produced from this model can also aid in specifying boundary conditions for further modelling.

The model results are mapped as the total water stored in surface depressions. An example of how the model may be applied is shown by the results of a simulation of a 10 mm and 50 mm event for a small area of catchment *A* (Figure 2.12). By reference to sink *A* in Figure 2.12b and its catchment area the sink can be seen to have a large spatial extent when full which may be considered of interest as it lies within a residential area. The results of the 10 mm and 50 mm events show that sink *A* and the sinks nested within its catchment area are practically empty for a 10 mm event (Figure 2.12a). A 50 mm event results in a large part of the sinks within the catchment overflowing (Figure 2.12b). Simulations of a range of events revealed that many of these sinks begin to overflow with events greater than 20 mm. This information can be used to focus attention on sinks that may begin to pose risks under smaller, more frequent events. Potential solutions and/or adverse impacts of developments within the catchment area can then be spotted. The sink layer can be used to consider the impact of enlarging existing surface depressions to store more water. For example, by reference to sink *B* in Figure 2.12b it can be seen that this sink receives water from over half of sink *A*'s catchment, and that it intercepts a major flow path. Sink *B* is not adjacent to any buildings and therefore it may offer an opportunity to store more water and prevent it from reaching sink *A*. The model may be used for other types of scenario analyses.

The model produces a raster file illustrating the total water that passes through each cell. This is used to identify the major flow paths. By examination of Figures 12c and 12d it can be seen that a major flow path passes along the boundary of the sink catchment. Any topographical changes in the proximity of location *C* (Figure 2.12d) can lead to significant changes in the delineation of the catchment area of sink *A*. The surface water accumulation layer can also be used to see if there is scope to intercept or redirect the flow away from flood risk areas.

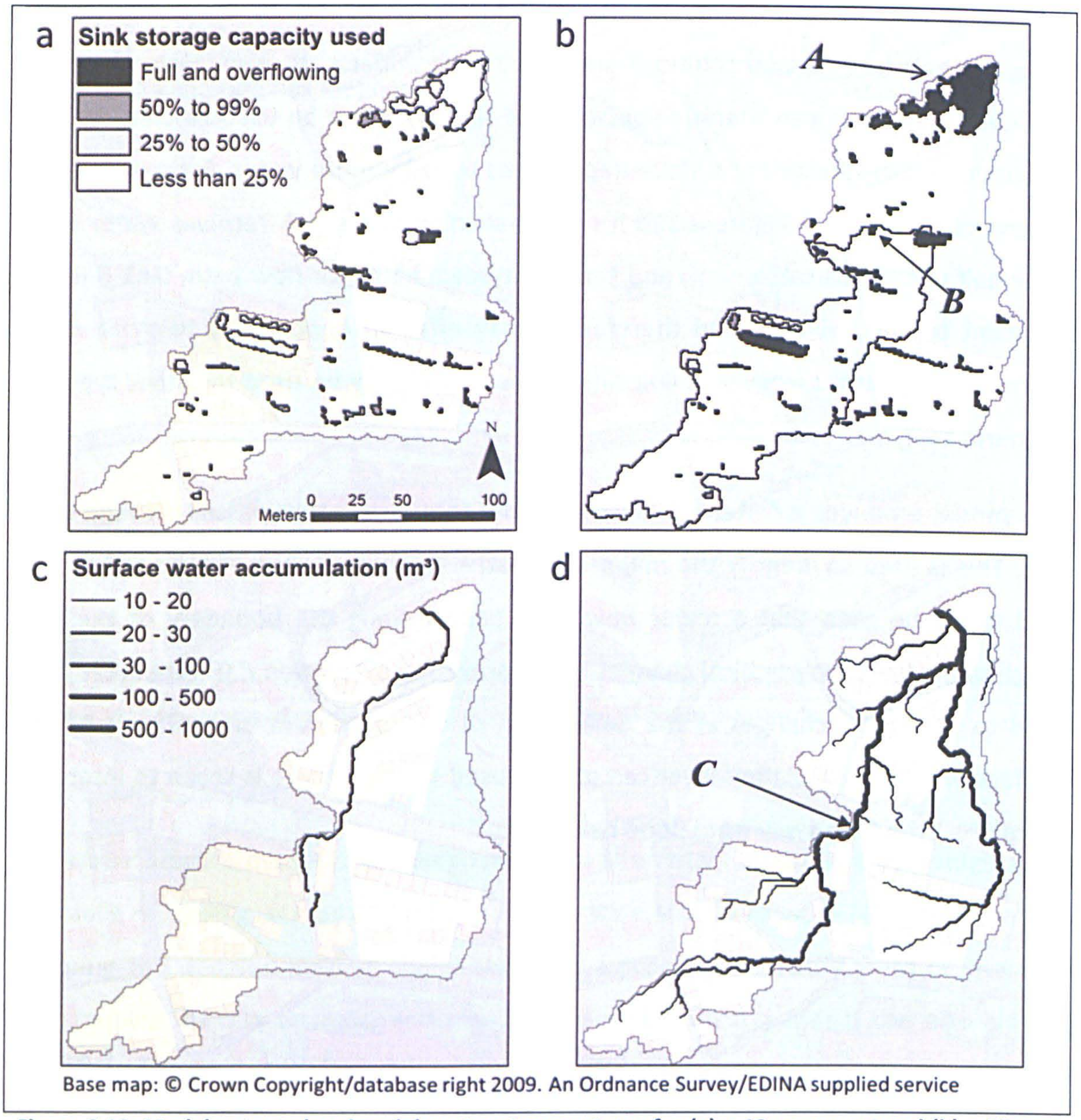

Figure 2.12: Model output showing sink water storage status for (a) a 10 mm event and (b) a 50 mm event, and surface water accumulation for (c) a 10 mm event and (d) a 50 mm event.

The sample application has focussed on a small sub-catchment, however the model produces catchment-wide results illustrating the wider hydrological connectivity. Combined with spatial planning information the model provides a simple but powerful approach to aid in decision making and allocation of resources for further conventional hydraulic modelling. If overlaid with maps of where development is likely to take place, opportunities based around urban development can be sought that will reduce flood risk or that will build in capacity. This is realized by combining spatial planning maps with information provided by the model regarding volumes accumulated and stored at sinks under different event sizes, catchment areas, nested sinks and indicative surface flow paths. Visualization of this information allows spatial planners to appreciate development sites within the context of the wider catchment. They can therefore begin to identify developments that may have adverse impacts and also to explore flood risk management scenarios.

It is a simple task to alter sink volumes (to represent sink removal or sink enlargement) and re-run the model. Similarly several runs can be executed using different excess surface water input files, thereby affording the opportunity to examine different rainfall events as well as climate change scenarios. An excess surface water input file can also be prepared taking into account the sewer system by making drainage assumptions based on land use or by making allowances for volumes that are drained at specified points. Similarly the impact of the spatial variability of runoff production associated with varying land cover within the catchment can be explored by altering the input excess surface water file. A modified input DEM can also be used to represent redevelopment scenarios or alleviation measures that would alter elevation (and therefore flow direction).

2.5. CONCLUSIONS

A screening tool to identify flood risk areas and to explore potential management options has been presented. It is a simple method that can be used by decision makers to analyse impacts and opportunities of development on surface water flood risks. The method fills a gap by providing a high level screening tool that can be used by decision makers without formal training in hydraulics and with minimal input parameters.

The model uses a water balance approach in conjunction with high resolution LiDAR DEM data within a GIS environment. The accumulation of excess surface water is simulated as it accumulates through a cascade of nested sinks identified, together with their catchments, from the DEM. The subsurface drainage system was assumed to be full and not to interact with surface water for the purpose of model demonstration. A recommendation for future model development is to account for urban drainage infrastructure in the calculation of the excess water input.

Sensitivity analyses were performed to test the main assumptions adopted in the model. It was demonstrated that the main catchment processes remained unchanged under the various tests. There was local variation; however, for the purpose of a screening tool that does not aim to accurately represent local detail, the assumptions produce acceptable model results.

Informal validation against anecdotal information on surface water flooding locations in Keighley suggests the model works well for its intended screening purposes. This simple methodology gives a quick assessment of sinks that are potential areas of flooding, or that are critical storage areas within in the catchment which could be used to alleviate flooding.

3. VALIDATING THE URBAN SURFACE WATER BALANCE MODEL

3.1. INTRODUCTION

Surface water flooding is defined as rainwater that is not adequately drained naturally or by man-made infrastructure, and which accumulates in urban surface depressions leading to disruption and loss. An urban surface water balance model is described in chapter 2. The model was developed as a screening tool to be used in flood risk management scenario analysis. It was developed in ArcGIS to be both computationally simple and user-friendly. The objectives of this chapter are:

1. To provide an overview and evaluation of the validation tests used for models that predict urban surface water flooding.
2. To present and justify the methodology chosen to validate the urban surface water balance model.
3. To assess the model through the validation process; whether the model works and how it can be improved.
4. To outline the lessons learnt from the validation exercise.

WHY VALIDATE AN URBAN SURFACE WATER FLOODING MODEL?

The importance of validating models in terms of rigorous and appropriate testing and better model analysis is well documented (Anderson and Bates, 2001; Kirchner, 2006; Kirchner et al., 1996; Wainwright and Mulligan, 2004). Models are considered useful if they are at least as reliable as the next best alternative, such as expert opinion (Kirchner et al., 1996), but it is necessary to test whether this is the case. The aim is to test the GIS urban surface water balance model to determine whether there is any value in using such a tool.

There are two terms that are commonly used in model testing; verification and validation. Depending on the discipline these terms can have different meanings or implications. In the Integrated Urban Drainage modelling guide (WaPUG, 2009), verification is defined as the process of checking a model against independent data to determine its accuracy, whereas validation is defined as the degree to which a model is representative of the real world from the perspective of its intended use. Mulligan and Wainwright (2004) note that in computer science verification is the process of checking computer code and removing bugs, whilst validation is testing that the model output gives the desired solution or result. Anderson and Bates (2001) suggest that the term validation is unhelpful altogether and suggest a neutral term such as evaluation or assessment.

In this section model validation is taken as the comparison of the modelled output with the observed data with the objective of quantifying how well the model results match observations. Validation should test critical model outputs in terms of the purpose of the model (Mulligan and Wainwright, 2004).The model purpose is as a screening tool to locate flood risk areas (defined as locations close to major flow paths and surface depressions that fill with water) and hence an ideal validation would test the model's capability to reproduce areas that in reality do suffer from surface water flooding, and those areas that do not flood. In this validation, we are testing the adequacy of the model as a screening tool for flood risk, i.e. is the model capable of directing a user to areas of high flood risk within a catchment?

CURRENT APPROACHES

DATA AVAILABLE FOR VALIDATING SURFACE WATER FLOODING MODELS

Models that predict surface water flooding should, as a minimum requirement, be validated against their ability to locate flooded areas. But what data is currently available for doing this? In the UK data on surface water flooding is sparse (Defra, 2009). This is because surface water flooding events are of short duration, very localized and unevenly distributed across the catchment. A further reason is that responsibility for surface water flooding has not previously been clearly defined (Pitt, 2008) and therefore no one organization has been concerned with gathering data. Despite this several potential sources of surface water flooding data have been identified:

- Water and Sewerage Companies are required to keep a record of flooding arising from sewers, such as overloaded and blocked sewers (Ofwat, 2007).

Although it is possible, it is unlikely that any record will be kept of incidents that were not considered to be directly related to flooding from the sewer system.

- Local Authorities may hold data on surface flooding incidents in various departments. Drainage departments typically have records of flooding incidents from sources such as culverts, storm drains and watercourses. Some of these incidents will be a result of heavy rainfall, others due to blockages or other failures. When incidents are deemed not to be the responsibility of the drainage department they are passed on, for example to sewerage companies or the land owner, in which case there are no further details of the incident on record. Similarly highways departments receive and record complaints regarding flooding that is believed to be due to blocked highway drains and gullies. Data held usually includes a location of the flooding incident and in some cases an indication of the extent, depth and duration of flooding. It is not always possible to determine the cause of flooding from records held.
- Anecdotal information such as personal accounts, photographs and videos of a flood event can be used to extract information about flood location, extent and depth.
- CCTV may prove a useful source of information as it can also provide time dependent information on the flood extents and flood depths may be inferred.

Further sources of information are discussed by WaPUG (2009). The main drawback, in terms of using the data described above for model validation, is that in most cases there is no confirmation of locations that did not flood, nor is there complete coverage of the flooded locations.

VALIDATION OF EXISTING MODELS USED TO PREDICT SURFACE WATER FLOOD RISK

It is recognised that standardized model evaluation tests are desirable but lacking (Kirchner et al., 1996). Until recently, it was mainly sewer network models that were used to predict locations of non fluvial urban flood risk. Sewer models tend to be built for a specific purpose (e.g. for issues related to CSOs) and the locations at which verification is carried out reflect this (WaPUG, 2002). It is therefore expected that the prediction of surface water flooding volumes and location is less reliable. The standards required for acceptance of a sewer network model vary according to the country. In the UK a code of practice exists detailing the conditions that must be met prior to operational use of the model (WaPUG, 2002). Verification of sewer hydraulic models normally starts by conducting a sewer flow survey, using flow monitors in sewers along with rain gauge data from the catchment. Modelled flows are then compared on the basis of flow rate and depth and in the form of a hydrograph which should meet the criteria for both shape and magnitude. WaPUG (2002) also state that the rainfall events captured for sewer flow verification should include three storm events of varying return periods and detailed guidance on rainfall events accepted for model verification is provided. The model should also reproduce all reported flooding in terms of location, severity and frequency where records permit. It is however recognized that good quality data on historical flooding is sparse.

Despite detailed requirements for sewer model acceptance, the process establishes confidence in the modelled sewer flows, but not so much in the predicted surface flood risk locations. It is not feasible to carry out flow surveys across the entire catchment, therefore strategic locations are sampled. Despite the recommendations to include storm flow in the verification process, flow surveys often have a limited duration and therefore extreme events are not always captured. There is high uncertainty in the results at locations not included in the flow survey and in simulations of extreme events. Sewer hydraulic models can only predict flooding at manhole locations. Some simplified sewer models may not represent all manholes, and therefore even where good surface water flooding records exist; the model is unlikely to identify all flood risk locations in the catchment.

Integrated Urban Drainage (IUD) modelling can be loosely defined as coupling the various models that have been developed to represent aspects of urban drainage (e.g. sewer systems, surface flow and fluvial systems). There is a drive towards IUD modelling (Gill, 2008), and guidelines for model testing have been produced (WaPUG, 2009). The guidance generally states that the models should be verified using the standards for each of the parts of the integrated model and also as an integrated model, and that the verification results of the integrated model should be greater than those of the parts since it is assumed that an integrated model provides a better representation. In terms of predicting surface flooding, the suggested validation methodology involves comparing model predictions with reported flood extents and flood routes. Site inspections are also required to check that the surface features that dictate surface flow routes are accurate. What is considered as an acceptable measure of agreement is not stated. The level of agreement between the model and data is not specified in terms of quantities and it is the responsibility of the modeller to define what is acceptable and this would be defined in the model reporting.

The greater availability of high resolution digital elevation models (DEMs) has led to a growing sophistication in urban surface flood risk modelling (e.g. Bradbrook, 2006; Maksimović et al., 2009). Table 3.1 shows that many locations have been studied using a variety of modelling approaches, and while most carry out some validation in terms of flood extents and some present comparative depth data, few make any statistical measure of the quality of the model fit. This is likely to be due to the quality (and quantity) of the observed data being inadequate, which does not allow for statistics or formal measures of agreement to be calculated. Furthermore it is unlikely that the existing data regarding known flood locations will represent a comprehensive dataset of all areas that were flooded and those that were dry.

Table 3.1: Model evaluation in surface water flooding studies (in IUD cases the sewer model verification has not been described in this table).

Broad classification of model	Details of model or study	Model evaluation
Surface	A 2D model (JFlow) was used to create national surface water flood risk maps for the UK (Environment Agency, 2010a; Environment Agency, 2010b).	Surface water incident data (mostly held by Local Authorities) was obtained and the model was evaluated in terms of its ability to reproduce the probability of incidents in a zone. A qualitative evaluation of historic records with modelled output was made for a selection of towns in the UK. In total 6 examples from the around the UK are presented.
Surface	A GIS based runoff and inundation model is developed (Chen et al., 2009)	Inundation depths are known for two observed storms. The percentage difference in the model predicted depths (for 12 model cells covering the known inundation depths) and the observed depths is reported. The modelled flooded extent is also mapped onto the known flooded locations.
Surface	Six 2D hydraulic models were tested by running them on an identical (benchmark) LiDAR DEM. (Hunter et al., 2008)	Six models were run for an area in Glasgow where flooding was known to have occurred. The model outputs were compared against each other in terms of time series of water depth at various locations in the study area and also the maximum extent predicted by each model. Reference is made to eyewitness accounts of the flooding patterns.
IUD	Two slightly varying dual-drainage approaches are described whereby overland flows (1D representation) are dynamically linked to a sewer	Four streets known to have flooding problems are described. The results of two modelling approaches are compared in terms of flow volumes in and out of the minor and major system along the four roads. Although it is known these roads suffer from flooding, flow

Broad classification of model	Details of model or study	Model evaluation
	model (Maksimović et al., 2009)	rates and volumes are not known and so cannot be compared with model output.
IUD	An IUD model was used to look at flood risk in the Brent North catchment. (Bamford et al., 2007) (Defra, 2009)	The areas highlighted as being at risk from flooding by the modelling were compared with photographic and video records made by the general public during flooding on the 20th July 2007. Storm data for the same date was also used to drive the models.
IUD	A comparison of 2 approaches to coupling surface and sewer models is made (Leandro et al., 2009)	It is noted that dynamically measured flood data does not exist for the case study location. The modelled depths and velocities are compared against each other. It is noted that the case study site is likely to flood (but confirmation of whether it does flood is not stated).
IUD	Two surface and sewer model coupling approaches are compared (Allitt et al., 2009)	In all cases a previously verified sewer model was used. The surface flooding was compared against known flooding. Modelled volumes and depths were compared with CCTV footage from known flood events. No measure of agreement is stated.
Surface	As part of the Strategic Flood Risk Assessment, areas susceptible to surface water flooding were identified using a 2D model, JFlow (described in (Bradbrook, 2006).	The Royal Borough of Kensington and Chelsea compiled a list of 373 properties that reported flooding during a heavy rainfall event of the 20th July 2007. An intense summer storm (100 year event) obtained from the FEH design rainfall procedure was used to run the model and the depth results were compared to the list of properties that reported flooding. JBA Consultring (2009) concluded that a visible (qualitative) correlation of modelled ponding areas and observed incidents existed.
IUD and Surface	Various surface water flood risk modelling approaches are compared. These include 1D, 2D, integrated and surface only (Bamford et al., 2008)	The results are compared qualitatively on the basis of their ability to replicate observed flooding for a number of design rainfall return periods. An example is provided of where the extent of flooding has been delineated from video footage and this is compared to the (2D) modelled extent.
IUD	A surface channel and ponding network is extracted in GIS and used in Infoworks CS to model both overland flow and sewer flow (Leitão et al., 2008)	The model results (extent, volume, velocity, depth) were compared against four different approaches (all based on 1D surface and 1D sewer representations) and no comparison with observed data was made although it is noted that some of the roads modelled as flooding, are also known to have flooding problems.
IUD	Describes the development of a model to extract 1D surface overland flow networks. The model is used with a sewer network to model surface water flooding (Boonya-Aroonnet et al., 2007)	Photographic evidence of flooding and known locations of flooding are compared to the surface water flooding results.
IUD	Development of integrated sewer and surface model (SIPSON) is described (Djordjevic et al., 2005)	Observed and simulated maximums depths at four points along a street during a flood event are presented graphically.
IUD	A sewer model (SWMM), a 1D channel flow model (HEC-1) and a 2D overland flow model are used to simulate the flooding observed in Taipei (Taiwan) during a typhoon event (Chen et al., 2005).	A mapped survey of flooded locations, following Typhoon Nari (2001) is presented and the model predictions of flood extents are compared qualitatively against the observations. No quantitative measure of agreement is stated.
IUD	A coupled storm sewer model with a 2D overland flow model is used to predict inundation (Hsu et al., 2000)	Inundated areas across Taipei from Typhoon Zeb (1998) were mapped by the government. These are compared graphically and discussed qualitatively against the modelled inundation extent.
IUD	An overland flow model is coupled with an existing Infoworks CS model. The purpose was to investigate surface water flooding problems in Nottingham (Harrison, 2000)	A previously verified Infoworks CS sewer model was coupled to an overland flow model. It is stated that it was not possible to verify the overland flow model.

VALIDATION OF FLUVIAL MODELS

Given that urban surface water flooding is now being modelled as overland flow to produce 2D inundation results, it may be possible to adapt methods that are used in the testing and validation of fluvial inundation models. Fluvial inundation models also use high resolution DEMs to predict flooding extent and this has required the development of appropriate validation measures. Typically, hydraulic models are validated on their ability to reproduce flow hydrographs (e.g. Bates et al., 2003). With advances in remote sensing data availability, flood inundation models are also evaluated on their ability to reproduce inundation extent or pattern.

Fluvial models have been tested with inundation data obtained from satellite borne data (Bates and De Roo, 2000; Horritt and Bates, 2001; Horritt and Bates, 2002) as well as with aerial imagery (Yu and Lane, 2006). Satellite borne data includes SAR (Synthetic Aperture Radar) which produces images with a ground resolution of tens of metres and airborne images have much higher resolutions. Techniques have been developed to classify inundation extent and pattern and these are compared to the modelled output (Horritt, 2006; Horritt et al., 2001). Satellite and airborne surveys provide excellent spatial coverage of the flood event but, unlike validation with time dependent flow hydrographs, the use of such data only provide one snapshot of the event with which to assess model accuracy. It is unlikely that currently available satellite remotely sensed data (e.g. SAR) will prove useful in determining urban surface water flooding locations and extents. Surface water flood events are often short lived and therefore the chance of a satellite capturing appropriate images is reduced. Furthermore surface water flooding occurs in small isolated patches distributed across the catchment which may be smaller than can be detected by the satellite.

Neal et al. (2009) describe an approach for model testing whereby following a flood event, an extensive survey of wrack and water marks was carried out across the study area. This provided not only inundation extent but also depth data. Using the survey data and gauged hydrograph data, it was then possible to compute a Root Mean Squared Error (RMSE) between the simulated and observed water depths. Such an approach is labour intensive as it requires an extensive field survey during or as soon as possible after the event. Whilst surface water flooding may not leave obvious traces or wrack or water marks, a simultaneous survey by several observers during the flood event could prove useful in obtaining depth and extent data. Connell et al. (1998) used a door to door survey of 40 floodplain residents (Waihao River in New Zealand) to collect data such as personal accounts, photographs and videos with which to validate a 2D flood plain model. Although there were difficulties in establishing whether photographic evidence of flood extent was post or pre flood peak, Connell et al. (1998) concluded that the exercise was a useful method of validation. Hull City Council in the UK carried out an exercise of a similar nature in 2007 (Coulthard et al., 2007; The National Land and Property Gazeteer, 2009). On the day following extensive surface water flooding, many members of staff were relieved from their day jobs in order to provide the necessary man power to carry out a house to house survey with the objective of identifying vulnerable residents in need of help. Hull City Council then realised they were collecting valuable data that could feed into their Strategic Flood Risk Assessment (SFRA), and therefore the aim of the survey was expanded to include collection of data regarding flood levels. All properties in the City of Hull were surveyed and the exercise lasted two weeks (Codd, 2008). The exercise produced an invaluable data set with which to compare results from modelling carried out for the SFRA. It was recognized however that caution had to be exercised given that it was a post flooding survey and conflicting results were returned whereby neighbouring residents would report varying flood depths.

3.2. METHOD USED TO VALIDATE THE URBAN SURFACE WATER BALANCE MODEL

CASE STUDY

Keighley is a town in West Yorkshire, UK, with a population of approximately 50,000. The urban area sits near the confluences of the Rivers Aire, Worth and North Beck. Much of the suburban area lies on slopes of 3 to 10 degrees (~7 and 18%). As outlined in chapter 2, one of the first steps of urban surface water balance model is to identify the major sub-catchments that drain to model boundaries (e.g. a river, watercourse or open drain). Four of the largest sub-catchments were selected, as this is where potential exists for the build-up of surface water to cause flooding and furthermore there are known surface water flooding issues in these areas. The four study catchments have a combined area of 362 hectares and each span approximately 2 km in length from the top of the catchment to the model boundary outlet (Figure 3.1). Of the 3956 properties in the four study catchments, ~60% of housing is characterized by rows of terraced housing (mainly in the lower and central parts of the town) and ~40% are detached and semi-detached properties with larger curtilage; these principally sit on the suburban slopes. Some of the terraced housing has cellars, many of which have been converted into basement living space.

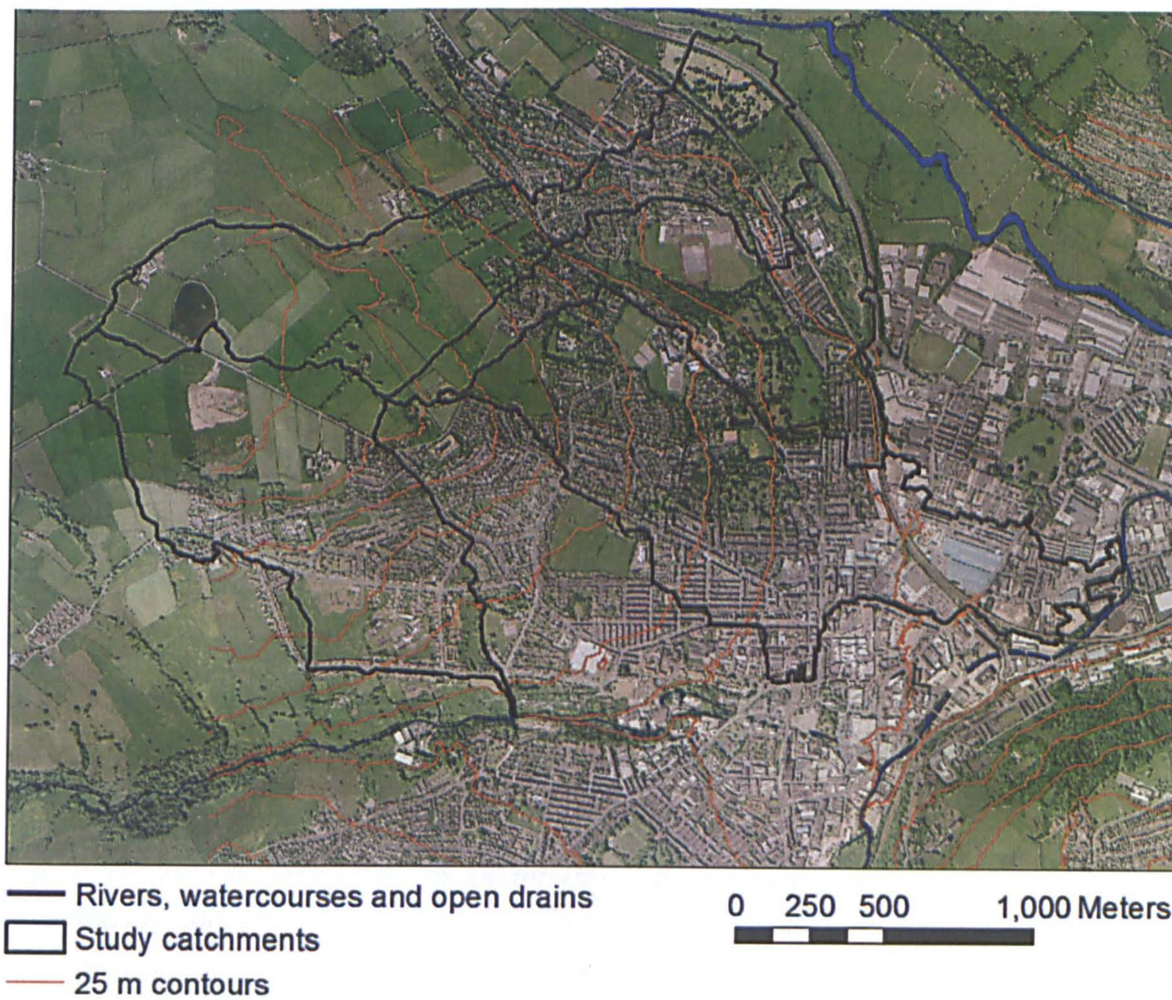

Figure 3.1: Study catchments and aerial photography.

OBSERVED DATA TO TEST THE MODEL

Having considered some of the major limitations of existing data sources, including the fact that the data held by local authorities may be not be digitally mapped or even in electronic format (but in paper based records), independent data collection in a standardized manner was opted for. Several options were considered, including mapping exercises with local authority drainage operatives, a residential door to door survey and waiting for a flood event and carrying out a field survey of flooded locations. These options were not considered effective given the time and resources available. A postal questionnaire survey was deemed the most resource efficient option.

The aim was to make the questionnaire as simple as possible with minimal questions to increase response rate. A further aim was to encourage replies not only from flooded residents but also to get confirmation of locations that have not been flooded. As an incentive, respondents who returned their completed questionnaires within three weeks were also entered into a £50 prize draw. A copy of the questionnaire sent out can be found in Appendix 3 and the online version can be viewed at www.flood.group.shef.ac.uk/quest.html. The questionnaire comprised 6 questions, of which only 3 were required; question 1 asked if they suffered from surface water flooding, question 2 asked for the length of residence at the address and question 3 whether they were happy to be contacted in the future. Questions 4, 5 and 6 were optional if respondents were willing to provide further details about the surface water flooding incidents. Further details regarding the flooding incidents, such as the date, exact location and depth would have been extremely useful, but it was felt asking for this type of information would only deter some people from filling out the questionnaire. Instead, respondents were simply asked if they had ever 'suffered' surface water flooding and providing further information was left as optional. Additional information clarifying the adopted definition of surface water flooding was distributed along with the questionnaires (Appendix 3). One of the required questions asked respondents to state the length of time living at that address. This was asked in order to determine whether during their time at the address there would have been any significant rainfall events that might have led to flooding. Rainfall that led to localised flooding was observed in September 2009 (Rahman, 2009) and therefore unless they had just moved in, most respondents should have knowledge of whether that event led to flooding at the property.

It was not feasible to send questionnaires to every resident in the catchment, so two random selections of properties were made using the results of model runs as described in chapter 2. The first selection consisted of properties that were considered to be at risk of surface water flooding, and a second selection was of properties well beyond areas considered at risk of surface water flooding. A total of 1000 properties were selected and each property was assigned a unique reference number which would enable the reply to be matched to its address on return. The questionnaires, along with freepost response envelopes, were sent out in August 2009. There was also the option of completing the questionnaire online and there was a webpage dedicated to Frequently Asked Questions regarding the questionnaire.

Figure 3.2 illustrates the addresses that were sampled and, for those that replied, whether or not flooding has been experienced. Table 3.2 summarises the replies of the questionnaires. Addresses were provided as points, however for the purpose of model validation, these points were then linked to the corresponding building footprint as provided by OSMM. Due to the random sampling used to select addresses, in two cases replies were received from separate addresses within the same building footprint. Fortunately the replies agreed, and therefore for mapping purposes and statistical analysis the two replies from the same building footprint are treated as one. The total number in the sample for statistical analysis is therefore 92. No one opted to complete the questionnaire online although in August 2009 there were 15 unique visitors to the website and in September 2009 there were 2. Two respondents posted back photographic evidence of flooding and one additional photocopied questionnaire was returned from an address that had not been sampled. Twenty two respondents provided details of flooding at locations further afield from their homes, this was not included in the statistical analysis but was mapped independently and is discussed separately. Two questionnaires were returned where it was clear from the additional information that the flooding was not on the property itself or street directly in front. Three questionnaire were returned where 'no' has been ticked but the details provided clearly indicated the flooding was adjacent to the property. These replies were therefore altered for the purpose of model testing.

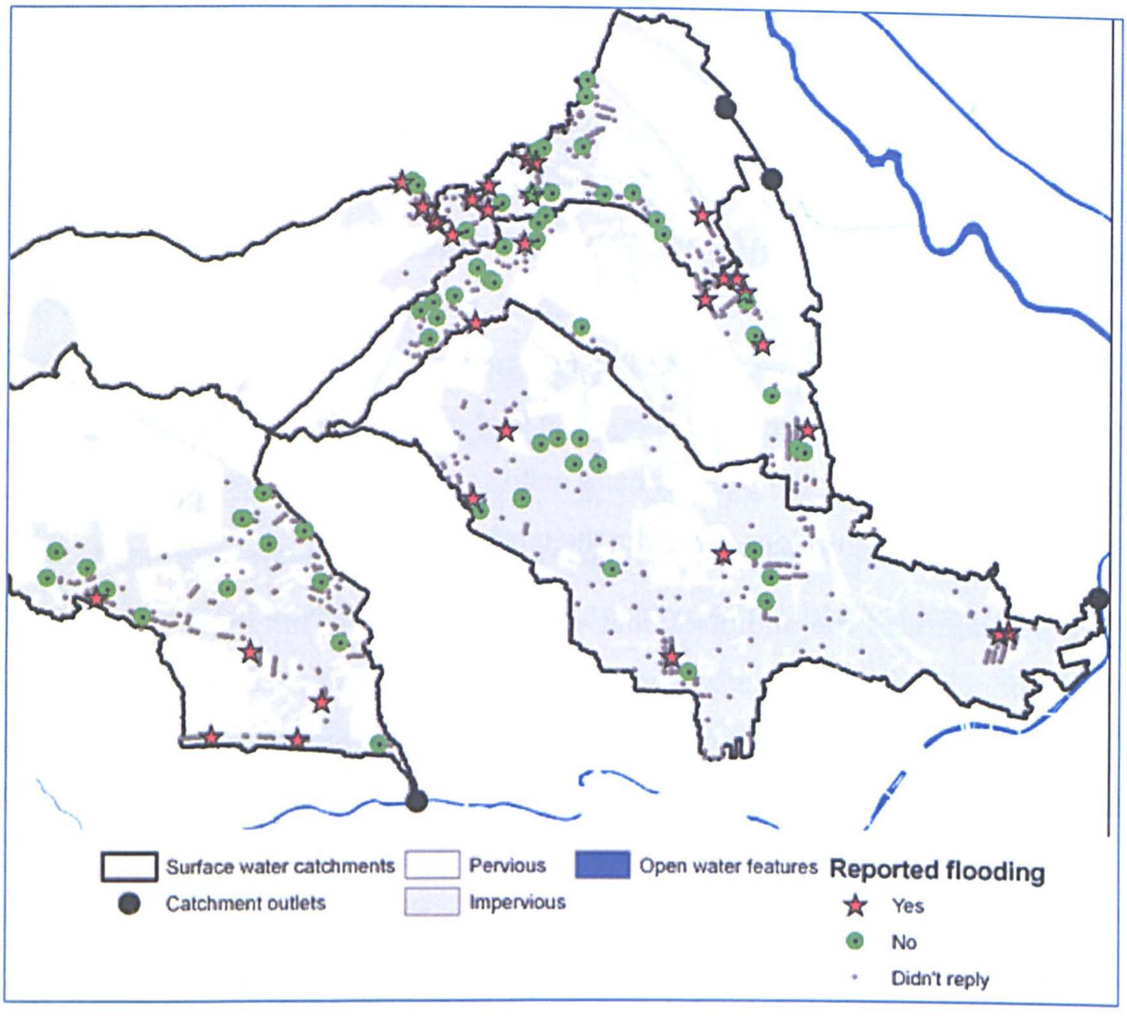

Figure 3.2: Sampled properties and responses.

Table 3.2: Summary of questionnaire replies.

	Number of replies Yes	No	Total
Reported suffering from surface water flooding	31	63	94
Residence time at the address less than 2 years	1	5	6
Residence time at the address between 2 and 5 years	6	10	16
Residence time at the address between 6 and 10 years	7	5	12
Residence time at the address greater than 10 years	16	42	58

RAINFALL EVENTS RESPONSIBLE FOR FLOODING

An appropriate input rainfall was required to test the model. Out of the 31 replies that reported flooding 24 provided some details regarding the frequency or dates of flooding. These were classified into those that indicated very frequent flooding, often stating something like "Every time it rains" or "Every time there is heavy rainfall" (although some of these were also accompanied with a specific mention of a date), and those which only provided specific dates (Figure 3.3). From those that provided more information regarding the date of flooding, six dates were identified using information from questionnaire replies and also from local newspaper reports (Table 3.3).

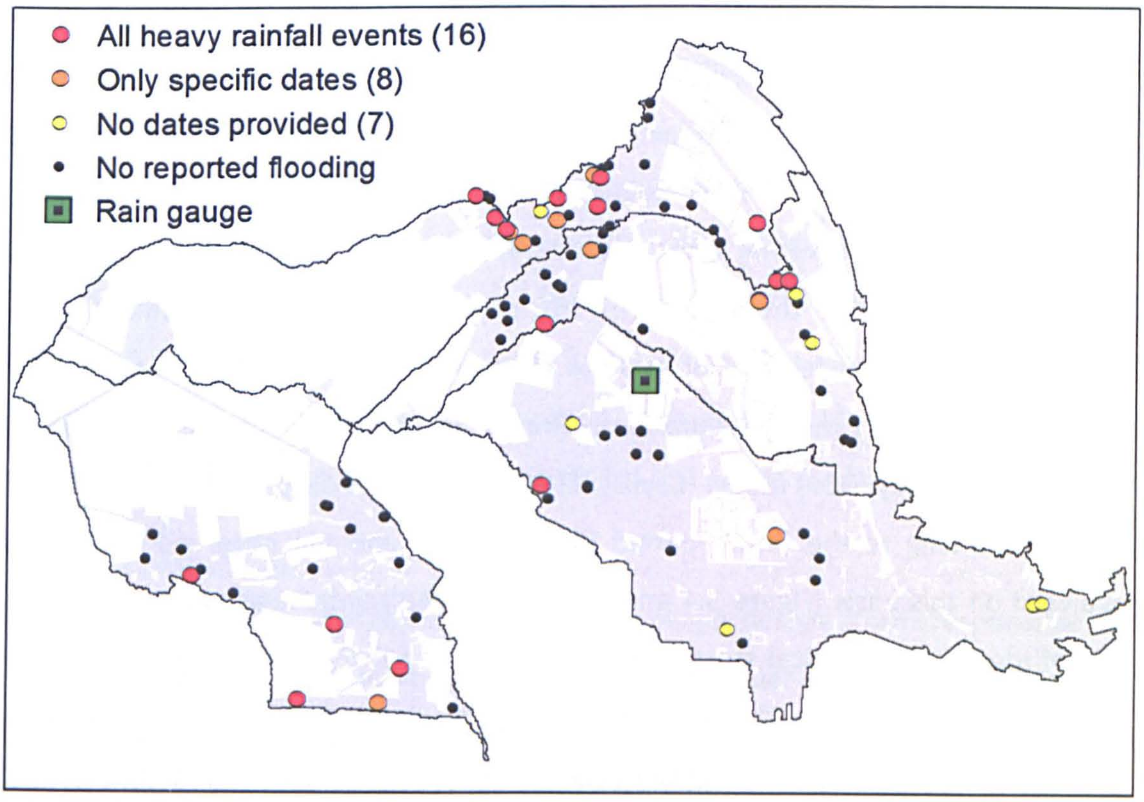

Figure 3.3: Analysis of dates of flooding.

Table 3.3: Dates that were identified as responsible for surface water flooding.

Dates	Mentioned in questionnaires	Mentioned in newspaper
1st Nov 2010	Mentioned specifically in 1 reply	No
6th Oct 2009	Mentioned specifically in 1 reply	Yes. "He said the water entered the house at about 3pm, on October 6, following hours of unusually heavy rain. " (Rahman, 2009)
6th Sept 2008	4 mentioned "summer 2008" (no rain gauge data until 31st Aug	Yes "Severe rain lashing the district for the past 24 hours has resulted in a September washout of sporting fixtures not seen for more than 30 years. " (Winrow, 2008)
21st Jan 2008	2 questionnaires "January 2008"	Yes. "The torrential rain has brought flooding chaos to Keighley and South Craven." (Shand, 2008a; Shand, 2008b)
25th Jun 2007	2 questionnaires mention "2007"	Yes. "Cellars in homes of Braken Street, Keighley, were flooded to a depth of four feet and had to be pumped out by fire-fighters" 26th June 2007 (Rush, 2007), and "Home owners fear they could be forced from their houses if water continues to rise following a second week of flooding" 28th June 2007 (Johnson, 2007)
15th Jun 2007	2 questionnaires mention "2007"	Yes. "The month's average rainfall arrived in only 24 hours, with Bingley declared the wettest place in Britain. West Yorkshire Fire & Rescue Service took 400 calls between 7am and 4pm yesterday from desperate homeowners wanting their flooded houses pumped out (Griffiths, 2007a; Griffiths, 2007b)

Rainfall data from two 0.2 mm tipping bucket rain gauges was obtained from the City of Bradford Metropolitan District Council (CBMDC) for these dates. One of the rain gauges (HF) is located within the study catchments as shown in Figure 3.3 and the other (SC) is located in the urban area 350 m south of the study catchments. The rainfall on the dates listed in Table 3.3 has been analysed to determine the maximum depth falling during a range of durations. The FEH (Flood Estimation Handbook) Depth duration frequency (DDF) model (Bayliss, 1999) was used to obtain depth and intensity values according to the return period for both sites and the observed rainfall was analysed on this basis (Figure 3.4 and Figure 3.5). The rainfall was analysed with the aim of identifying a typical storm profile responsible for flooding, with which to test the model. Table 3.4 provides a summary of the maximum rainfall depth observed at different durations centred on these dates.

Table 3.4: Maximum rainfall depth (mm) for a range of durations observed on dates of flooding.

Date	Rain gauge	30 mins	1 hour	6 hours	24 hours	48 hours
01 November 2010	HF	4.80	8.80	26.20	31.60	34.80
	SC	4.40	8.20	25.60	29.60	32.60
06 October 2009	HF	12.20	19.20	25.40	32.80	33.00
	SC	13.60	21.00	28.00	34.60	34.80
06 September 2008	HF	4.60	4.80	17.60	42.40	48.80
	SC	7.60	7.60	19.80	51.60	58.00
21 January 2008	HF	4.40	8.20	28.40	40.80	50.40
	SC	NA	NA	NA	NA	NA
25 June 2007	HF	2.20	3.60	19.00	38.20	44.00
	SC	3.00	4.40	21.60	45.20	51.40
15 June 2007	HF	5.60	7.20	26.40	46.00	62.40
	SC	7.80	8.80	27.60	50.00	70.40

The times of concentration for the study catchments, were computed using the Bransby-Williams formula (Derwent Estuary Program, 2005); these ranged from 43 to 95 minutes. It was therefore expected that the rainfall responsible for flooding would have durations of approximately 1 hour. The maximum depth and intensity for a 1 hour duration storm on five of the dates that led to flooding was characteristic of a frequent event, in most cases with a return period of less than 1 year and in all cases with a return period less than 5 years. It was the longer duration rainfall, of 24 and 48 hours of each of the events that was associated with the highest return periods (between 5 and 10 years). The only storm for which this was not the case was on the 6^{th} October 2009, which was a short duration, high intensity storm. The maximum 1 hour rainfall depth and intensity of this storm lies just above the DDF modelled 10 year return period.

It is evident from this analysis that selecting a single design storm responsible for flooding is complex, and especially given the limited number of storm dates that were obtained. From this limited number of dates when rainfall is reported to have led to flooding, it is the rainfall durations between 6 and 48 hours that are associated with the highest return period (with one exception on the 6^{th} October). The 24 hour duration 5 year return period was selected for model testing and the storm profile was generated using the FEH methodology (Faulkner, 1999).

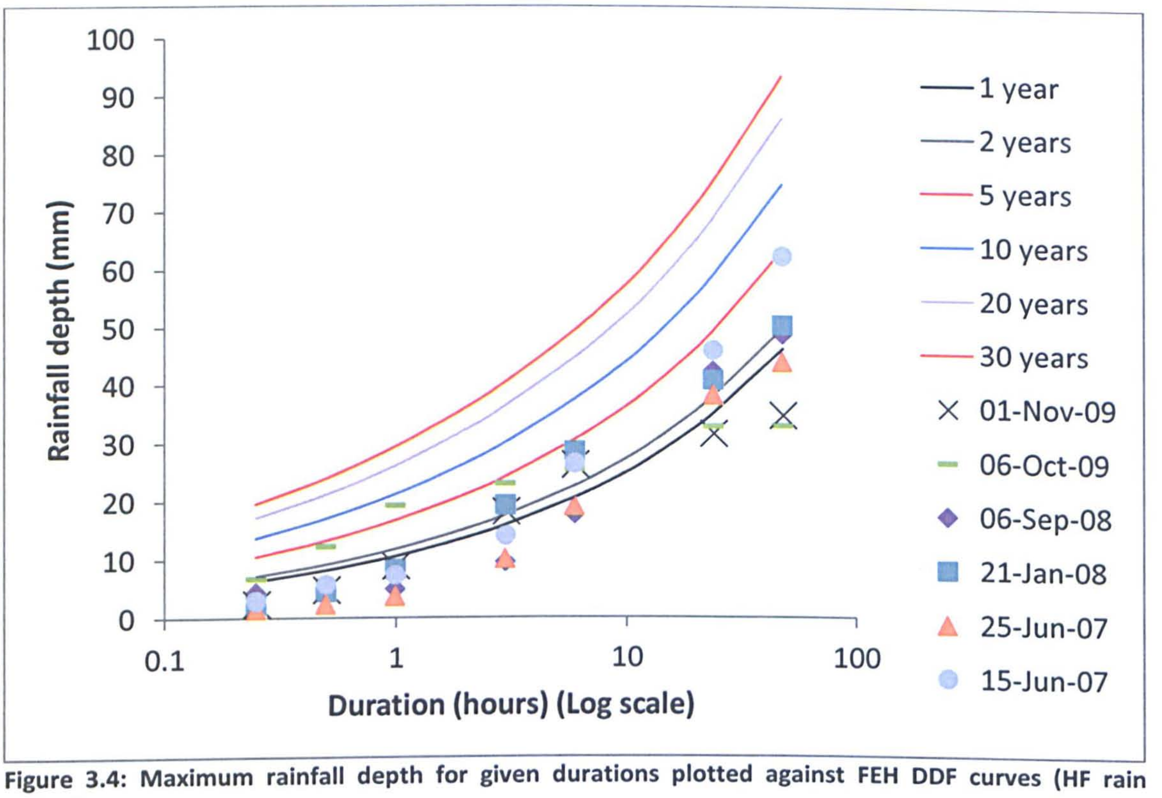

Figure 3.4: Maximum rainfall depth for given durations plotted against FEH DDF curves (HF rain gauge).

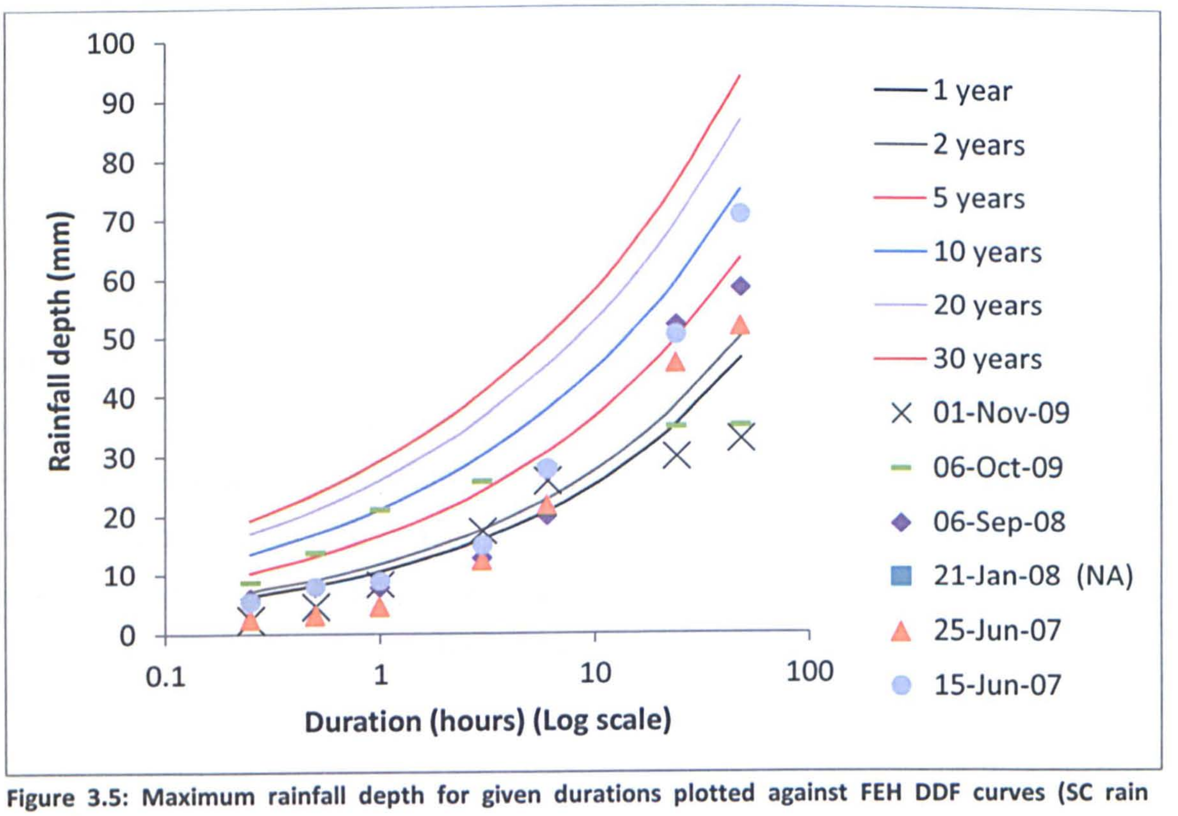

Figure 3.5: Maximum rainfall depth for given durations plotted against FEH DDF curves (SC rain gauge).

Excess water input for urban surface water balance model

From the limited analysis presented above, it is assumed that it is generally the longer duration storms that are responsible for much of the surface water flooding in Keighley. Long duration storms have lower rainfall intensities which the sewer system is expected to be able to drain away; the assumption made is that in these types of events the surface water responsible for flooding originates predominantly from natural surfaces that are not served by the sewer system and that begin to contribute runoff once the soil approaches saturation following prolonged rainfall. A more sophisticated method of estimating the excess surface water produced by natural areas, not served by the sewer system, is therefore required.

The method is based on a simple classification of the study catchments into areas expected to be served by the sewer system and those areas that are not. Using OSMM data, buildings and roads were given a 10 m buffer and this area was assumed to be served by the sewer system. A 10 m buffer was selected as this distance was found to also include many other typically urban surfaces which were not buildings or roads (e.g. gardens and courtyards) but that are likely to also be drained by the sewer system. This also assumes that runoff from within the 10 m buffer also ends up in the sewer system. All remaining areas were classed as not served by the sewer system, and are predominantly natural surfaces (Figure 3.6). Using the Bransby Williams formula (Derwent Estuary Program, 2005) the average time of concentration for the catchments was found to be approximately 1 hour and standards dictate that urban drainage should be designed to drain the rainfall intensities of a 30 year return period event (Water Research Centre, 2006). The model accounts for the capacity of sewers by assuming that these design standards are met.

Using the FEH methodology (Faulkner, 1999), the average rainfall intensity of the 1 hour 30 year return period event for Keighley was calculated to be 29.44 mm/hr. Based on this, the maximum sewer conveyance capacity is set at 30 mm/hr and all areas classified as 'served by sewer' will be able to drain off rainfall intensities of up to

30 mm/hr. The area of the hyetograph above the 30 mm/hr threshold is therefore deemed as excess water that remains on the surface. The maximum rainfall intensity of the design profile for the 24 hour duration, 5 year return period rainfall is 5.39 mm/hr therefore for the event used in model testing, no excess water is produced in the areas classed as served by sewer.

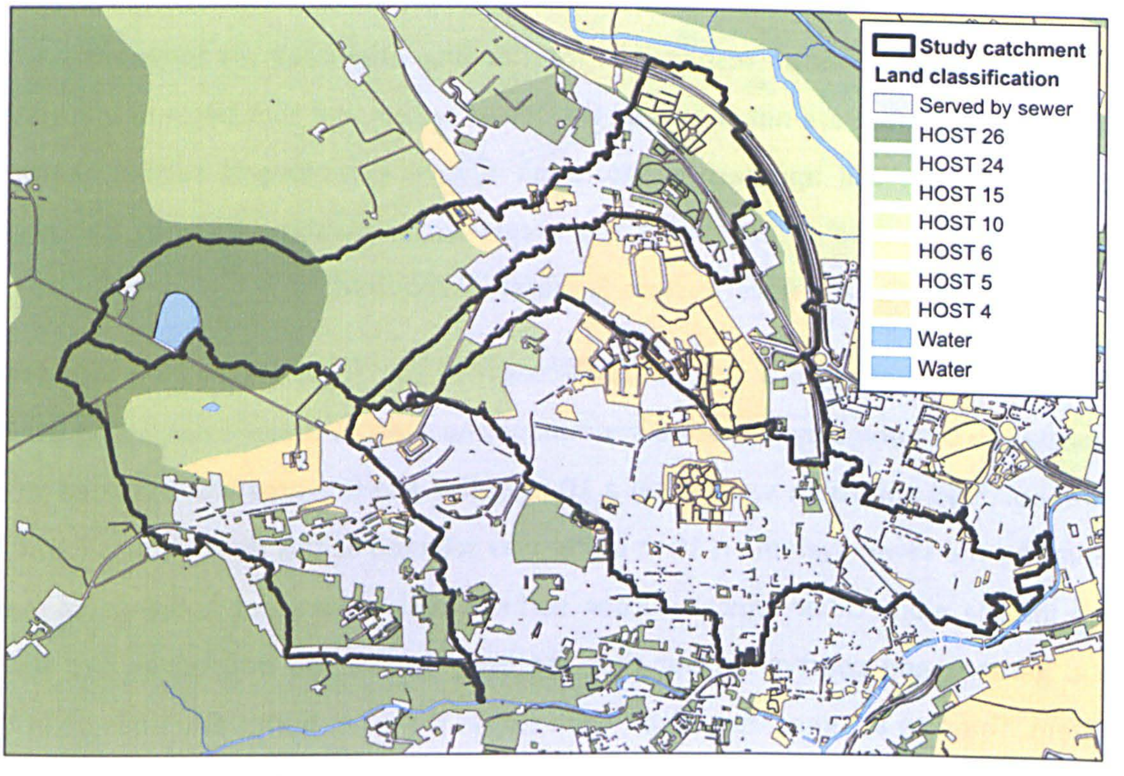

Figure 3.6: Land cover classed as served by sewer and soil HOST classes for natural land cover types.

The FEH variable percentage runoff equation was used to calculate the runoff volumes from the natural surfaces (Houghton-Carr, 1999). This method was selected as it is dynamic in reflecting changing runoff rates according to catchment antecedent conditions and storm magnitude, and it is recommended for the calculation of greenfield runoff rates (Balmforth et al., 2006b). It requires minimal data inputs as shown in Equation 3.1, where PR_{RURAL} is the percentage runoff from the natural part of the catchment, SPR is the standard percentage runoff (which is determined from the HOST soil type), DPR_{CWI} is the catchment wetness index and the DPR_{RAIN} is variation in runoff depending on the storm magnitude.

$$PR_{RURAL} = SPR + DPR_{CWI} + DPR_{RAIN} \quad \textit{(Eq. 3.1)}$$

This method relies on the HOST (Hydrology of Soil Types) classification to obtain the SPR, which is then adjusted according to DPR_{CWI} (Eq. 3.2) and DPR_{RAIN} (Eq. 3.3).

$$CWI = 125 + API5 - SMD \quad \textit{(Eq. 3.2)}$$

Where API5 is the antecedent precipitation index (as in Houghton-Carr, 1999) and SMD is the soil moisture deficit.

$$DPR_{RAIN} = 0.45(P - 40)^{0.7} \quad \textit{(Eq. 3.3)}$$

Where P is the catchment rainfall (mm) and P = 0 where the catchment rainfall is less than 40 mm. For model testing using design profiles, the API5 and the SMD were assumed to be zero. Table 3.5 presents the excess surface water depths used as model inputs.

Table 3.5: Excess water depths (mm) calculated according to land cover. The 1 hour duration, 30 year return period values are also shown for comparison.

	24 hour duration, 5 year return period	1 hour duration, 30 year return period (summer)
Total design rainfall depth	49.15	29.44
Served by sewer	0	9.94
HOST soil type 26	29.82	15.81
HOST soil type 24	20.48	10.22
HOST soil type 15	24.75	12.78
HOST soil type 10	13.40	5.98
HOST soil type 6	17.58	8.48
HOST soil type 5	8.09	2.80
HOST soil type 4	1.95	0

MEASURES OF MODEL AGREEMENT

The objectives of this exercise are to 1) compare observed data and quantify model performance and 2) determine if there is any value in the using the model. To achieve the first objective a suitable measure of agreement is required. The latter objective will be addressed with a qualitative discussion based on a range of data sources and field trips. In this case the modelled and observed results can be summarized by a contingency matrix as shown in Table 3.6. A number of descriptive statistics can be derived from a contingency matrix, as summarized in Table 3.7.

Table 3.6: Example of a contingency matrix.

		Observed flooding	
		Yes	No
Modelled flooding	Yes	*a*	*b*
(predicted)	No	*c*	*d*

Table 3.7: Descriptive statistics that can be derived from a 2 x 2 contingency table, a, b, c and d are as shown in Table 3.6 and *N* is the number of matched samples. (Source: Fielding and Bell, 1997; Kohavi and Provost, 1998).

Measure	Description	Calculation
Overall accuracy (percentage correctly classified)	The rate of correct predictions made by the model	$(a+d)/N$
True positive rate (also Recall, Sensitivity)	The conditional probability that case X is correctly classified	$a/(a+c)$
True negative rate (Specificity)	The conditional probability that case X is incorrectly classified	$d/(b+d)$
Precision (also Positive predictive power PPP)	Assesses the probability that a case is X if the model classifies as X.	$a/(a+b)$
Negative predictive power (NPP)	Assesses the probability that a case is not X if the model does classify the case as X	$d/(c+d)$
False positive rate		$b/(b+d)$
False negative rate		$c/(a+c)$
Prevalence		$(a+c)/N$
Overall diagnostic power		$(b+d)/N$
Misclassification rate		$(b+c)/N$
Cohen's Kappa	Measures the strength of agreement	$\frac{(a+d)-(((a+c)(a+b)+(b+d)(c+d))/N)}{N-(((a+c)(a+b)+(b+d)(c+d))/N)}$

Cohen's Kappa is one of the only available measures of agreement for categorical data (Everitt, 1977). The Kappa statistic was selected as the main measure of model agreement, although other measures such as the false positive rate, false negative rate and the overall percentage correctly classified are also used to assess model performance. The Kappa statistic takes into account the classifications that could have occurred by chance and provides a value that ranges from 0 to 1. A value of 1 is a perfect agreement and values nearer to zero are considered to have occurred by chance. Negative values are rare but are said to have an agreement that is weaker than what would have occurred by chance. There is little guidance on the exact interpretation of the Kappa statistic, with the exception of the benchmark proposed by Landis and Kock (1977, cited in Everitt, 1977) as shown in Table 3.8, especially with regard to model testing. The confidence interval of the Kappa statistic can be calculated which provides an indication of the possible range of the result.

Table 3.8: Suggested benchmark for evaluating Kappa values by Landis and Kock, (1977) cited in Everitt (1977).

K	Strength of agreement
0	Poor
0 – 0.2	Slight
0.21 – 0.40	Fair
0.41 – 0.60	Moderate
0.61 – 0.80	Substantial
0.80 – 1	Almost perfect

3.3. Results of the model testing and discussion about model validation

Model calibration

The model has few input parameters that can be calibrated and the sensitivity of some of these was tested in chapter 2. Table 3.9 summarizes the model properties that could be used for model calibration. Given the limited surface water flooding observations, these are reserved for model testing rather than calibrating. It is expected that that model testing will highlight the important model inputs that require calibration, and therefore appropriate data can be collected.

Table 3.9: Summary of the model properties that may require calibration.

Model properties	Calibration options
DEM	Minimum level of detail required (inclusion of walls, curbs etc..) Inclusion of elevated underflow structures (bridges, canopies etc..)
Excess water method	Method used to account for urban drainage conveyance. Method used to calculate excess water from pervious and impervious land cover
Land cover classification	Number of land cover classes Assignation of excess water method for each land cover class
Surface depressions (sinks)	Properties of sinks to be excluded or included in the model (i.e. minimum depth, volume or surface area of sinks)
Flow direction algorithm	Unique cell flow direction or flow apportioning algorithms
Treatment of surface water passed down from multiple exit sinks	Method for computing water stored and passed down at each of the exits of a multiple exit sink
Translation of model outputs into flooded locations	Determining sink and flood route properties that classify as a location as flooded

Classifying properties as flooded

Once the model results have been generated, an interpretation of model output for use as a predictor for surface water flooding was required. To use the model output as a predictor it was necessary to identify a set of criteria that could be used to classify the status of a property as flooded or not flooded. The classification is based on proximity to model output in the form of areas where water ponds (sink polygons) and indicative major flood routes (polylines). Flood routes are cells with high total accumulated surface water; they are termed indicative flood routes as they are identified as 1 cell wide, whereas in reality the flood route may span the width of a road for example. Using these two principal model outputs, appropriate selection criteria for classifying properties as experiencing surface water flooding were explored. A suitable selection criteria is required that does not highlight over-large proportions of the catchment as being at risk, as this would not be a useful tool. A limited number (84) of combinations of selection criteria were explored manually and the general findings are summarised in Table 3.10. The findings in Table 3.10 are based on a single model run which produced one set of model results which are the basis of the validation.

Table 3.10: General findings of the exploratory analysis of selection criteria.

Description	Range looked at	General findings
Depth of water in sink	15 cm to 50 cm	A greater water depth resulted in a better match with known flood risk areas. A water depth of 15 cm resulted in approximately 50 % of the properties highlighted as at risk compared to less than 10% if a 50 cm water depth is used.
Distance of sink from building footprint	1 and 2 metres	Using a distance of 2 metres generally highlights slightly more properties as at risk
Sink surface area	All sinks and those with a surface area greater than 5 m^2	There was a better match with flood risk locations when all sinks were included. Generally this resulted in more properties highlighted as at risk
Total accumulated volume of flow path	50, 150, 250, 300 and 500 m^3	Overall the best matches with flood risk areas were obtained using accumulated volumes of 300 m^3 and these highlighted approximately 3% of properties as at risk. Using a higher volume did not improve the correspondence with known flood risk areas.
Distance of flow path from property	1, 2 and 3 m	Using a distance of 2 and 3 m generally produced similar results in terms of matched flood risk areas, with only 3% of properties selected as at risk
Selected based on (1) flow paths only, (2) sinks only, (3) near sink and flow path (4), near sink or flow path		These selection criteria made a significant difference to the percentage of properties highlighted as at risk and also the matches with locations known to flood. Generally the better results were produced by satisfying the criteria of being near a 'flow path or sink' or only flow paths. Using only sinks generally produced poor results in terms of highlighting known areas of flooding. Using selection criteria of 'sinks and flow paths' produced poor results as very few locations satisfied both criteria.

From the limited analysis and using expert judgement the selection criteria that had to be met for a property to be highlighted as flooded was ≤ 2 m from a sink with a water depth ≥ 50 cm or ≤ 2 m from a flow route with a total accumulated volume of ≥ 300 m^3. Application of these criteria with the event selected for model testing results in 6%

of properties being selected as experiencing surface water flooding. Using these criteria also flags 6235 m (~11%) of road length that coincides with a major flow path and 2396 m^2 of ponding ≥ 50 cm deep on roads (~1% of road surface) (Figure 3.7 and Table 3.11).

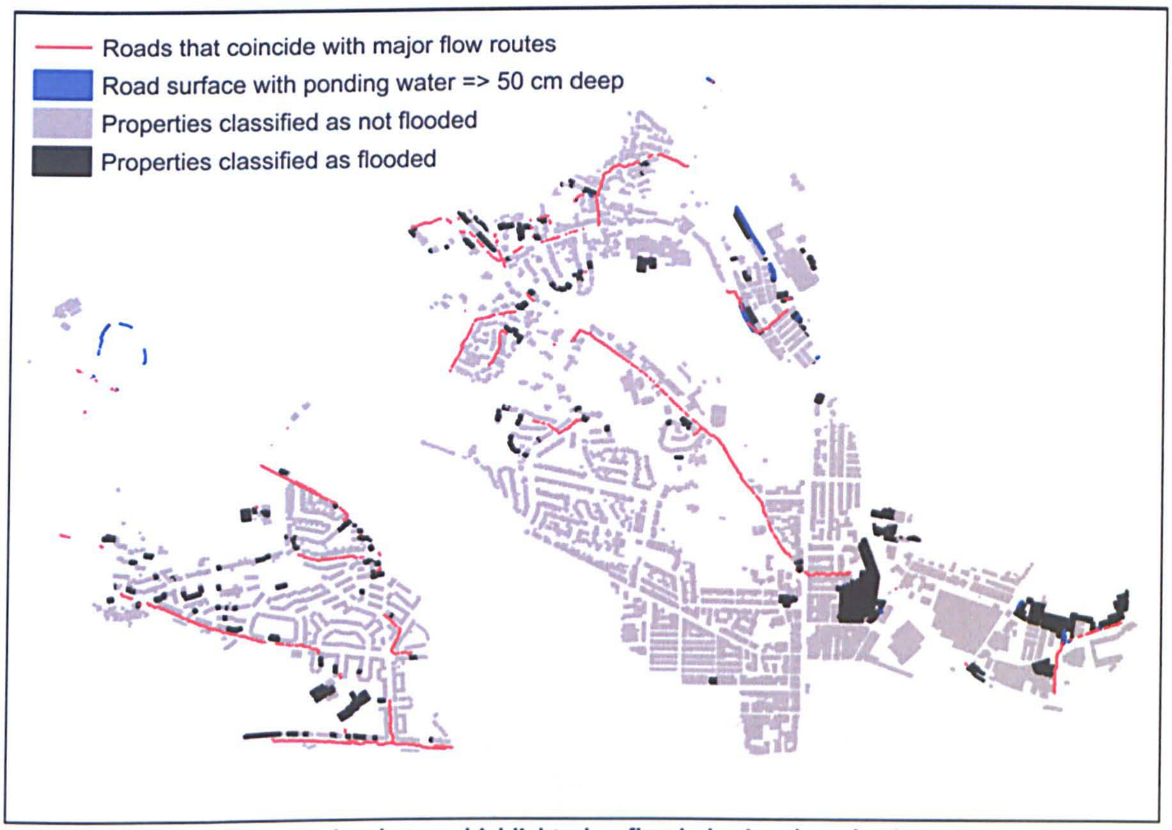

Figure 3.7: Roads and properties that are highlighted as flooded using the selection criteria.

Table 3.11: Properties and roads that are classified as flooded.

	Entire study area	Catchment A	B	C	D
Flooded properties (%)	6	12	7	2	13
Road length that coincides with a major flood route (%)	11	12	9	6	25
Road surface with ponding ≥ 50 cm deep (%)	1	2	2	0	0

Model performance assessed against reported flooding

The 24 hour duration rainfall event of a 5 year return period produced a Kappa statistic of 30% for the study area, which according to the benchmark reproduced in Table 3.8 means that the model has a 'fair' strength of agreement with observed data.

Computing the 95% confidence intervals of the Kappa statistic reveals that the lower and upper limits are 7% and 53% respectively, indicating the wide range in possible interpretations. This is due to the very small sample size, and drawing conclusions regarding the model performance in reported flooded areas is further constrained given that only one third of the sample reported flooding. The spatial distribution of the results in shown in Figure 3.8 and Table 3.12 summarizes the findings across the four study catchments. The building footprint of five properties that replied fell in two catchments; this is because roofs often mark catchment boundaries. These five cases were looked at individually and a decision about which catchment they corresponded to was made on the basis of the likely processes that would lead to flooding.

Table 3.12: Model agreement statistics and number of replies that reported flooding.

	Study area	Catchment			
		A	B	C	D
Kappa statistic	0.30	0.54	0.09	0.00	0.29
Fraction correctly classified	0.73	0.77	0.74	0.68	0.70
False positive rate	0.10	0.00	0.10	0.00	0.27
False negative rate	0.63	0.46	0.83	1.00	0.40
Reported flooding	30	13	6	6	5
No reported flooding	62	13	21	13	15

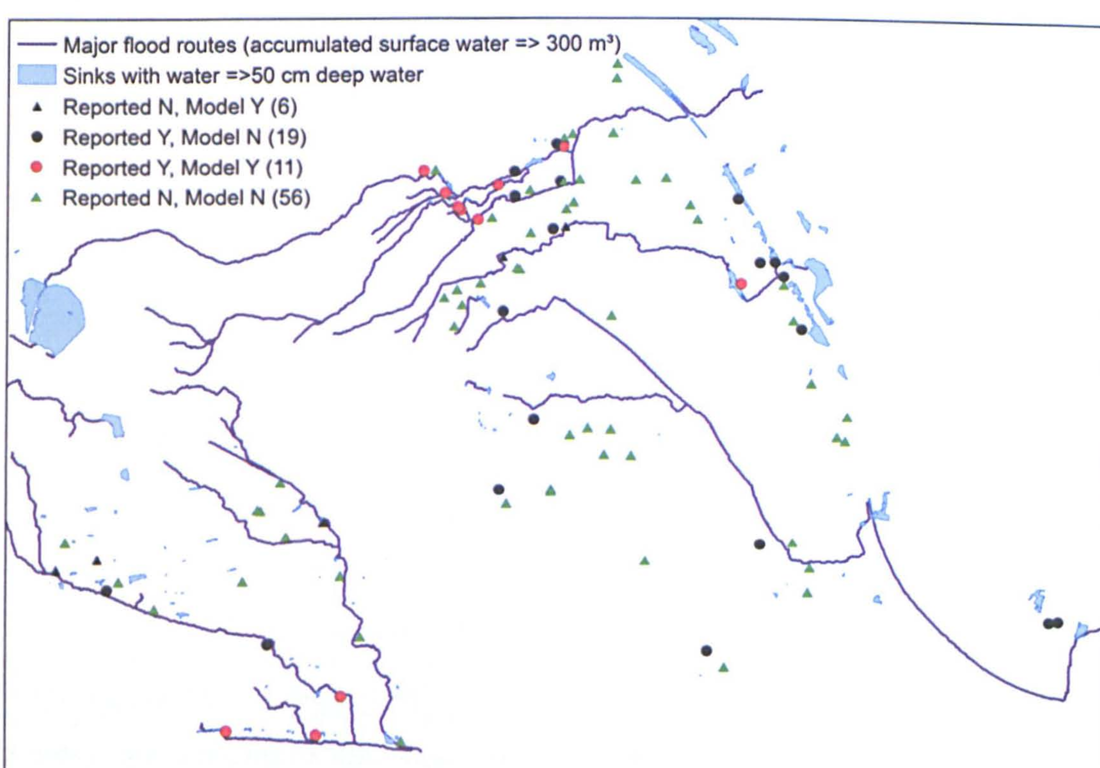

Figure 3.8: Reported and modelled results.

There is a clear difference in the strength of agreement across the four catchments (Table 3.12). The model best represents flooded locations in catchments A and D but, according to the Kappa statistic there is a slight and poor agreement with observed data in catchments B and C. Despite the high percentage correctly classified (> 68%) in catchments B and C, the Kappa statistic tells us this may be purely down to chance. The false positive rate is low, but it is the false negative rate which is very high, making the use of the model in these areas questionable. Across the study area a total of 25 properties were misclassified (Figure 3.9). The misclassified properties were evenly distributed across the four catchments. These were looked at on a case by case basis, and 12 of these locations were investigated by means of a field visit, in order to try to establish the possible reasons for misclassification. The detailed analysis is outlined in Appendix 4 and a summary of the reasons why the model has failed to correctly classify the properties is found in Table 3.13.

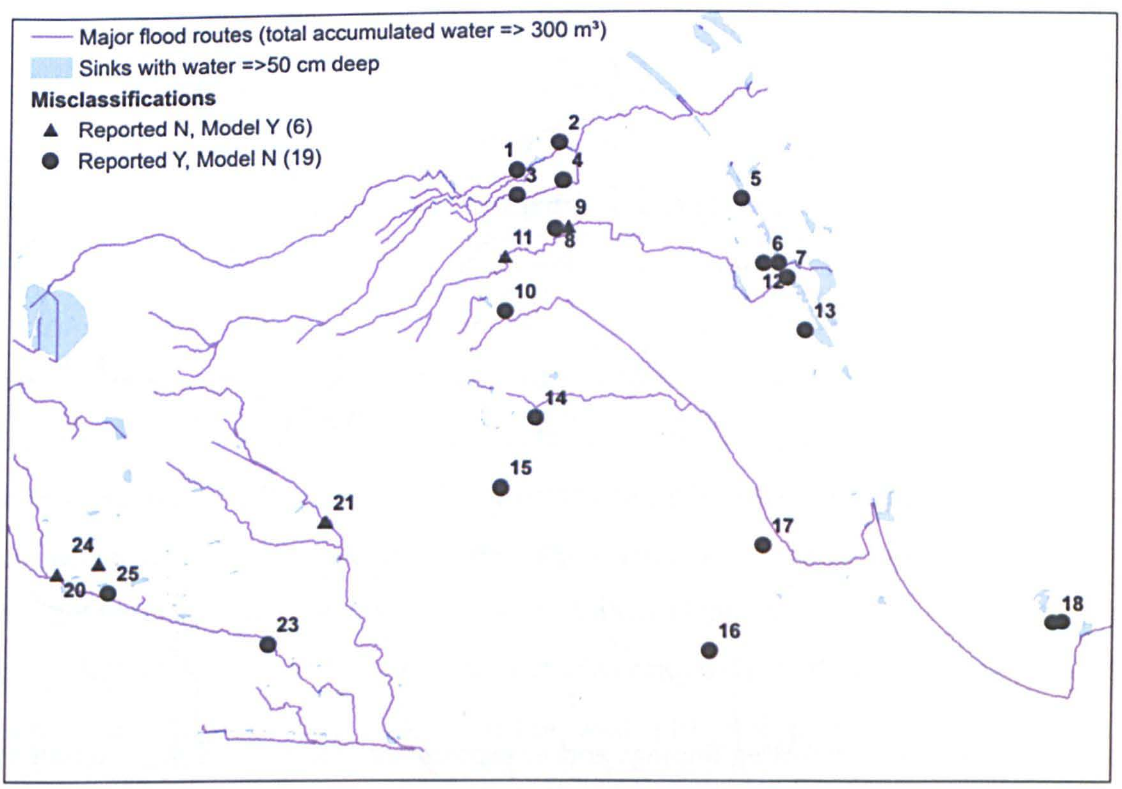

Figure 3.9: Misclassifications: locations where observed and model results do not agree.

Table 3.13: Summary of the most likely reasons for poor model agreement.

Reason for misclassification	Total	Field visit	Properties (Label numbers as in Figure 3.9)	Catchments
Limitation with DEM	10	5	1, 4, 9, 11, 14, 15, 21, 22, 24, 25	All 4
Selection criteria	10	5	2, 5, 6, 12, 13, 16, 18, 19, 20, 23	All 4
Rainfall event	5	2	7, 16, 17, 18, 19	B, C
No representation of drainage assets	3	3	3, 8, 9	A, B
Excess water method	2	1	6, 13	A, B
Interpretation of flooding	1	0	10	B
Multiple exit sink problem	1	0	5	A

The limitations of this somewhat subjective analysis are acknowledged. Primarily there are very few observations on which to make generalizations. Only the misclassified properties were looked at in detail. It would be possible to go a step further and look at all 92 properties on a case by case basis to establish whether in fact many of the correctly classified properties could have occurred by chance. For example, could the resident be reporting flooding in the road to the front of the property but the property is identified as at risk due to a sink filling at the rear of the property? That analysis was not undertaken and it is assumed that properties have been classified for the right reason.

The explanations attributed to the properties that were visited should be given more weight and some interpretations are more conclusive than others (see Appendix 4 for details on the explanations given and on what basis). Nonetheless the results are very revealing indicating that limitations associated with the DEM can account for many of the incorrect model predictions. It may be that alternative selection criteria could be developed to identify flooded locations in the model. Although in the questionnaire design phase it was felt that the definition of surface water flooding was sufficient and would produce homogenous replies, it was evident from replies that there was a great range of interpretations of surface water flooding. Another potential explanation for the low model agreement in catchments B and C, is that the type of event that leads to flooding is different to that which was used to test the model.

Some of the more interesting findings and interpretations for each of the catchments are detailed below. These discussions incorporate some of the additional data provided by respondents about flooding in other parts of Keighley. They also draw on drainage incident data and locations of known culverts and watercourses that were obtained from CBMDC. At the start of this phase of the research local authority drainage incident data for Keighley was only available in paper based records. As a result of the new surface water management responsibilities assigned to local authorities, CBMDC deemed it a worthwhile exercise to digitize drainage incident records. These were made available for this research. The quality of this data set was not evaluated, however it is noted that the precise location of an incident was not always known from the paper records and therefore was placed in the middle of a stretch of street to which the incident related. Similarly although the database aimed to record further details about the incidents, these were not always obvious from the paper based records.

CATCHMENT A

Based on the statistical analysis, the best results of the model were obtained in catchment A with a Kappa statistic of 54% and 0% false positive rate. In this catchment the sample sizes that reported flooding and no flooding was equal, which provides comparable confidence in computed false positive and negative rates. There is a well-known surface water flooding spot at the top of the urban part of the catchment where many of the properties along a particular road often complain of flooding (Figure 3.10). There is also known flooding lower down in the urban parts (Figure 3.11). The flooding in this catchment can be principally explained as a result of runoff from the upstream fields. In the urban area this runoff accumulates into major flood routes, and properties near those flood routes suffer from surface water flooding, either directly from the flood route itself or from surface depressions filling with water.

The main conclusion that can be drawn from the detailed analysis is that the model performs well in this catchment because the major flood routes are modelled well. This is confirmed by photographic evidence that was provided by respondents and is shown in Figure 3.10 (locations a, b, c and d). Furthermore, some of the major flood routes identified by the model coincide well with the location of culverts and watercourses as in location f in Figure 3.10, which provides further confirmation that the model is representing the major catchment flood route patterns. Some of the CBMDC land drainage incidents can also be explained by the model results. The land drainage incidents shown in location e in Figure 3.10 coincide with major flood routes and sinks as identified the model. Many of the land drainage incidents don't provide further details, but location c in Figure 3.11 mentions 'water flooding road' and this is corroborated by model results showing a major flood route along the road. Also in Figure 3.11 the land drainage incident at location d is in very close proximity to a major flood route.

Location a in Figure 3.11 illustrates where local features not represented in the DEM limit the accuracy of model results. The wall shown at location a is not represented in the DEM and the neighbouring resident confirmed that significant ponding occurs at this point, so much so that the resident takes it upon himself to regularly maintain the gulley at this location so as to alleviate flooding in this location which is adjacent to his property. The properties downstream of location b in Figure 3.11 commented that flooding has occurred when there are issues (e.g. blockages, failures, or flooding) with the culvert shown in the photo. Whilst this example highlights where the presence of urban drainage assets may lead to erroneous model predictions (when performing as required), the presence of the culvert grate in the same location as a modelled major flood route provides confirmation that a major flow path traverses this location. Furthermore scouring and fine sediment deposition was evident upslope of the culvert (as seen in the photograph of location b) indicating the presence of flowing water.

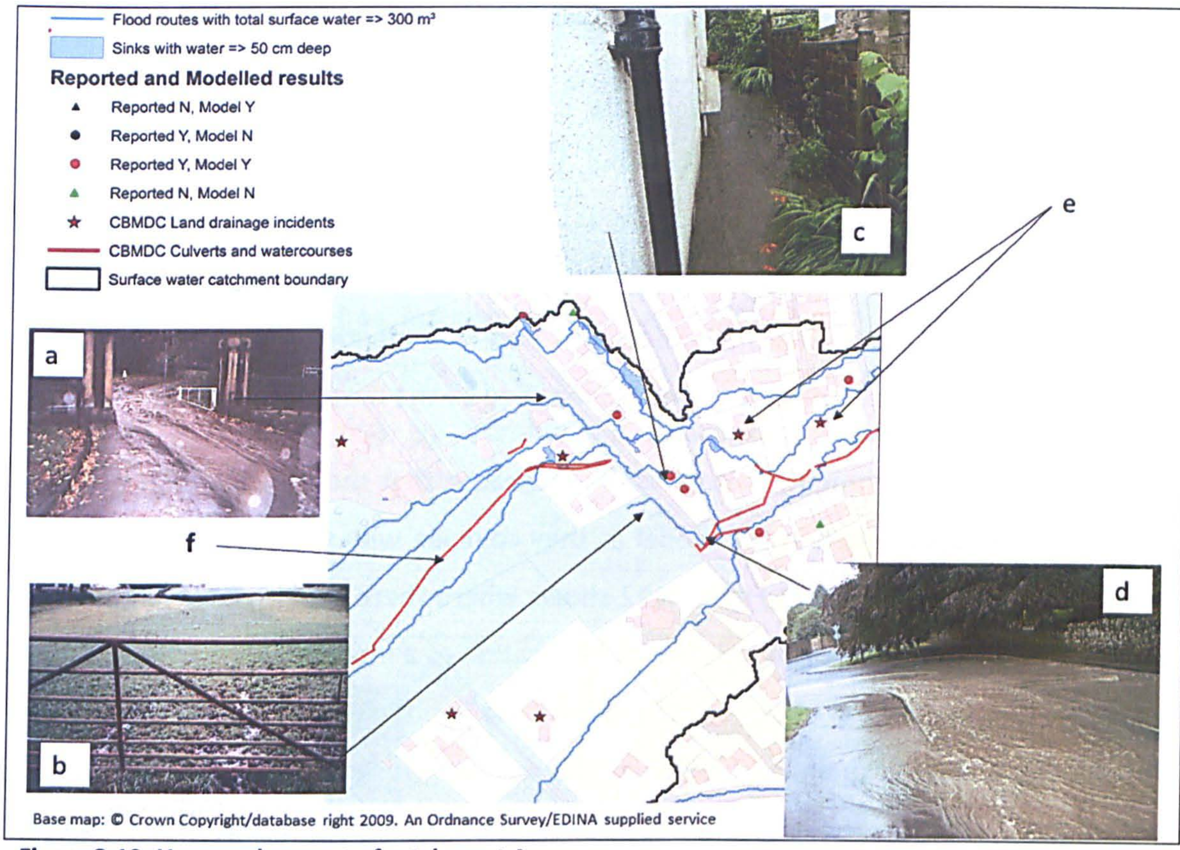

Figure 3.10: Upper urban part of catchment A.

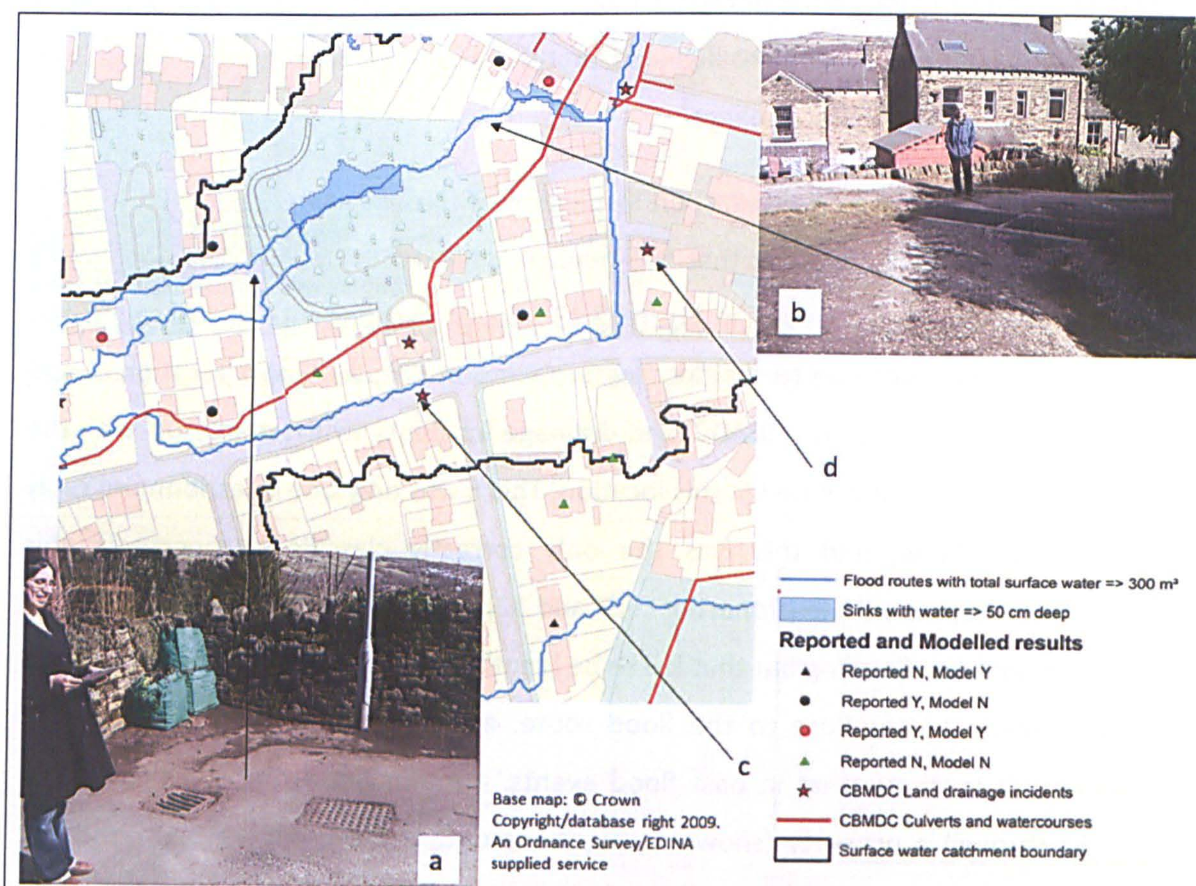

Figure 3.11: Lower down in the urban area of catchment A.

Catchment B

Catchment B has a high false negative rate (86%) which raises questions about the model for predicting surface water flooding, as many flooded areas would fail to be identified. Whilst the percentage of correctly classified properties is high (74%), this statistic is heavily biased by the correctly classified non-flooded properties which are two thirds of the sample. The model performs poorly in identifying the six properties that did report flooding (only 1 is correctly identified by the model as flooded).

At the top of the catchment, there is some assurance that the principal flood routes are fairly well represented in the model as they coincide with the presence of known drainage assets. Location a in Figure 3.12 shows where there are three closely spaced gullies in the road in approximately the same location as a modelled flow path. CBMDC records also confirm a short stretch of culvert or watercourse in the vicinity. Downslope of this location, a resident confirmed the presence of a culvert that by-passes her property: the approximate location of the culvert as described by the resident is shown in location b of Figure 3.12. This coincides with a modelled flow path. These two examples also serve to highlight that the exclusion of urban drainage assets account for poor model performance.

At the lower end of the catchment, on inspection of the anecdotal and photographic information one may conclude that the main flooded areas are represented in the model, as in locations a and b in Figure 3.13. Eleven respondents from around the study area made reference to the flooding problems on Skipton Road (location a) and there is also a collection of CBMDC land drainage incidents which match up with the properties classified as flooded in this location. There was only one questionnaire reply from Skipton Road, and this was the only correctly classified property in this catchment. There are three properties (6, 7 and 12) downslope from the main ponding area that reported flooding but that fail to be identified by the model. Properties 7 and 12 are however very close to the flood route, and property 6 is on a catchment boundary. It is known that in past flood events, a major flood route in this area is straight through a property (shown by locations c, d and e in Figure 3.13) and not solely through the alley way further down the road as the model predicts. It may be that the cumulative errors resulting from the failure to accurately model the flood route explain the three properties that are not correctly identified by the model. This catchment illustrates the influence that local features, not represented in the DEM, have on the major flow paths and sinks that collect surface water. Location c in Figure 3.13 was a major flood route in the event pictured, however when the site was visited in 2010, the resident had installed a flood gate (photo in f in Figure 3.13). Local features that can greatly influence results can be temporary and variable. It is therefore a complex task to identify and incorporate them into surface water modelling.

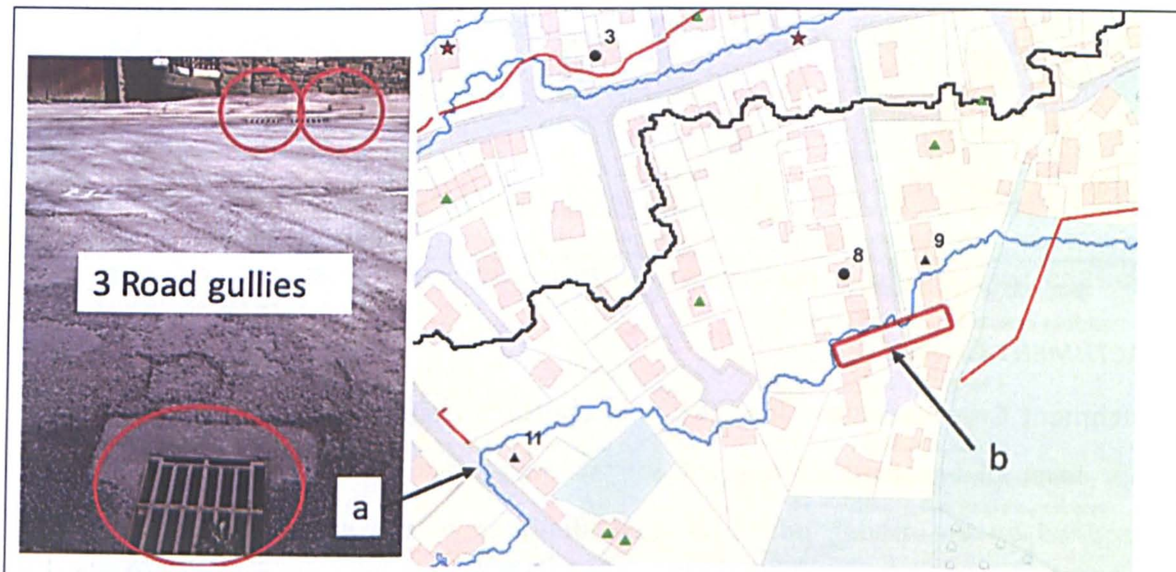

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Figure 3.12: Upper urban part of catchment B (see Figure 3.10 for the legend).

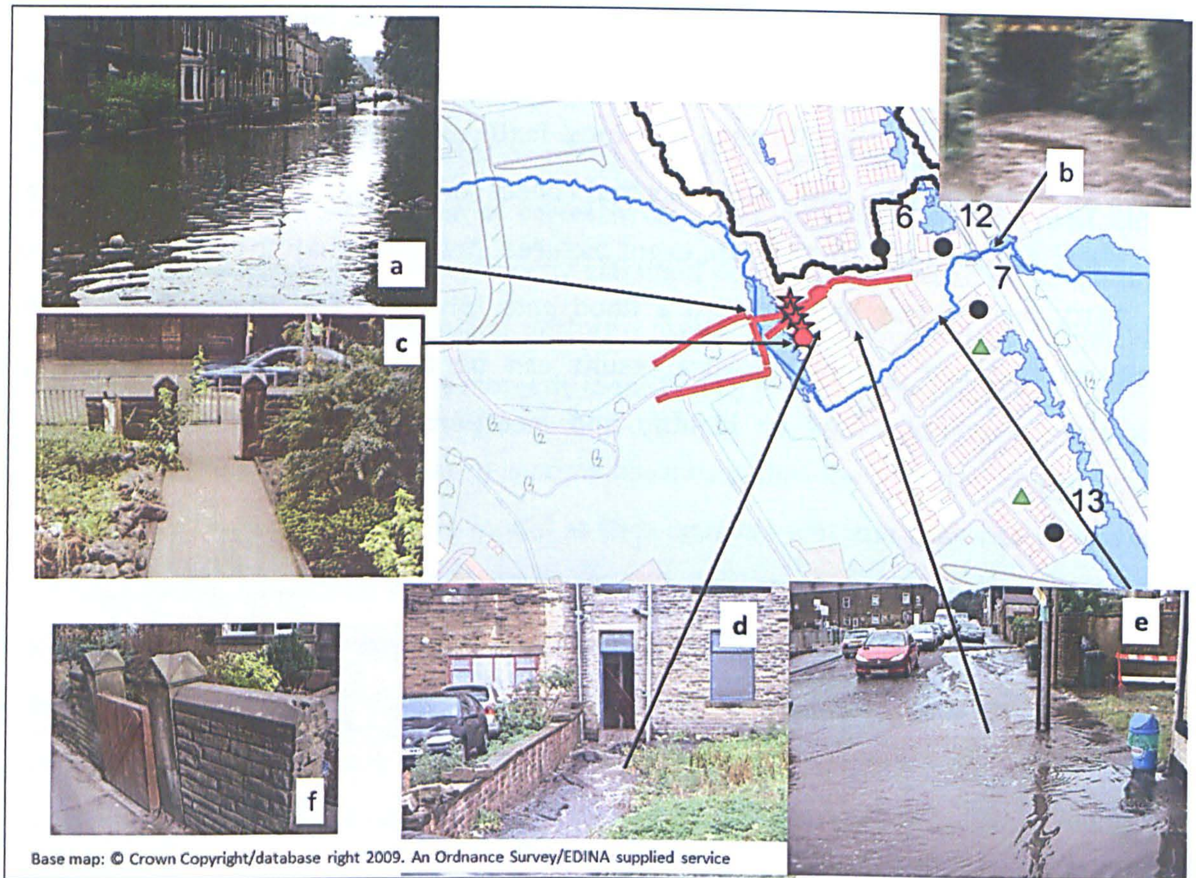

Figure 3.13: Lower urban part of catchment B (see Figure 3.10 for the legend).

CACTHMENT C

Catchment C produced the lowest Kappa statistic of all the catchments indicating a poor level of agreement. None of the six locations that reported flooding were identified by the model, but the model identified all the dry properties (0% false positive rate). Using additional information gathered, it is ascertained that at least three points along the modelled major flood route are known to pose flooding problems. One questionnaire respondent mentioned that there is flooding at the bottom of the road as shown in location a in Figure 3.14, CBMDC representatives also made reference to this location where a wall was toppled by flood waters. A known problem of surface water flowing, along Mayfield Road at location b (very near to the modelled flood route), led to the installation of a series of stepped swales along this road (Stovin et al., 2007). At location c in Figure 3.14, the modelled flow path coincides with a short stretch of culvert that crosses the railway line.

This catchment has the least pervious land cover of the four study catchments (~20%). Using the 24 hour duration rainfall event of 5 year return period produces no excess water in 80% of the catchment as it is classified as 'served by sewer' and for the associated rainfall intensity it is assumed there is no water remaining on the surface, and that the sewer has sufficient capacity for the entire flow. This explains why many of the reported flooded locations are not identified by the model. It is therefore inferred that either the sewer system is not effective at draining these areas for the test event (for example it has insufficient capacity), or that the event that leads to flooding is different to that which was used to test the model. Figure 3.15 shows the major routes and sinks that are modelled when a 1 hour duration rainfall event of a 30 year return period is used. Using the method outlined in section 3.2, this event produces 8.88 mm (out of a 29.44 mm event) that remains on the surface that is classed as 'served by sewer'. The properties labelled 16 to 19 would now be classified as flooded.

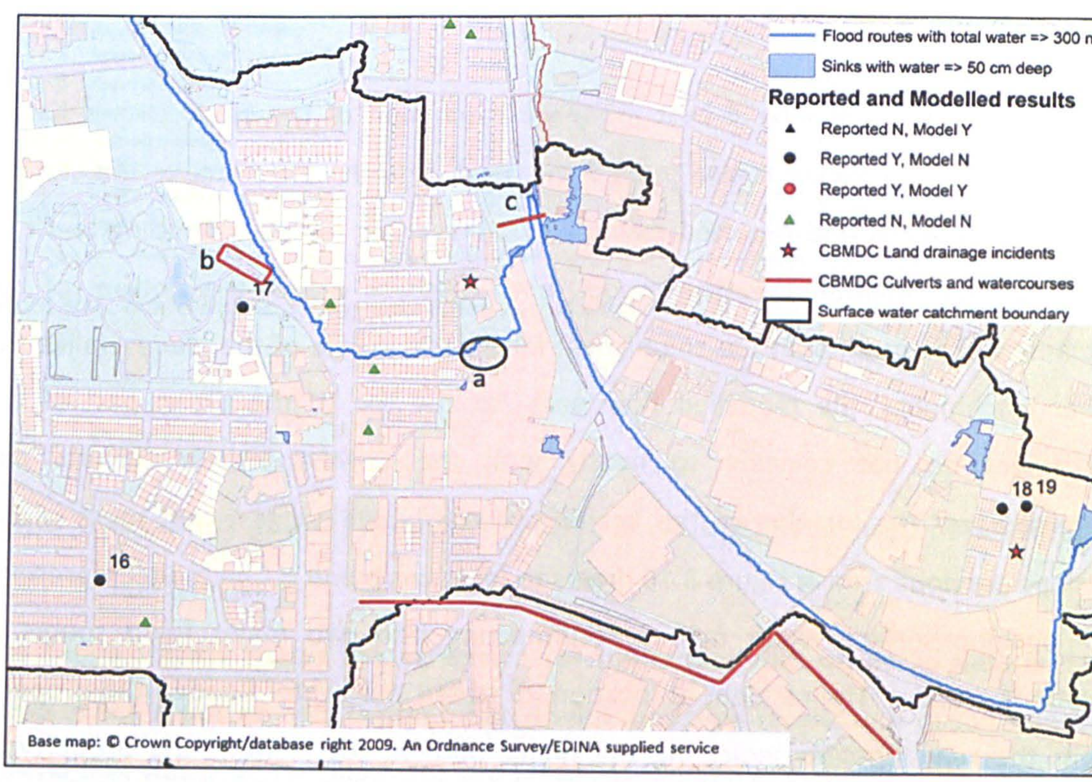

Figure 3.14: Lower part of catchment C.

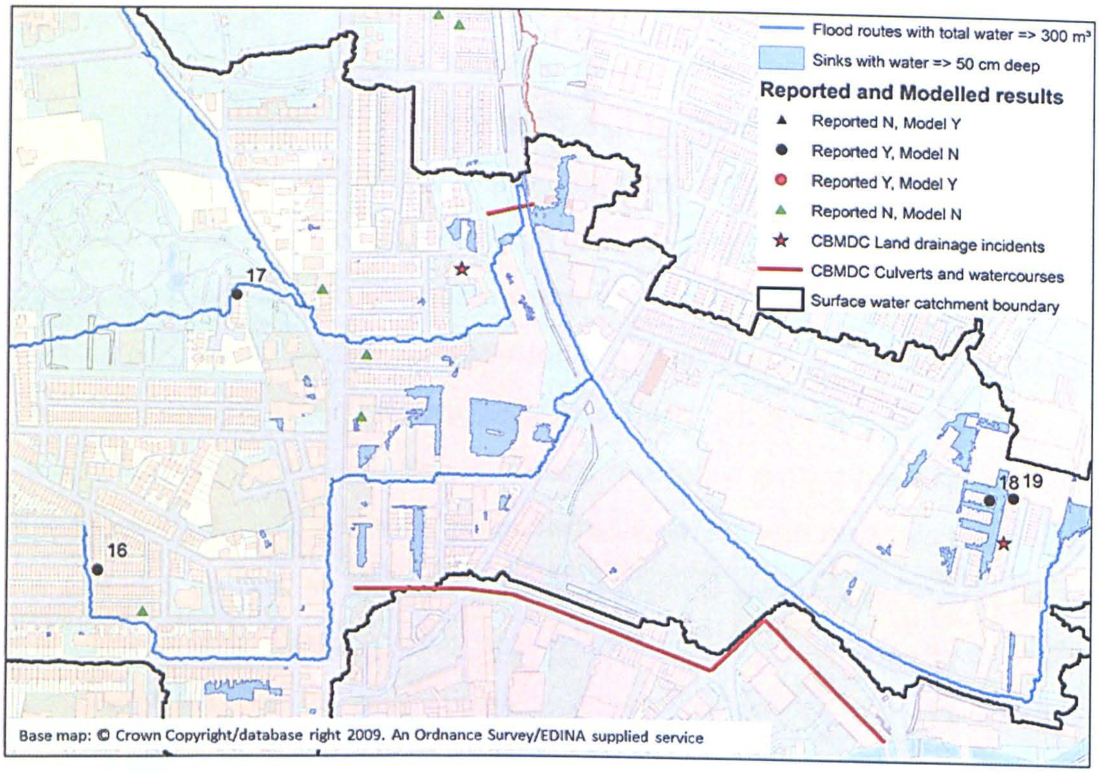

Figure 3.15: Model results for a 1 hour duration rainfall event of a 30 year return period.

Catchment D

Catchment D was the second best modelled catchment of the study with a Kappa statistic of 29%, however it also proved the most difficult catchment to understand using the modelled and reported results. Five properties reported flooding and two were correctly identified by the model, both of these are at the bottom of the catchment. The catchment has the highest false positive rate of the study. Unlike the other catchments, the modelled flow paths at the top of the urban part of the catchment do not coincide so neatly with the CBMDC known culverts and watercourses. The location of the known culverts would suggest that most of the upslope pervious area in Figure 3.16 drains to locations b and c. The model represents the upslope surface water mainly accumulating into two major flood routes at locations d and e. The resident at location 25 stated that water flooded the property from the rear, possibly indicating the major path is not in front the property as depicted by the model. The resident at location 23 stated that although it did not result in a flooding problem, the road in the front of the property has had flowing water of up to 1 inch in depth.

Some of the CBMDC drainage incidents however do show a good correspondence with the modelled locations of surface ponding ≥ 50 cm deep as in locations f, g and h. This catchment clearly requires further investigation to understand the major process responsible for the flooding and highlights the need for complementary site visits coupled with enhanced local knowledge on past events and urban drainage assets.

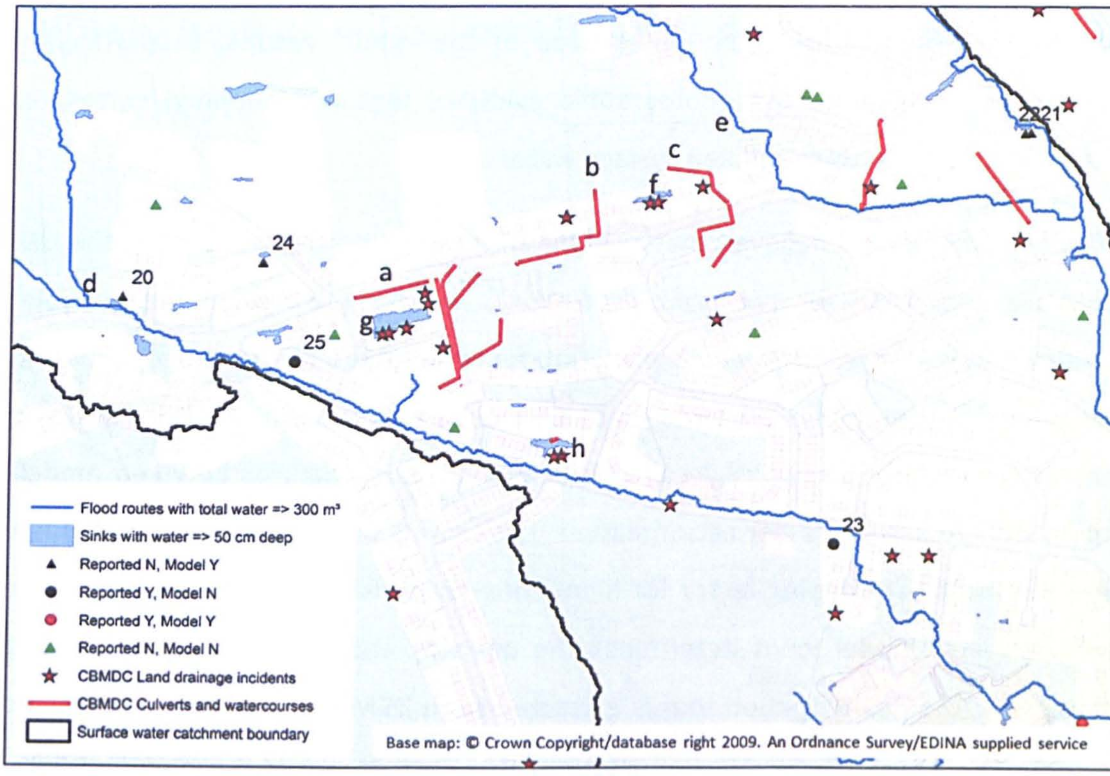

Figure 3.16: Model results at the upper urban part of catchment D.

3.4. Discussion

What was learnt about the model from the validation exercise? And how can it be improved?

The Kappa statistic states the agreement of the model with observed data is 'fair'. Some of the reported results don't match with modelled results due to the selection criteria that was used for classifying properties as flooded or not. When some of these locations are looked at closely, the model produces results that correspond to the additional details provided in the questionnaire. For example, a resident mentioned surface water collecting in a tennis court, and inspection of the model results also shows this. Having looked at the model results in the context of a range of data sources and anecdotal evidence, it can be ascertained that many of the principal processes responsible for surface water flooding are represented in the model. I believe this is clearly illustrated in catchments A, B and C where some of the major flow paths and major locations of surface water ponding, that are the source of much flooding are on average well represented in the model results. In particular in Catchment A, much of the photographic evidence that was supplied corresponds extremely well with the modelled surface water routes.

In all catchments, it is believed that local details that are not represented in the LiDAR DEM are responsible for inaccurate predictions, and in some cases it was possible to confirm this with a site visit. The explanation for some of the misclassifications was not conclusive and may also be due to cumulative inaccuracies in the DEM which are difficult to identify but which locally result in large discrepancies between modelled and observed surface water accumulation. The DEM is one of the main model inputs and the main determining factor for identifying flood risk areas. Although the excess surface water model input determines the quantity and source location of surface water, it is the flow direction that is extracted from DEM which ultimately influences where excess surface water will accumulate. Further work is recommended to determine the sensitivity of model results to small local features that influence surface water accumulation. Such features include gaps between properties that have canopy structures, passages between terraced housing and walls (including field boundaries) and gates. In catchment A, a major flood route through a field gate is correctly identified (location b in Figure 3.10). In this case the lowest cell elevation in the vicinity coincided with the gate location, which is why the flow route is depicted. Local features that influence surface water flow direction can also be temporary and variable. Residents can use sandbags to prevent surface water flowing along a road from entering properties or can alter features by erecting walls or creating gaps in walls. An interesting question to try and answer is, what is the cumulative effect of small and localised model inaccuracies due to the misrepresentation of local features in the DEM? To answer this question requires extremely detailed and wide coverage of data on actual flow routes. A suggested source of such data is CCTV coverage. At present, the current network of CCTV cameras in the study area, as shown in Figure 3.17, would not allow for this type of analysis as there is not sufficient coverage over a large enough spatial area. Furthermore, CCTV coverage is mainly focussed on major roads and city centres. This model testing exercise looked at model agreement with flooded locations, but it was not possible to verify modelled volumes of water. Future model testing should also seek to obtain data on water depths at flooded locations.

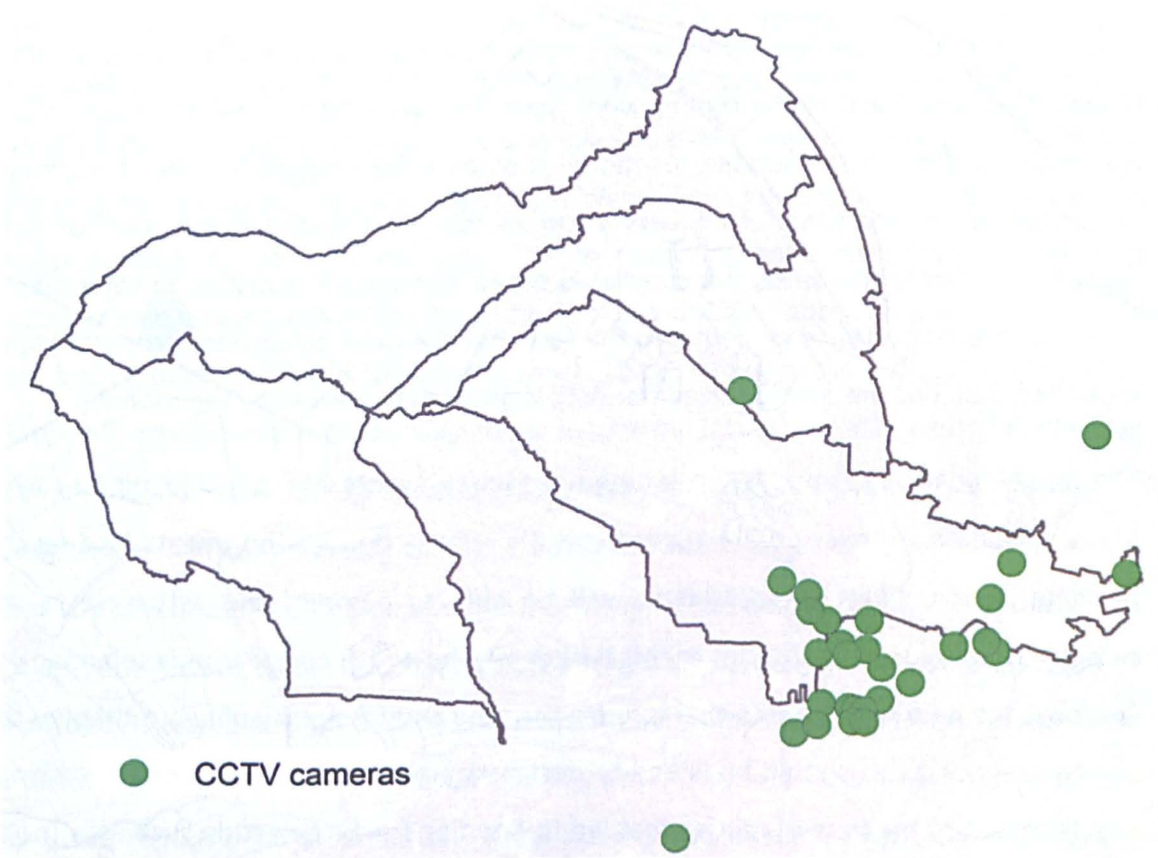

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Figure 3.17: Local Authority CCTV coverage (source: CBMDC).

The presence of properly performing drainage assets may also explain the difference in modelled and observed results. Assets include the sewer system and also features such as culverts. The accuracy of model results could be improved with a better representation of the performance of the sewer system and also by accounting for culverts. It may be possible to use output from sewer network models to assign spatially varied sewer conveyance rates linked to the level of sewer performance. In terms of urban drainage structures such as culverts, the location of these is not always known, or it is not known where culverts discharge to. This is highlighted in Figure 3.16, where there are several stretches of culverts; these may link into the sewer system, or may be linked to culverts downstream.

LESSONS LEARNT REGARDING THE DATA COLLECTION EXERCISE BASED ON QUESTIONNAIRES

The two major limitations of the data collection exercise were the small sample of 92 locations and their limited information content, which hampered rigorous model testing. Only one third of the replies were from flooded locations, which means that the statistics derived for flooded locations, such as a false negative rate or positive predictive power are based on a very small sample. The spatial distribution of the replies also greatly influences the computed model agreement statistics. In catchment B, the anecdotal evidence all points to the fact that the main catchment processes are modelled well, but the few reported flooding locations are missed by the model.

The questionnaire replies refer to a range of rainfall events and it is difficult to carry out a validation exercise without more specific information on the events leading to flooding. It is unlikely that residents will be able to pinpoint the actual dates of flooding, but in further exercises of this type it may be worth considering a selection of tick boxes to help respondents characterize the type and frequency of event that led to the flooding and this should be linked to design storms. This could be done by asking residents to tick the type of rainfall that led to flooding from a selection such as:

- On average how often do you suffer from surface water flooding?
    - Only on specific dates (and provide a box to enter the dates if they can be recalled)
    - Once every 10 years
    - Once every 5 years
    - Once a year
    - Several times a year

- What type of rainfall generally leads to flooding? (tick all that apply)
    - Short and intense storms (up to 2 hours in duration)
    - When it's been raining for more than a couple of hours (but less than 24 hours)
    - When it's been raining non-stop for approximately 24 hours?
    - When it's been raining for 2 or 3 days?

It was noted in the methodology section that several questionnaires had to be re-assessed and corrected because due to the information given it was determined that the flooding was not directly on their property or the street in front. Also in the detailed case by case examination it was evident that respondents' interpretations of flooding varied. In one case a respondent classified a flooded tennis court (which is approximately 15 m from the property) as 'suffering from flood risk', whereas in another case a respondent had ticked the 'no' box but also noted that water collects in the back garden (which in this case is much closer to the property). Whilst trying to keep information required by respondents to a minimum, more specific information about the location of flooding is desirable for assessing model performance. Suggestions for future exercises might be to include a diagram of a house, curtilage and street and ask the respondents to mark where flooding occurs. Alternatively, tick boxes with a list of places (e.g. front of property, back garden, front drive etc.) could be provided. It would also be desirable to extract approximate depths of water and make a distinction between flooding from flowing water and locations where water ponds. All these requests for information would need to be balanced with maintaining the questionnaire short and simple, as I feel that the high response rate (9.4%) was due to the straightforward nature of the questionnaire (taking less than 1 minute to complete the required questions).

Finally, there is always a risk of wrongly rejecting a model when it does not agree with observed data, when in fact it is the poor quality of the data that is at fault. In this exercise it was assumed that respondents are stating the truth and that the question has been interpreted as expected. In future it is worth considering methods for cross checking the observed data and weighting replies according to the level of verification.

It may be that responses can be cross checked against photographic, CCTV footage or media reports.

3.5. CONCLUSIONS

This exercise illustrated the model's level of representativeness to be satisfactory for its purpose as a screening model. It is shown that many of the major surface water flood risk processes are represented in the model. Some localized areas of flooding are misrepresented by the model and this underperformance is principally attributed to the limitations in the DEM in representing local features that influence surface water accumulation.

Despite the limitations in the questionnaire design, the data was collected in a standardized format and therefore it is a considered an improvement on using anecdotal data alone. A questionnaire is a good source of historical flooding information; however, one of the main challenges that need resolving for a future exercise of this nature is how respondents can identify the key event that led to flooding, in order to associate this with a design storm.

Several papers that were reviewed in section 3.1 carried out a visual analysis and made conclusions regarding the apparent correlation between modelled flood risk and observed incidents. A similar conclusion was also arrived at in Chapter 2, when the surface water balance model was compared to known flood risk locations prior to the model testing exercise. Having carried out a more formal statistical test of model agreement, it is clear that the results are not as good as a visual inspection may suggest. This therefore proves the need for rigorous statistical validation and cross checking in order to highlight areas where the model is weak. In this case it was highlighted that the model performs better in some surface water catchments than in others. It is believed that in some catchments it is the cumulative effect of local errors in the DEM which leads to a poor representation. We therefore require methods to collect detailed information on the interaction of surface water movement with local topography.

4. MODEL APPLICATION

4.1. INTRODUCTION

The GIS urban surface water balance model is a tool designed to support planning decisions in relation to the impacts and opportunities for surface water flood risk management. The aim of this research is to apply the model in a scenario analysis based around proposed solutions for surface water management and to evaluate whether such options build in capacity for adapting to climate change. To answer this question, the following aims and objectives are set out:

1. To identify flooded locations and determine general causes of flooding.
2. To propose surface water management solutions.
3. To generate climate change perturbed model inputs.
4. To represent the solutions in the model and evaluate their impact.

CLIMATE CHANGE

Future climate change is expected to result in changes in precipitation patterns and amounts (Jenkins et al., 2009; Solomon et al., 2007) and it is now a requirement that climate change be taken into account in surface water management plans (CIRIA, 2011; Department for Communities and Local Government, 2008). Output from General Circulation Models (GCMs) used to predict climate change is coarse, both in terms of spatial resolution (~300 km) and temporal resolution (daily), and therefore cannot be used directly for urban drainage applications which require short term intensities and over small areas. The minimum temporal resolution required for time dependent urban drainage modelling has been shown to be sub-hourly, and the spatial resolution for small catchments should be in the region of 1 km^2 (Liguori et al., 2011; Schellart et al., 2011).

Many methods have been developed to extract climate change information for impact and adaptation studies, and a state of the art review can be found in Wilby et al. (2009). Various statistical downscaling techniques have been developed to improve the spatial resolution as well as better represent rainfall patterns at a local scale (Kilsby et al., 2007; Wilby et al., 2002). Such tools have been widely used, and generally accepted for providing appropriate rainfall input for hydrological applications and for making projections regarding changes in rainfall patterns on a daily time scale (Harpham and Wilby, 2005; Haylock et al., 2006). The main assumption in the statistical downscaling techniques is that the relationship between local precipitation (predictand) and the large scale factors (predictors obtained from a GCM or RCM) remains under climate change. In a study that compared eight methods of downscaling, including both statistical and dynamical, it was found that mean precipitation and maximum consecutive dry days were the better modelled statistics by all the methods. The success in downscaling in terms of describing extreme events and heavy precipitation, such as the fraction of total rainfall from heavy events, the 90^{th} percentile rainfall and precipitation intensity was not as good (Haylock et al., 2006). In some cases negative correlations were found between the predictors and the predictand (local precipitation) which implies that there is site specific behaviour that is not captured by the large scale predictors.

In addition to the challenges associated with downscaling for analysis of extreme conditions, these methods remain limited in terms of providing suitable temporal resolutions for urban drainage applications, which require details on the frequency of short duration events as well as hyetographs with time steps in the region of minutes. Recently, a range of techniques have been proposed to obtain climate change scenario precipitation data, at a sub-daily time scale, for use in urban drainage applications. Nguyen et al. (2010) used statistical downscaling (SDSM) and then further temporal downscaling using the general extreme value distribution to produce IDF curves and design storm profiles. Results using output from two GCMs (HadCM3A2 and CGCM2A2) were compared. The HadCM3A2 produced slight decreases in rainfall intensities with progressive future time periods, whereas CGCM2A2 showed an upward trend with larger increases associated with the 2080s time period. He et al. (2006) used a method whereby an Intensity Duration Frequency curve is established by empirically adjusting GCM precipitation data to match observations, and then an extreme value distribution analysis is applied to the annual maximum daily rainfall to produce design storm profiles. Semadeni-Davies et al. (2008) opted to apply change factors obtained directly from six hourly output of a Regional Climate Model (RCM) to perturb observed high resolution precipitation data. Larsen et al. (2009) extracted extreme events from the output of an RCM and fitted a generalized pareto distribution to the data in order to predict changes in the frequency and intensity of extreme events under climate change. Onof and Arnbjerg-Nielsen (2009) propose a method to further downscale based on disaggregation of hourly precipitation output from an RCM into minutes.

The general findings regarding the impacts of climate change for urban drainage are that conditions worsen, regardless of the method used. Madsen et al. (2009) found that precipitation intensities would increase over Denmark, and Larsen et al. (2009) found the greatest increases in rainfall intensity associated with increasing return periods and shorter durations, and that the greatest changes were observed in winter and spring (with factors as high as 1.6). For the UK, a 20 year 1 hour event becomes a 10 year event and a 100 year event becomes a 41 year event (Larsen et al., 2009). He et al. (2011) used artificial neural networks fed with downscaled precipitation data and found both that runoff peaks and volumes increased under climate change. Willems and Vrac (2011) used two different types of downscaling methods to generate sub-daily precipitation values under climate change and found both methods produced similar results in that given storm depths are likely to occur twice as frequently. A limited number of studies have used climate changed storm profiles as an input for urban drainage modelling. CBMDC (2008) used a sewer network model (InfoWorks CS) with climate change factors applied to rainfall data, coupled with scenarios based on current trends in urban change and found greatly increased volumes of surface water and greater numbers of surcharged manholes. Semadeni-Davies et al. (2008) used climate change perturbed rainfall, coupled with storylines to reflect urbanisation and SuDS management trends, modelled in DHI MOUSE (Danish Hydrological Institute Model of Urban Sewers) to conclude that, even without further urban development, climate change alone would lead to an increase in the number of discharges from combined sewer overflows. Similarly He et al. (2006) found that, using PCSWMM, climate change resulted in greater surcharging of sewers. Nie et al. (2009) also found with the use of DHI MOUSE that climate change would lead to increased flooding from manholes and more discharges from CSOs.

Despite the clear emerging picture of the need to develop flexible adaptation strategies to cope with future climate change, there have been fewer studies that evaluate potential solutions. By use of storylines to represent the increased implementation of SuDS, Semadeni-Davies et al. (2008) conclude that SuDS may become essential for reducing the impacts of climate change as the study showed that although stormwater disconnection did not reduce the number of combined sewer overflow spills, it reduced the total volume of spills compared to scenarios without SuDS. Karamouz et al. (2011) used statistical downscaling and also developed an optimization tool to select options to adapt to climate change, and these are discussed under the section surface water management.

This study is concerned with assessing potential surface water management solutions in terms of the potential to build in capacity to adapt to climate change. UK planning and flood risk guidance documents suggest the use of climate change factors to take account of climate change (DCLG, 2008). Furthermore, given that the urban surface water balance model uses input excess water volumes and not high resolution time dependent data, the use of change factors is simple and straightforward and involves fewer assumptions. It is therefore considered the most appropriate method for generating climate change data for this study. The time period of 2055 – 2085 is chosen, which is translated into a future climate change scenario by applying the suggested +20% change to the rainfall intensity of the selected design profiles (DCLG, 2008). The design profiles under baseline and climate change conditions are shown in Figure 4.1 and Figure 4.2. Table 4.1 summarizes the resulting excess surface water once the excess surface water methods are applied as described in section 3.2 (Excess water input for urban surface water balance model). Runoff coefficients are empirically derived and there is currently little scientific basis on which to alter runoff coefficients to account for climate change. It is assumed that the method used to calculate runoff from pervious surfaces (Eq. 3.1) is valid under climate change. This results in a direct increase of 20% in excess water produced by the pervious surfaces in the short duration event, and under the long duration event, the average increase in excess water produced varies from 22% to 57% according to soil type (Table 4.1). Maximum sewer conveyance rates are assumed to remain unchanged under climate change, and this leads to areas classed as served by sewer exhibiting a 42% increase in surface water for the short duration storm, i.e. the area above the maximum sewer conveyance rate as shown in Figure 4.2.

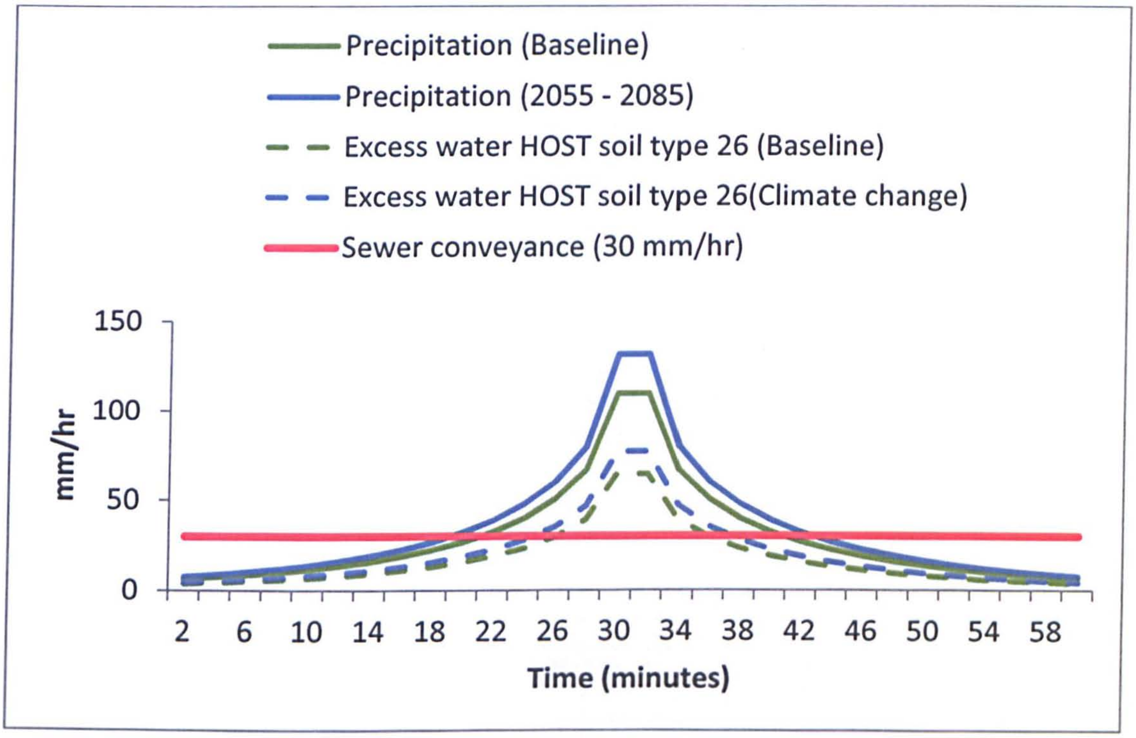

Figure 4.1: Rainfall profiles under current (baseline) conditions and with climate change factor for the period 2055 -2085 applied to a one hour duration storm of a 30 year return period. The computed excess surface water is shown for HOST soil type 26. The sewer conveyance is the assumed maximum sewer conveyance as defined in section 3.2.

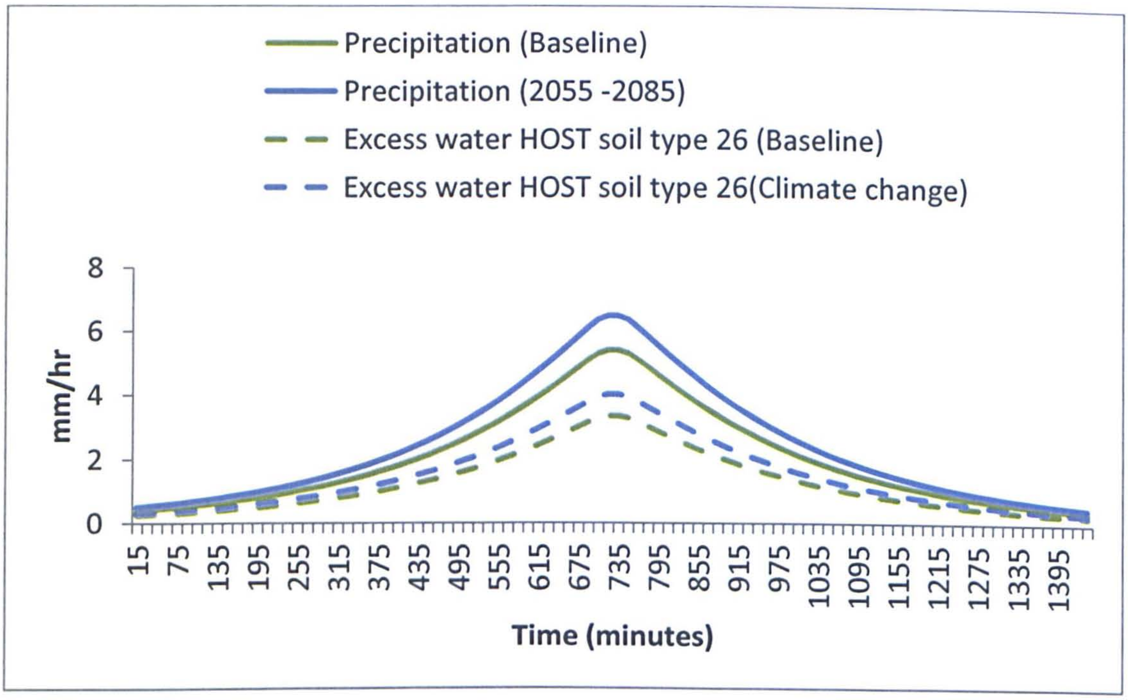

Figure 4.2: Rainfall profiles under current (baseline) conditions and with climate change factor for the period 2055 -2085 applied to a 24 hour duration storm of a 5 year return period.

Table 4.1: Excess surface water depths (mm) for various land cover types after applying methods as described in section 3.2

	1 hour duration 30 year return period		24 hour duration 5 year return period	
	Current	2055 -2085	Current	2055 -2085
Total rainfall	29.44	35.32	49.15	58.97
Served by sewer	9.94	14.07	0.00	0.00
Soil type 26	17.28	20.74	29.82	36.51
soil type 24	11.69	14.03	20.48	25.30
Soil type 15	14.25	17.10	24.75	30.43
Soil type 10	7.45	8.94	13.40	16.81
Soil type 6	9.95	11.94	17.58	21.82
Soil type 5	4.27	5.12	8.09	10.44
Soil type 4	0.59	0.71	1.95	3.07

Surface water management

The changes in rainfall patterns predicted under climate change are likely to increase the frequency and severity of flood events (as discussed above) and this, coupled to increasing pressures from urban growth and urban creep, mean that urban surface water flooding will be exacerbated. There is a need for solutions that will increase adaptability to future pressures (Faram et al., 2010). Finding solutions is a multi-faceted process involving key stakeholders, as well as appropriately designed (hard or soft) engineering solutions (Ashley et al., 2007). Engineering solutions that focus on the underground assets are not considered economically or environmentally viable (Evans et al., 2004b), and do not provide the flexibility required for climate change (Sieker et al., 2008). As part of good drainage design, it is recommended that the surface is appropriately developed to cope with rainfall events that cannot be drained entirely by the sewer system (Balmforth et al., 2006b). Suggestions include the use of dual purpose surface storage and surface conveyance as well as a consideration of the building layout for managing flow routes. Conveyance features may include highways, footpaths, ditches, swales, car parks and natural or artificially created vegetated channels. In terms of detailed design of specific features, well established and detailed design guidance documents exist (Balmforth et al., 2006b; Suds working party, 2009; Woods-Ballard et al., 2007).

SuDS (Sustainable drainage systems, or BMPs Best management practices) are an alternative to (and are also used in combination with) conventional piped drainage. Solutions that manage water on the surface, and that mirror natural processes are more environmentally and economically sustainable, and additionally they provide greater headroom for dealing with uncertain futures since they require less effort to renew than underground solutions (Faram et al., 2010). To date, the main drivers for SuDS have included water quality improvements, a reduction in CSO spills and urban surface water flood risk reduction. Recent changes in legislation (Defra, 2010; Goodson, 2011; The Flood and Water Management Act, 2010) will also lead to greater implementation of more sustainable practices. It is expected that as a result of the Flood and Water Management Act (2010), SuDS will become mandatory in new construction and will have to comply with national standards. New design guidance documents are also emerging (Burns et al., 2010; CIRIA, 2011; Islington Council, 2010) to support regulatory changes. In the last few years there have also been changes to permitted development aimed at reducing urban creep (Secretary of State, 2008) and new developments are required to achieve greenfield runoff rates (HR Wallingford, 2004). These relatively new regulations may curtail the pressures of urban growth and urban creep (dependent on successful enforcement), but challenges associated with climate change will remain and therefore effective retrofit design solutions are required.

SuDS features include those aimed at runoff management at source (e.g. green roofs, pervious pavements, water butts), features that allow infiltration into the ground (e.g. soakaways, infiltration trenches, pervious pavements), conveyance features (e.g. swales) and storage features (ponds, storage basins). Detailed design guidance on individual SuDS components as well as aspects of SuDS implementation, including SuDS philosophy, stakeholder engagement, selection, and maintenance is covered in Woods-Ballard et al. (2007). Central to the SuDS philosophy is the idea of a treatment train which aims to mimic natural processes by incorporation of multiple components which collectively reduce peak discharge rates and pollutant loadings.

There has been much research into the production of decision support frameworks for the identification of opportunities for retrofitting SuDS as well as the optimization of SuDS, in terms of cost and/or performance and according to given drivers (Ellis et al., 2004; Sakellari et al., 2005; Scholz, 2006; Singh et al., 2005; SNIFFER, 2006; Stovin and Swan, 2007; Swan, 2003; Viavattene et al., 2008). The reduction achieved in terms of volumes and rates of SuDS features has been studied (e.g. Gerolin et al., 2010; Kellagher and Udale-Clarke, 2008; Stovin, 2009) and a limited number of studies have evaluated and quantified the performance of SuDS at large catchment scales. Vivattene et al. (2010) coupled a SuDS selection tool with a hydraulic model to a 170 ha catchment and showed that the use of green roofs and porous pavements reduced surface water runoff rates by up to 28%. Ashley et al. (2010) applied a hydraulic model (Infoworks CS) to three sub-catchments in London to illustrate how implementing SuDS, in order to disconnect over 10,000 hectares of impervious surfaces that drain to a combined sewer system, reduces the number of CSO spills and reduces overflow volume by 55%. Software has also been developed that can model a treatment train in terms of various SuDS components (MUSIC Development Team, 2009) and which are capable of predicting the runoff reductions that can be achieved. Burns et al. (2010) used MUSIC to conclude that rainwater harvesting could retain rainfall events of up to 29 mm in hypothetical 5 km^2 catchments. This study concluded that whilst rainwater harvesting has the potential to contribute to flood risk reduction, it is likely that flood risk can only be significantly reduced with a combination of retention components acting at a range of scales. Fang et al. (2010) looked at urban development combined with detention storage of various sizes and in various locations of a catchment in order to assess the effectiveness for flood control. This study found that in many of the development scenarios the larger regional detention storage led to the greatest reduction in peak flows when compared to local storage ponds. Karamouz et al. (2011) developed an optimization algorithm (based on a mathematical objective function) with the aim of identifying the minimum cost solution. Inputs to the algorithm include the costs of the SuDS management practices and the flood damage costs. The process involves proposing a number of management practices and simulating these in a stormwater model to determine the flood damage. A range of combination of options that included increased green space, detention ponds, increased capacity of channels and creating new diversion channels were considered for a 110 km^2 catchment. Karamouz et al. (2011) found that the optimal combination to be a 1700 m diversion channel and a detention pond of 30 000 m^3. This combination reduced flood volumes and flooded areas in the 110 km^2 catchment. Using Infoworks CS CBMDC (2008) showed that increased development and climate change are likely to lead to significant increases in surface water flooding, in terms of the number of locations and surface water volumes as well as the frequency of flooding. In terms of solutions, CBMDC (2008) focussed principally on demonstrating the importance of integrated approaches and stakeholder engagement, and made the point that options of managing surface water on the surface are more cost effective than underground solutions.

In summary, the studies reviewed above point to the fact that in terms of surface based solutions large storage and planned flood routing are viable solutions with potential to reduce catchment scale flood risk. Guidance exists for the siting of regional storage (Woods-Ballard et al., 2007). In terms of surface conveyance, suggestions are proposed for land uses that can serve as dual purpose for conveyance, and hydraulic design details are provided (Balmforth et al., 2006b; Woods-Ballard et al., 2007). Kunapo (2009) illustrated how LiDAR DEMs can be used to understand the drainage pattern at the land parcel scale and use this information for SuDS design and implementation. In terms of exploiting high resolution DEMs with land use information to design catchment wide conveyance solutions; little guidance exists. Faram et al. (2005) state that the biggest challenge in implementing SuDS is indeed working within the constraints of the built environment. However, the use of planned flood routes is being proposed as a retrofit solution; for example CIRIA (2011) suggest retrofitting roads for flood conveyance when roads are resurfaced or redesigned for traffic calming. Whilst designers and engineers may be able to identify opportunities for managed flood routes based on experience and inspection of the various factors that influence the outcome (e.g. land use, topography), there is a need for an objective methodology that will enable the most optimal routes to be identified in the light of all the contributing factors.

Chapter 3 illustrated that many of the surface water flood risk problems in the study catchment are a result of the convergence of surface water into major flood routes through the urban area. The flood routes themselves are considered a flood risk and they also lead to large areas of ponding in undesired locations. The selection of sustainable drainage design options and their design is fairly well understood and documented, and has been shown to reduce flow volumes, but it is also likely that without managed flow routes and large scale storage, such features will not significantly reduce surface water flood risk. This part of the research develops and uses a methodology to identify suitable flood routes through an urban area, via or to potential regional storage areas, in order to reduce surface water flood risk. The resulting methodology aims to form the basis for a long term strategy for identifying key areas for maximising opportunistic implementation of managed flood flow routes.

4.2. METHOD

Figure 4.3 illustrates the modelled current flood routes for a long duration rainfall event (24 hours) of a five year return period. A very broad categorization of the types of flooding can be made on the basis of contributing area. For example, the area labelled *a* in Figure 4.3 illustrates flooding that arises from a small, mainly urban contributing area. In such an area SuDS features, such as the approach presented by Ashley et al. (2010) may significantly reduce flood risk. The area labelled *b* is flooded as a result of a large contributing area, which is mainly grassland and therefore not served by the sewer system, and where in certain rainfall events runoff converges into major flood routes that enter the urban area and lead to flooding. In this case source control SuDS in the urban part of the catchment are not likely to significantly reduce the overall flows. There is therefore a need to firstly identify locations suitable for large scale storage features and find appropriate flood routes to divert problem inflows to appropriate storage areas. This section describes the development of a method for identifying optimal managed flood routes through an urban area. The aim is to find managed flood routes that do not pose a risk and where implementation is least costly.

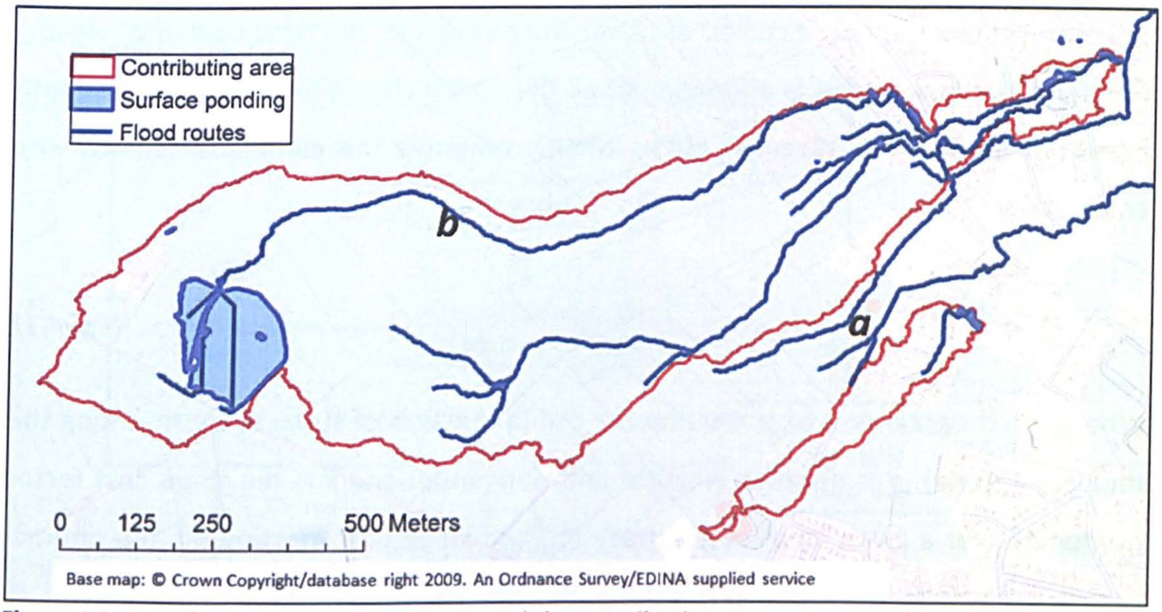

Figure 4.3: Snapshot of current flow routes and the contributing areas at two problem locations.

Least cost path analysis has been used in the planning and design of linear features where multiple criteria determine the optimal route, such as roads, pipelines and power lines (Bagli et al., 2011; Ebrahimipoor et al., 2009). Least cost path algorithms have also been developed so that the cost assigned to a cell is dependent on the direction of movement (Collischonn and Pilar, 2000), so that for example if the path is uphill through a cell it can be given a different cost than if it is downhill. In hydrology the use of LCP has also been proposed as an alternative method for drainage network extraction (Metz et al., 2011). One of the main challenges in using least cost path analysis to identify optimal solutions where many criteria are involved is the correct weighting given to each criteria to be considered (Bagli et al., 2011) and different weightings can result in quite different optimal routes.

The method is based on optimum path or continuous space routing principles (Longley et al., 2001). The objective of optimum path algorithms is to find the least costly path from a given point to a destination (ERSI, 2009). The user identifies key costs which do not have to be financial and could represent the degree of unacceptability of taking a given path. There may be several factors that determine the overall cost of traversing a particular point, and each factor is represented as a continuous cost surface, with each cell representing the cost incurred of traversing through it. The total cost of traversing through a particular point is a function of all the cost surfaces, and the least cost path algorithm used in this research (ERSI, 2009), computes the cumulative cost of the entire route, *r*, by:

$$r = \sum cds \qquad \textit{(Eq. 4.1)}$$

Where *c* is the total cost of traversing the cell (a function of surfaces representing the multiple criteria), *d* is distance (vertical and horizontal) and *s* is the slope cost factor (optional). For a given input cost surface (c), and slope cost function (s), the optimal path will always be the same, as it is the path with least accumulative cost.

Assigning monetary costs involves myriad factors that are not easily translated into a value per cell. For this reason in this study, cost simply refers to relative cost on an arbitrary scale. Figure 4.4 outlines how the optimum path methodology is applied for finding flood conveyance routes through an urban area. Key steps are discussed in detail below.

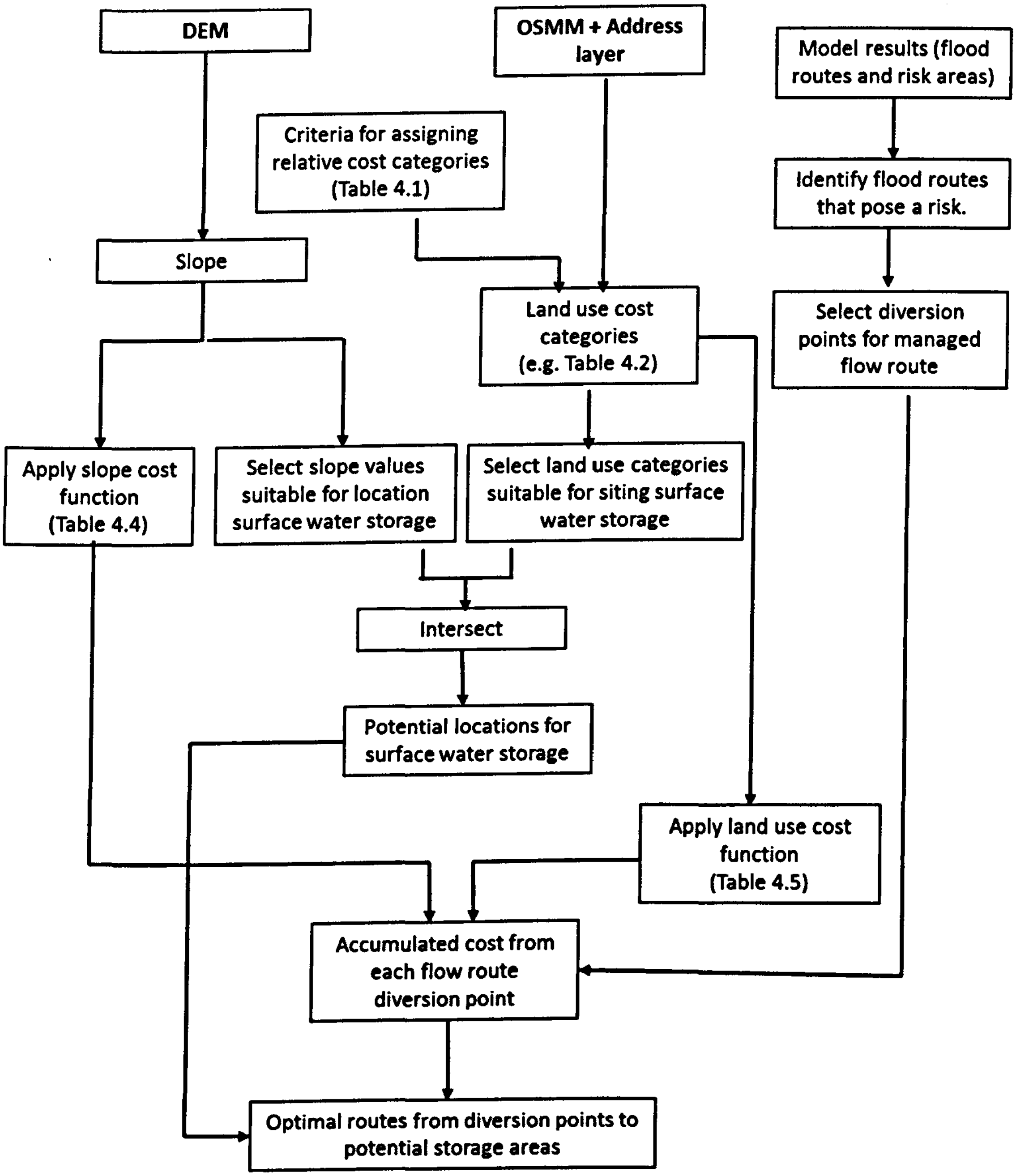

Figure 4.4: Flow chart illustrating methodology.

LAND USE CLASSIFICATION

Land use should be classified according to the unacceptability of siting flood management solutions (storage or managed flood routes). In practice, assigning cost is not straightforward and would require consideration of social issues as well as land acquisition and demolition costs. For this study a simple five tier classification system is proposed, ranging from the most unacceptable places to site flood management solutions to the most acceptable. The basis on which a particular land use is assigned to a category is summarised in Table 4.2. Land use was determined by Ordnance Survey Master Map (OSMM) data. Table 4.3 details the category that was assigned to the most common land uses in the study area. In summary, residential buildings were considered the most unacceptable locations and non-residential buildings were assumed to be slightly less unacceptable solutions, as commercial and industrial buildings have higher turnover rates and there are more redevelopment opportunities arising that may permit use of these sites (with less effort required to change the land use). The most acceptable locations included natural surfaces and urban green spaces, followed by private gardens and property curtilage.

Table 4.2: Basis on which to assign land use category representative of relative cost required for implementation.

Relative cost category	Basis
1	Ideal locations for flood routes and surface water storage - water flowing or stored in these locations does not pose a risk. No changes required.
2	Locations where flood routes or flood storage poses a low risk and minimal changes required.
3	Locations with a primary function that is sacrificed during surface water events. Some change is required but it is relatively easy to implement.
4	Locations where flood routes and flood storage pose a risk and therefore some changes would be required to allow water to flow through or be stored in these locations. Changes are more likely and less costly than category 5.
5	Highly undesirable locations for flood routes or surface water storage. Water flowing or stored in these areas would pose a very high risk (and therefore significant changes would be required associated with high costs).

Table 4.3: Cost categories assigned to the top 10 land uses (in terms of area) in the study area.

OSMM land use information	Total Area (m^2)	Additional Notes	Cost category
General Surface, Natural,	2170313	Mainly parks, green areas, rural periphery	1
General Surface, Multi Surface, Multiple,	742186	Gardens, property curtilage	2
Road Or Track, Manmade,	370981	Urban roads,	4
Building, Manmade, DWELLING	249843	Residential, dwellings, properties	5
General Surface, Manmade,	218061	Courtyards, curtilage of industrial buildings etc..	2
Building, Manmade, OTHER BASE FUNCTION	178331	Non-residential buildings	4
Natural Environment, ALL,	161734		1
Roadside, Manmade,	148985	Pavements, pedestrian walkways	2
Roadside, Natural,	97835		1
Building, Manmade,	92808	Mainly garden sheds, garages and other non-residential buildings.	3

This simple method of ranking land use according to the assumed cost of siting flood management solutions is not based on existing planning frameworks that would potentially eliminate many land uses as options for implementing solutions. Current planning frameworks are generally based on relatively short timescales (25 years) and furthermore policies can change. Instead this study adopts a more philosophical approach based on longer time scales and where there is greater scope for change, for example in the next 100 years. The classification system is dynamic and can be altered to reflect changes in paradigms and policies. If, for example it becomes more feasible to acquire and demolish residential areas to accommodate flood risk solutions, then this can be incorporated into the analysis by assigning these areas a lower cost.

POTENTIAL AREAS FOR SURFACE WATER STORAGE

The flood risk management approach developed here is dependent on identifying suitable locations where there is scope for appropriate surface water storage to which surface flood waters can be diverted. For the purpose of this research, and given that the GIS urban surface water model is not time dependent, the issue of whether online or offline storage is adopted is not addressed. This methodology aids in large scale screening for potential storage locations. Once options have been evaluated at this scale, detailed hydraulic design and details such as whether it is online or offline can be dealt with. For the screening approach, suitable locations for building in surface water storage features were determined by areas that satisfied the following criteria;

1. Land use cost category of 1, 2 or 3 (Table 4.1)
2. Slope of up to 5% (as recommended in Woods-Ballard et al. (2007)
3. More than 5 m from a building, this is so as not to eliminate the option of infiltration if site conditions permit Woods-Ballard et al. (2007)
4. A surface area greater than 100 m^2 (as large scale storage features are sought)

Using spatial queries in GIS the locations that satisfied the above criteria were identified for the case study area and these are shown in Figure 4.5.

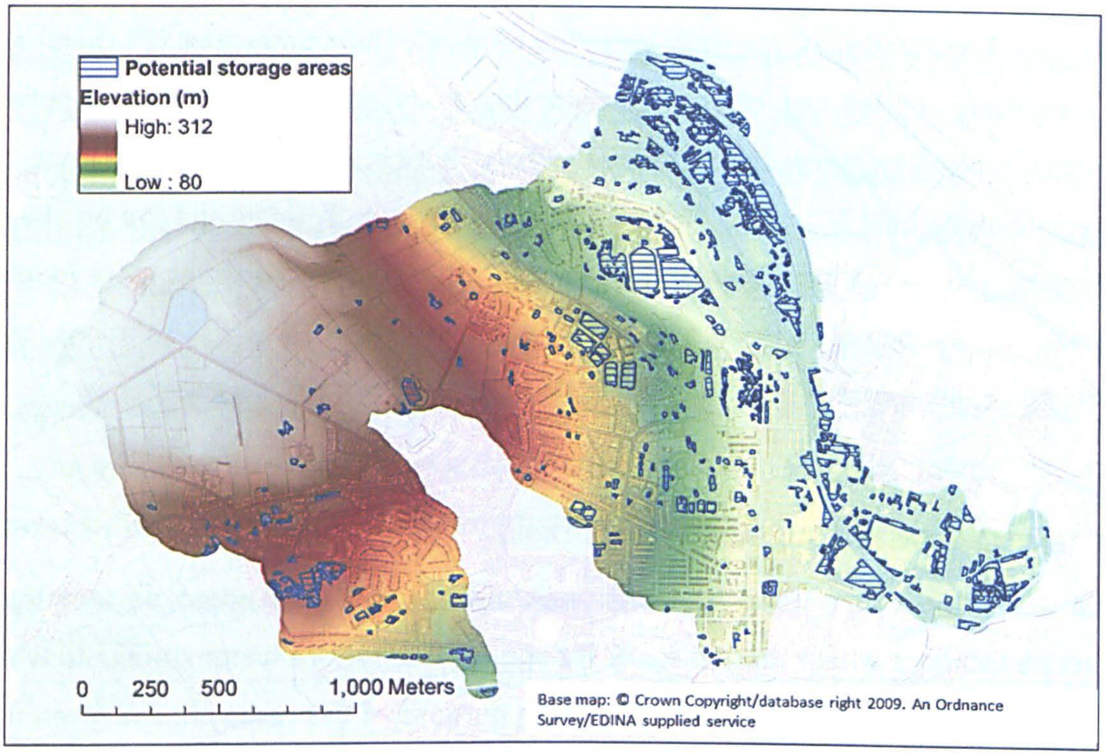

Figure 4.5: Potential surface water storage areas in the four study catchments (storage areas in the natural upper part of the study area are not shown).

COST FUNCTIONS AND COST SURFACES FOR LEAST COST PATH ANALYSIS

The principal limiting costs identified with respect to implementing flood conveyance routes are slope and land use. Slope and direction of slope is of importance because only routes that principally flow downhill are viable and the cost of implementing a flood conveyance solution varies according to flow velocities which are highly dependent on slope. Furthermore, in terms of flood routes through urban and populated locations, gentler slopes with lower flow velocities pose less risk. In order to derive appropriate cost functions, slope was explored individually prior to combining it with land use.

DERIVATION OF SLOPE COST FUNCTION

In line with current sustainable drainage principles, it is envisaged that a desirable conveyance solution would take the form of a swale, although depending on the slope and site conditions other types of channel may be required. Swales should be designed following standard hydraulic principles as outlined in Woods-Ballard et al. (2007). The method proposed here is concerned with finding optimal routes that require the least engineering or the least amount of change in order to create a conveyance feature such as a swale. At this level the method is not concerned with the detailed design of the conveyance feature (e.g. channel depth and width) but more with siting the conveyance features according to the two major constraints of slope and land use.

The ideal slope cost function should delineate a route which involves the least surface re-profiling in order to achieve downslope conveyance and which produces a path principally composed of gently sloping terrain. Flood routes with steep downhill gradients are not eliminated as it may still be viable to implement solutions, albeit at greater cost. The algorithm used could be set up to eliminate routes incurring uphill slopes, but this has not been done since the aim of the cost function is to identify the least costly route overall. Therefore, if a route exists which is principally along a gentle downhill gradient, but there is a small uphill gradient such as a building or wall along the path, it may remain a viable option if the additional cost of eliminating the uphill slope is cheaper overall than the alternatives. Naturally, transporting water uphill is expensive and does not mirror natural processes, and involves significant re-profiling. Similarly, steep drops are not ideal conveyance solutions as the potential erosion would necessitate reinforced structures.

Woods-Ballard et al. (2007) state that the longitudinal slope of a swale should not exceed a gradient of 5%. The framework proposed by Swan (2003) also states that to allow infiltration the gradient should be no greater than 5.88% (1 in 17) and to prevent erosion should not be greater than 2% (1 in 50). Stovin et al. (2007) illustrate the implementation of a stepped trenched swale on a road in Keighley, which according to the DEM used in this study, has a slope of approximately 10% (the steps ensure each section maintains a low gradient). These gradients are used as a basis on which to assign the least costly cell values. Outside of this range of slopes, there are, to the author's knowledge, no published rules of thumb that may be used to associate increased slopes with cost values. Only with hydraulic and erosion calculations would it be possible to determine approximate costs based on the flow velocity and the types of structures that would be required. This is considered beyond the scope of this simple methodology and would be one of the next steps in selecting and designing the planned flood route. Using engineering calculations at this stage would add over complexity for this feasibility approach, and therefore an empirical approach was adopted to determine the cost function for slope. The following basic set of principles were used as a starting point for a trial and error approach to establish an appropriate slope cost function;

- The optimum cells for siting conveyance solutions are downhill slopes of up to 5%
- Downhill slopes greater than 5% are increasingly more costly and beyond a given downhill slope, incur a high flat rate cost.
- A small uphill gradient can be re-profiled but the cost associated with uphill slopes steeply increases (more so than downhill slopes).

A limitation of the least cost path algorithm used in this methodology is that it cannot account for the total length of earthworks that would be required to remove protrusions and ensure a downhill path. For example a wall would incur a high cost associated with the uphill and downhill stretch of the path (as represented by the slopes either side of the wall). A path that traverses a long hillock also incurs an uphill and downhill high cost, but then assuming the top of the hillock is fairly flat, the length of route that traverses the top of the hillock is given a low cost. Therefore whilst slope may be capable of minimising uphill and steep downhill stretches, it may not mirror very well the cut and fill costs associated with removing protrusions of varying width.

Several slope cost functions, with different ranges of values, were developed (Figure 4.6). The routes mapped by the least cost path analysis for each of these slope cost functions were then visually evaluated for their suitability based on the spatial delineation of the route and the route profile. Slope cost functions (SF), with increasing cost associated with greater slopes and that were approximately symmetrical along the slope value of -5% were tested but these proved to be inappropriate as some of the optimal paths to uphill locations had lower costs than paths to downhill locations.

It was therefore learnt that uphill slopes should be assigned a greater cost than similar downhill slopes. It also became apparent that to favour a longer route, with a gentler slope, over a short steep drop, a greater difference in the cost associated with steep slopes was required.

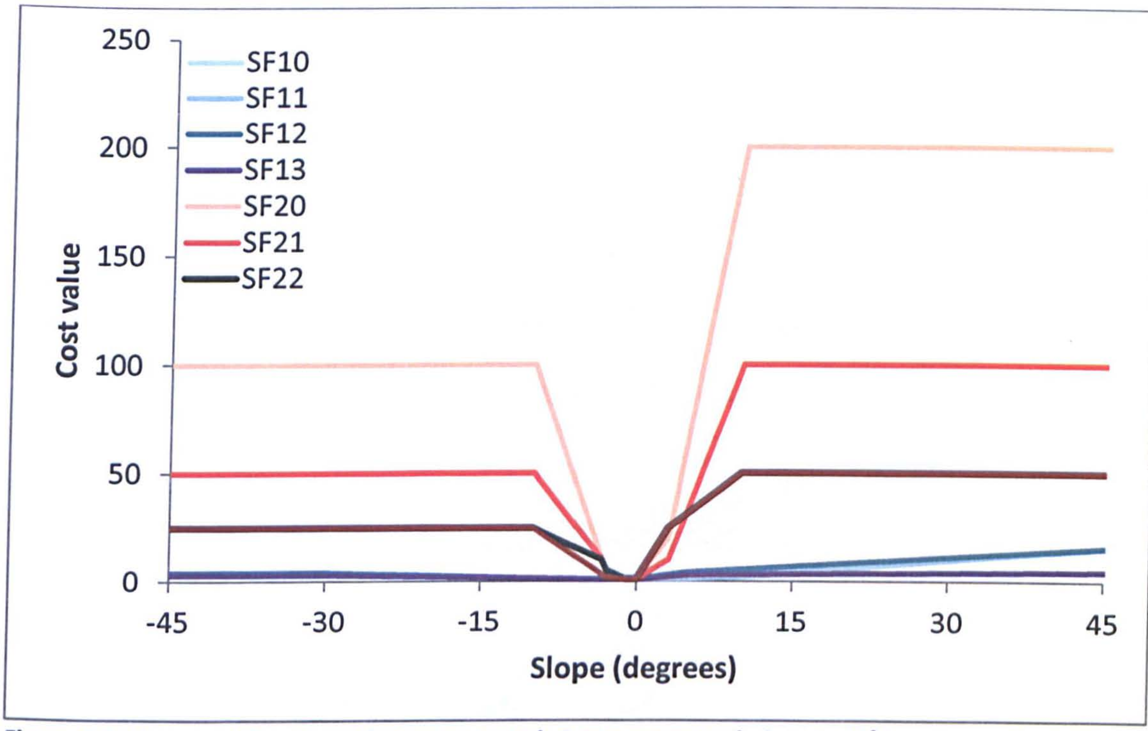

Figure 4.6: Slope cost functions that were tested. Costs are extended up to 90° by means of a flat line.

The optimal path for each SF (Figure 4.7) and respective profiles (Figure 4.8) to a selected storage area were compared in detail to reveal further insight into the relationship between slope cost functions and the delineated optimal routes. In Figure 4.8 it can be seen that SF10, SF11 and SF13 all have a short stretch of uphill route just prior to reaching the storage area (shown by the arrow on the graph). These examples confirm that uphill slopes should have a much greater penalty. It can also be appreciated from Figure 4.8 that whilst SF12 does not involve an uphill stretch, the entire route is steep with an average gradient of 1 in 10 (10% slope), similar to SF10, SF11, and SF13. This illustrates the need to have a greater difference between the ideal slope range and the steeper slopes. At the other extreme SF20, SF21 and SF23 all achieve lower overall gradients ranging between 1 in 22 (~3% slope) and 1 in 32 (~4% slope), but this occurs through delineating a zigzag path (Figure 4.7), which in practice would not be implemented. This occurs because the cost for siting the path on cells of high downhill slopes is too high.

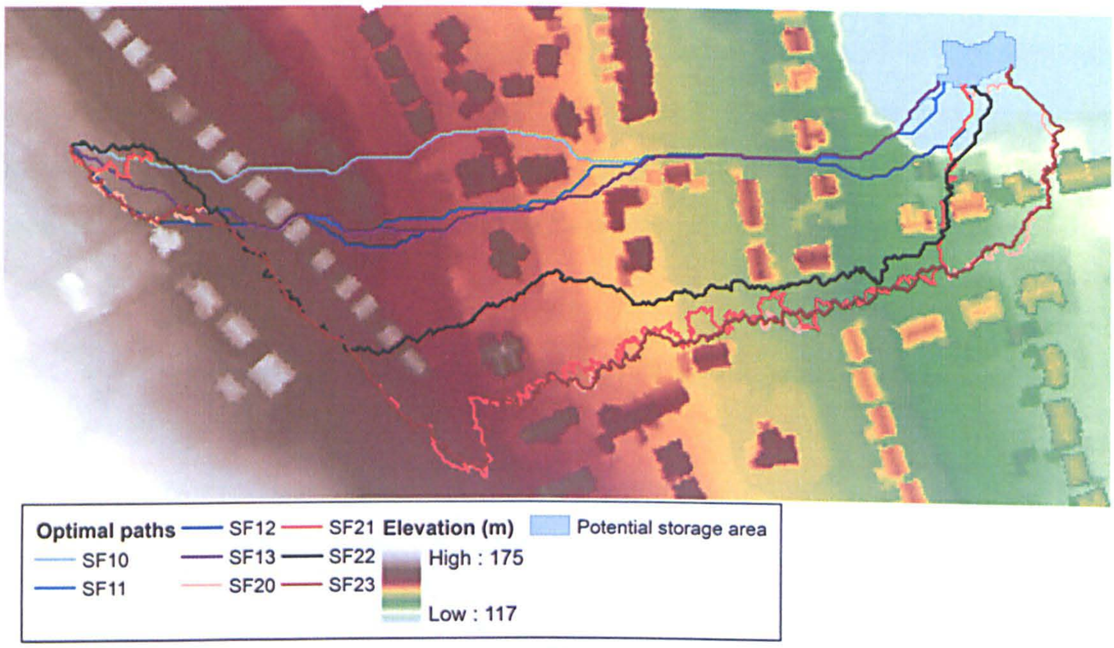

Figure 4.7: Spatial delineation of optimal paths to a given storage area for various slope cost functions

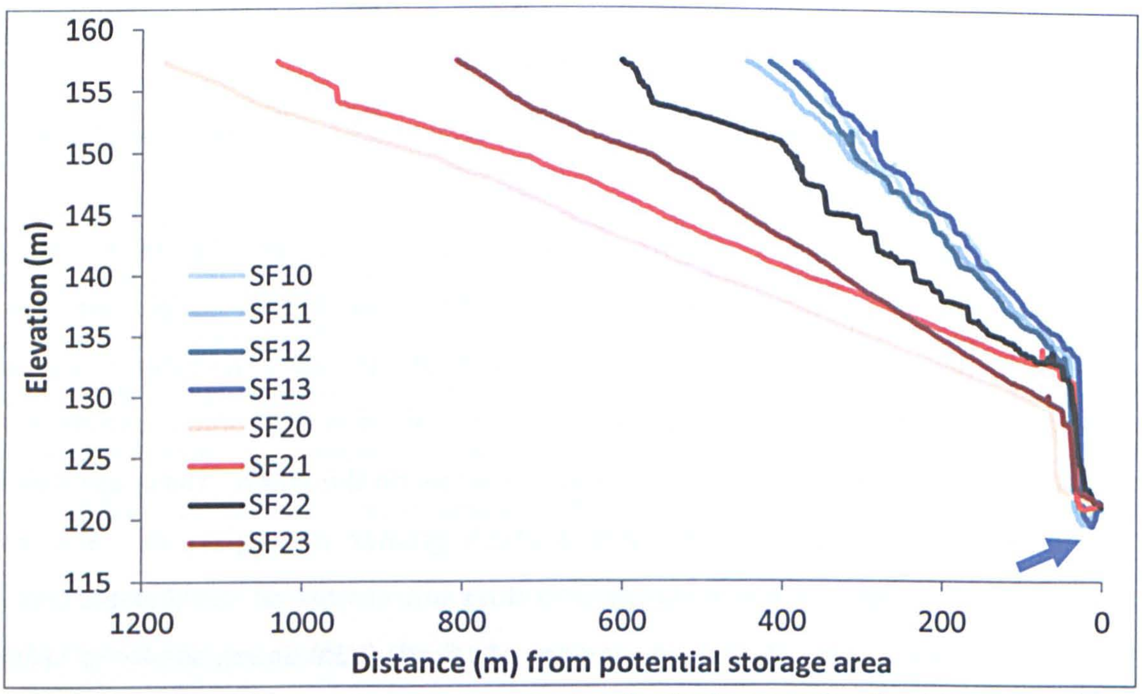

Figure 4.8: Route profiles to a given storage area according to slope cost function. The arrow points to the slope functions that result in an uphill stretch prior to the storage area.

Based on this limited trial and error exercise, the slope cost function that was selected as most appropriate was SF22, which gives the best compromise between slope and distance travelled. The values in Table 4.4 are used by the optimal path algorithm to compute the cost of each cell according to slope, and values are interpolated by assuming straight lines (ERSI, 2009). The overall gradient of the route that uses SF22 is 1 in 16 (~6% slope) and this slope cost function does not lead to overly zigzagged paths. However, a unique feature of the SF22 profile to the selected storage area is that it is the most stepped like route (Figure 4.8), i.e. an approximately uniform slope is achieved for stretches of path with several steep falls along the way. Clearly the selection of an appropriate cost function that best represents the engineering costs associated with re-profiling deserves more attention. The cost function needs to be optimized in terms of the acceptability of the mapped route as well as slope. There is a need to develop a method to systematically discriminate a good slope cost function from a bad one in this respect.

Table 4.4: Selected slope function.

Gradient (m/m)	1 in ..	Slope (%)	Slope (degrees)	SF22 cost values
			-90.00	25
-0.18	-6	-17.63	-10.00	25
-0.06	-17	-5.88	-3.37	10
-0.05	-20	-5.00	-2.86	5
-0.02	-50	-2.00	-1.15	1
		0.00	0.00	1
0.05	19	5.24	3.00	25
0.18	6	17.63	10.00	50
			90.00	50

LAND USE COST FUNCTION

A cost is assigned to each of the categories in Table 4.1 that reflects the acceptance and difficulty in using land for flood routing. Ideally a flood route should not be located near properties and should be sited on land uses that can be used to this effect with minimal effort (such as grassed road verges). Two land use cost functions (LU) were explored as shown in Table 4.5. The land use factors on their own produce the same optimal path, but with a different total cost. The land use cost factors were therefore explored in combination with the selected slope factor. The results are shown in Figure 4.9. By increasing the difference in the cost associated with the most acceptable and least acceptable land uses categories, the optimal routes are encouraged to flow along the more acceptable locations. Figure 4.9 shows that LU2 ensures that the flood path flows for a greater length along a roadside as shown at location *a*. Also at location *b*, the route mapped out using LU2 is considered to be more desirable as it flows along a natural area, rather than the middle of road as is the case with LU1. There is also a notable difference in the mapped flood routes downstream from location *c*. The optimal path using LU1 involves a steep drop and the path mapped with LU2 finds a longer route that avoids the steep drop (not shown). This is because the steep drop is classified as a 'Cliff' in OSMM data and this was consequently categorized as cost category 4. Use of SF22, coupled with LU2 means that the resulting cost of traversing the cliff becomes excessively high, so that it finds an alternative route. Assigning appropriate land use cost functions is an area which is worthy of further research and an objective method of validating the optimal paths that are mapped with different functions is needed. In this research it was opted to use LU2 as the mapped flood route is considered more desirable.

Table 4.5: Relative cost category as presented in Table 4.2 and the land use cost functions (LU1 and LU2) that were tested.

Relative cost category	LU1	LU2
1	1	1
2	2	4
3	3	9
4	4	16
5	5	25

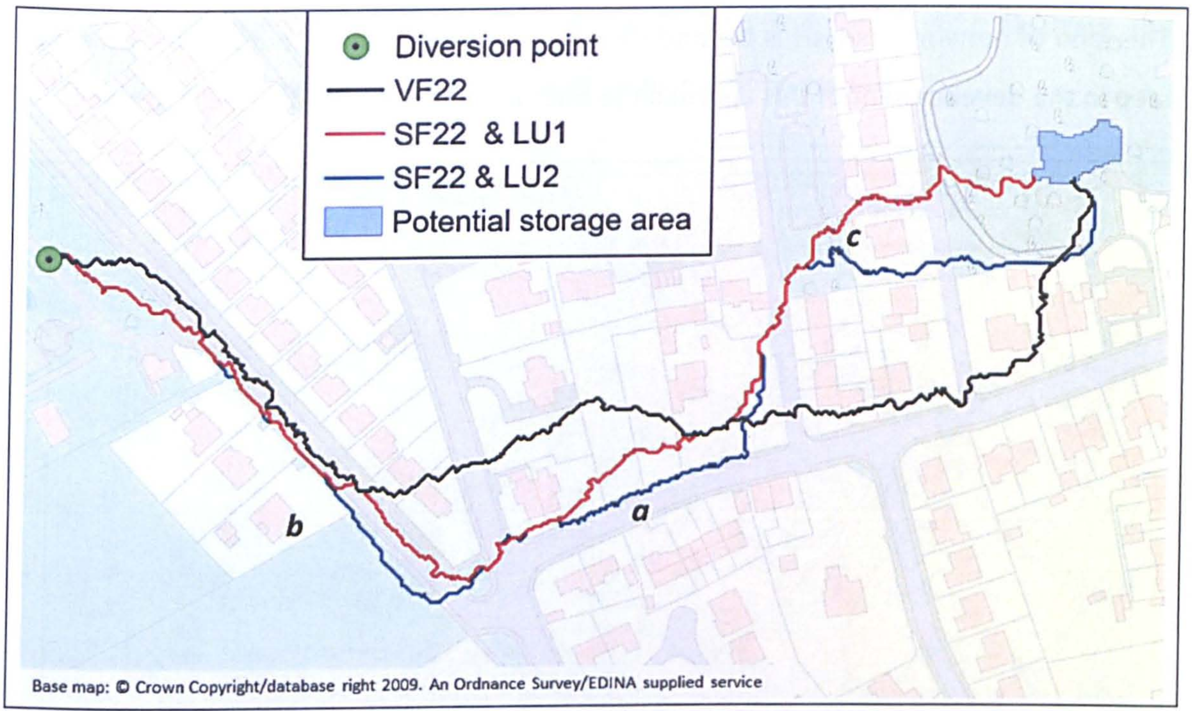

Figure 4.9: Results of the land use cost factors combined with the slope cost factor.

4.3. Results and Discussion

Identifying solutions using least cost path analysis

Using the method outlined above, the optimal paths from a number of diversion points to each potential storage area can be identified as shown in Figure 4.10. The optimal onward path from each storage area to all the downstream potential storage areas can also be identified by applying the same methodology. In this way all the potential route options for getting surface water from a given point to a suitable outlet can be mapped. Options may include a managed flow route directly from the surface water problem area directly to the catchment outlet, which may alleviate flooding within the surface water catchment but might not offer much attenuation. Alternative options include a managed flood route which incorporates various storage areas en route. As can be appreciated from Figure 4.10, there are a huge number of options. Translating the flood route costs along with storage volumes en route, into a network, would allow network optimization techniques to be applied to identify combinations of managed flow routes and storage areas based on maximising the storage potential, whilst keeping the implementation costs low (as expressed by the optimal route cost values).

This kind of network analysis is beyond the scope of this research, but is a critical next step in the development of this approach to finding surface water flooding solutions.

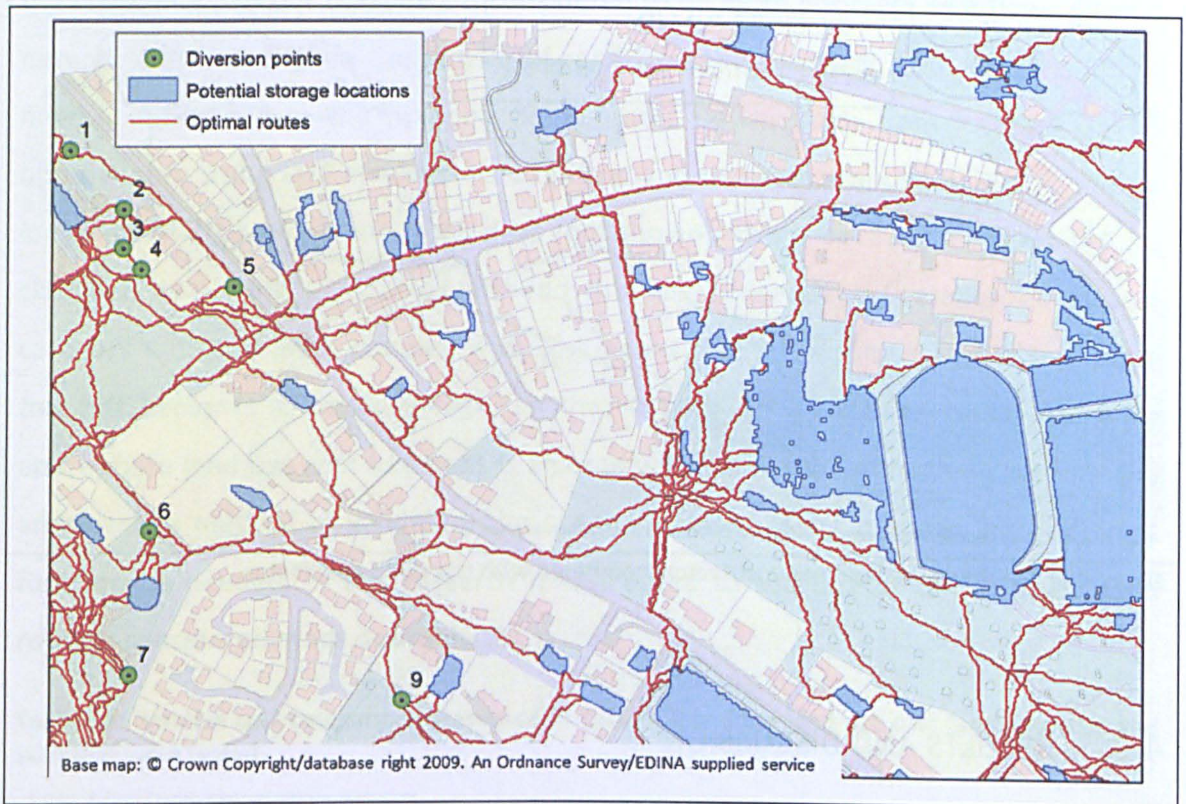

Figure 4.10: Example results of optimal path identification from diversion points and between storage areas.

Two diversion points were selected for comparison of potential flood routes. The diversion points are located upstream of the urban area and a small number of what were judged to be sensible options were selected for the purpose of a comparison (Figure 4.11). For the purpose of this analysis, the locations for potential surface water storage were converted into the maximum storage area possible, therefore they were all depressions 3 m deep (based on the maximum depth of water as suggested in Woods-Ballard (2007) and the length to width ratio was not considered. Scenario 1 uses some of the least costly flood routes to transport surface water directly to storage areas near the catchment outlet (Figure 4.11b). Scenarios 2 and 3 (Figure 4.11c and Figure 4.11d) incorporate some of the larger storage areas that were closest to the managed flood routes used in Scenario 1. Table 4.6 summarizes the cost values and the total storage for each scenario and Figure 4.12 and Figure 4.13 illustrate the current elevation profiles for the proposed managed flood routes.

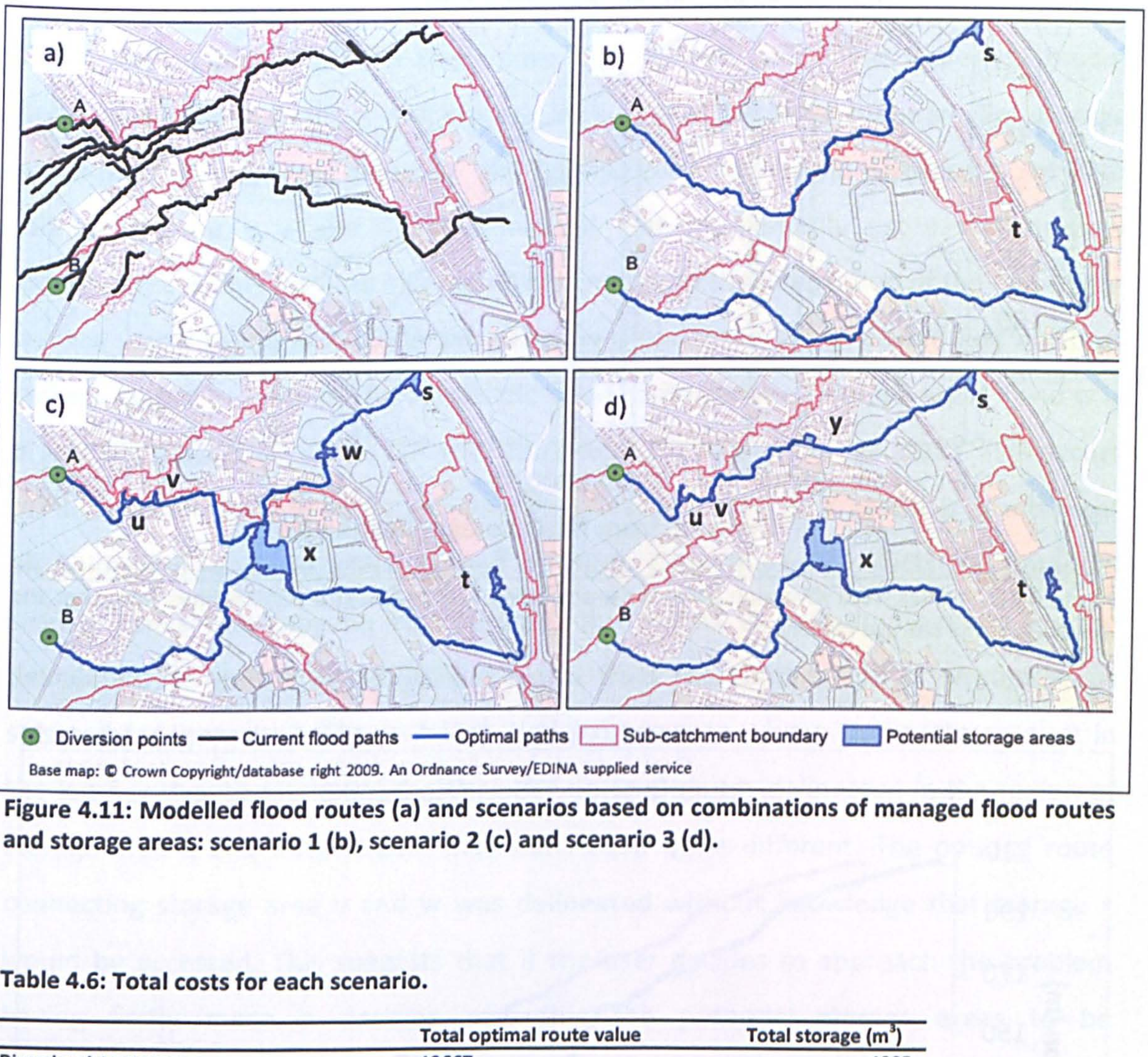

Figure 4.11: Modelled flood routes (a) and scenarios based on combinations of managed flood routes and storage areas: scenario 1 (b), scenario 2 (c) and scenario 3 (d).

Table 4.6: Total costs for each scenario.

	Total optimal route value	Total storage (m^3)
Diversion A to storage s	12667	4005
Diversion B to storage t	10536	3288
SCENARIO 1 (Total)	**23204**	**7293**
Diversion A to storage u, v and w	12720	8300
Diversion B to storage x and t	11616	29962
SCENARIO 2 (Total)	**24336**	**38261**
Diversion A to storage u, v and y	14926	5345
Diversion B to storage x and t	11616	29962
SCENARIO 3 (Total)	**26542**	**35307**

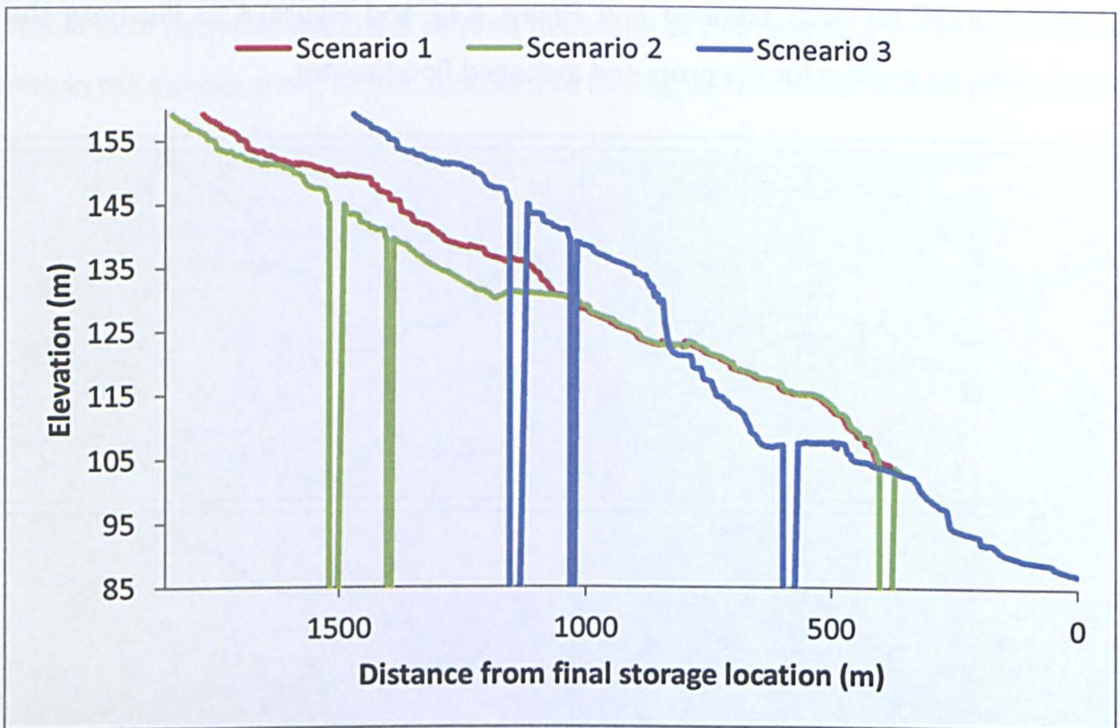

Figure 4.12: Profiles from diversion point A for scenarios 1, 2 and 3. The vertical lines represent the locations of the storage features.

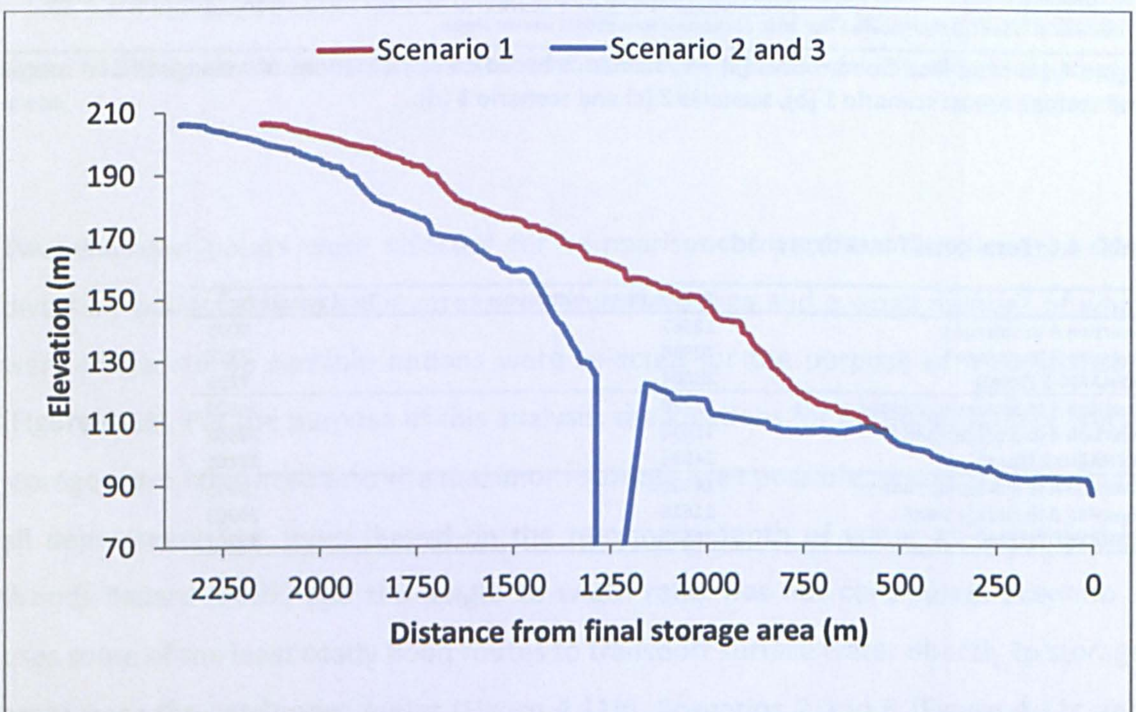

Figure 4.13: Profiles from diversion point B for scenarios 1, 2 and 3. The vertical lines represent the locations of the storage features.

For scenario 2 a number of large storage areas were selected in upper parts of the catchment. A large potential storage area (x) was identified between diversion point B and storage area t and the optimal paths connecting these locations were delineated. There was no potential for a single very large storage area in the upper catchment between diversion point A and storage area s, and therefore three smaller storage areas (u, v and w) were selected. The optimal path connecting diversion point A to storage areas u, v, w and s was delineated, and unexpectedly also passed through storage area x. This resulted in a significant change to the delineation of the two major surface water catchments, with the catchment boundary being located just north of storage area x. In practice this means the flood route between storage areas x and w is practically redundant, as the outlet of catchment x drains to storage area t. This occurs because when optimal paths are identified between storage areas, it is the current elevation and land use which is used as input. Once the user selects the potential storage areas that may be incorporated, this begins to have implications for the delineation of optimal paths, as was learnt from the combination of storage areas selected for scenario 2 (Figure 4.11c). Had storage area x been taken into account in the least cost path methodology, then the optimal routes delineated in the region of storage area x and downstream may have been quite different. The optimal route connecting storage area v and w was delineated without knowledge that storage x would be accessed. This suggests that if the user decides to approach the problem having firstly made a decision regarding the potential storage areas to be implemented, it may be worth firstly incorporating these into the DEM and then delineating optimal paths. Figure 4.14 zooms into an area of the optimal path which reveals a further interesting feature of Scenario 2. The optimal path starts by flowing along a downhill road, and then diverts down another road only to return to the original road further downhill. The optimal path is delineated in this way, as a more ideal profile with a slope of 2 degrees is achieved by adopting this route, compared to a 3 degree slope for the stretch of road that is avoided (Figure 4.15).

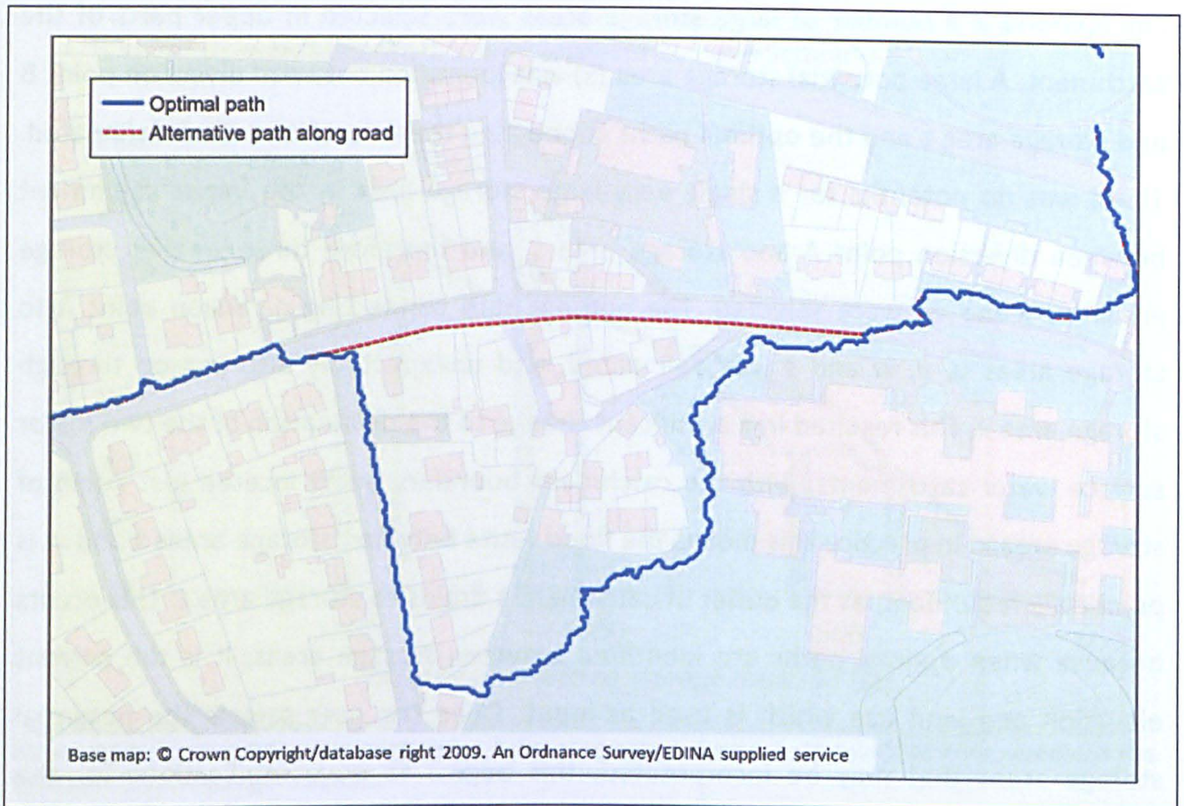

Figure 4.14: A section of optimal path that diverts off from a road and re-joins the same road downhill.

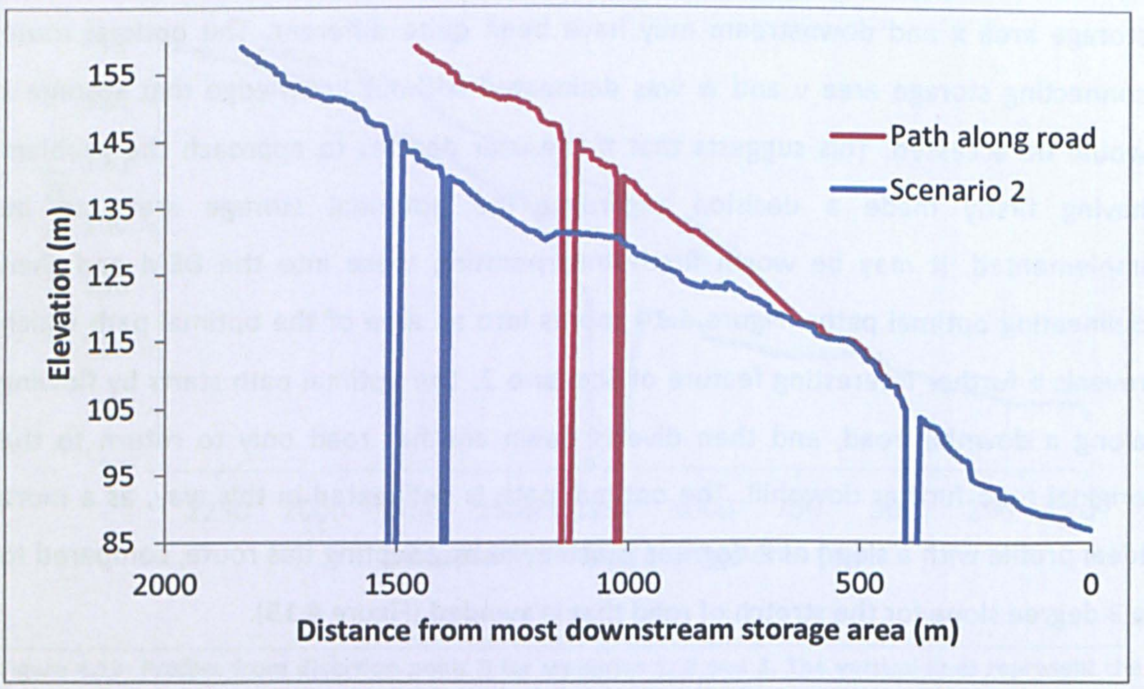

Figure 4.15: Elevation profile of optimal route and route downhill road as shown in Figure 4.14.

The storage areas in scenario 3 were selected with the aim of avoiding the issue encountered in scenario 2, whereby there were significant changes to the sub-catchment delineation. A storage area en route was selected that was linked by an optimal path that was not so close to the current sub-catchment boundary. Table 4.6, however, shows how the resulting total optimal route value is the highest of the three scenarios which is understandable as Figure 4.12 illustrates the steep drop that this route involves (at around a distance of 800 m from the most downstream storage location).

There are clearly engineering challenges associated with profiling all of the routes demonstrated in Figure 4.12 and Figure 4.13, if these are to be used as managed surface flood routes. The methodology presented here assigns a relative cost value that reflects the difficulty in implementing solutions and which is capable of identifying the more viable options. Detailed engineering design would necessarily adapt and modify the optimal routes identified by this methodology to a more realistic solution to implement.

SCENARIO ANALYSIS

Two rainfall events were used to run the urban surface water balance model for scenario analysis as shown in Figure 4.1 and Figure 4.2. The 24 hour duration, 5 year return period event was chosen because it was apparent from the questionnaire exercise that this type of long duration rainfall often led to flooding. The short duration 1 hour event of 30 year return period is also used in the scenario analysis as short duration, high intensity events are often assumed to be the critical events in urban areas. In this case, using the Bransby-Williams equation (Derwent Estuary Program, 2005), the time of concentration for the two surface water catchments used for scenario analysis is 63 and 47 minutes for the respective catchments of diversion point A and diversion point B (as shown in Figure 4.11). Scenarios 1, 2 and 3 as shown in Figure 4.11 were incorporated into the DEM using software built with landscape and built environment designers in mind and that allows interactive modification of DEMs (Simmetry 3D, 2011). The managed flood routes are imported into Simmetry 3D as shapefiles and the software allows the user to interactively carve out the routes along the polylines and represent these in the DEM. The software has the additional advantage of providing enhanced visualization of the managed flood routes in a 3D perspective. Due to the resolution of the DEM the minimum width of the managed flood route channels is limited to 1 m. However, through trial and error it was learnt that in order to carve out an approximately smooth channel that would ensure a downhill flow direction and minimal creation of small depressions that would not be assigned a flow direction, a minimum channel width of 3 m was needed. Similarly, the depth of the channel varied and was carved out in order to ensure a downhill path. The least cost path methodology is a screening tool to identify the location of optimal routes, and further detailed analysis would lead to the design of a more realistic solution (e.g. with less bends) and hydraulic analysis would determine the optimal channel width and depth. The channel dimensions used in this approach are not suggestions for channel design; this simply enables a DEM to be created that allows the water balance model to compute the surface water accumulation whilst ensuring that the managed flood routes are represented in the model. Indeed the model output, in terms of indicative flood routes, remains only one cell wide because the major flow accumulation is identified as a single cell width downhill along one of the cells representing the managed flood route. Three new DEMs were created to represent scenarios 1 to 3 and these were used as an input to the urban surface water balance model.

Guidance exists for evaluating flood risk management options using costs based on flood depths and damage curves (Penning-Rowsell et al., 2005). In this research the surface water management solutions are evaluated using measures of catchment flooding as permitted by the model output. These measures are based on the criteria that were found to have highest agreement with observed accounts of flooding as presented in section 3.3 (Classifying properties at risk of surface water flooding). Risk locations are properties that are within 2 m of a flood route with a total accumulated volume ≥ 300 m^3 or within 2 m of a sink that has a water depth ≥ 50 cm. The total excess water produced in the study catchments increases by 24% and 27% for the long duration and short duration events respectively (Table 4.7). The increase in surface water is less for the long duration event as the areas served by the sewer do not generate excess surface water. In the short duration event, the land classed as served by sewer does produce excess water as the short duration storm produces rainfall intensities that are assumed not to be drained by the sewer. The increase in total excess water produced in the catchments is greater than the climate change factor (+20%) and this is a logical result as it is not expected that sewer capacities will be increased under change conditions and urban drainage modelling studies conclude that more water will remain on the surface under climate change (CBMDC, 2008). In both events the proportion of the total excess water that leaves the catchment increases (Table 4.7), indicating the reducing capability of the catchment to retain its surface water.

The increase in the number of flooded properties is 5% and 11% for the long duration (Figure 4.16) and short duration (Figure 4.17) events under climate change. These increases may seem modest, but in fact the total water stored in risk locations increases by greater amounts, 8% and 19% (Table 4.8) for the long and short duration storms respectively, suggesting that properties that currently suffer from mild surface water flooding may in future have to deal with greater depths of flooding or a greater extent of flooding.

Table 4.7: Water balance under current and climate change scenarios.

		Total excess water (m^3)	Water stored at non risk locations as a % of total	Water stored within 2 m of a property or road as % of total	Water leaving at catchment outlet as a % of total
D24RP5 (long duration)	Current	19802	16	20	64
	Climate change	+23.85%	15	18	67
D1RP30 (short duration)	Current	16400	23	31	46
	Climate change	+26.76%	23	29	48

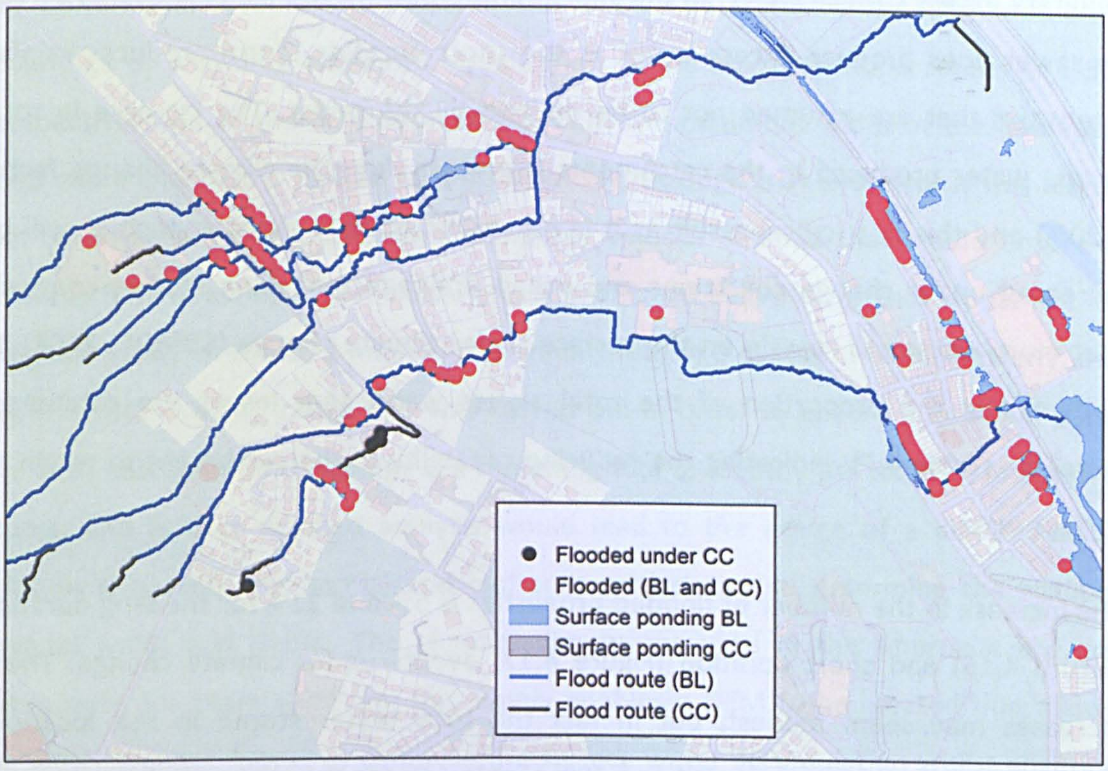

Figure 4.16: Properties at risk of surface flooding for the 24 hour duration, 5 year return period event under current (BL) and climate change (CC) scenarios.

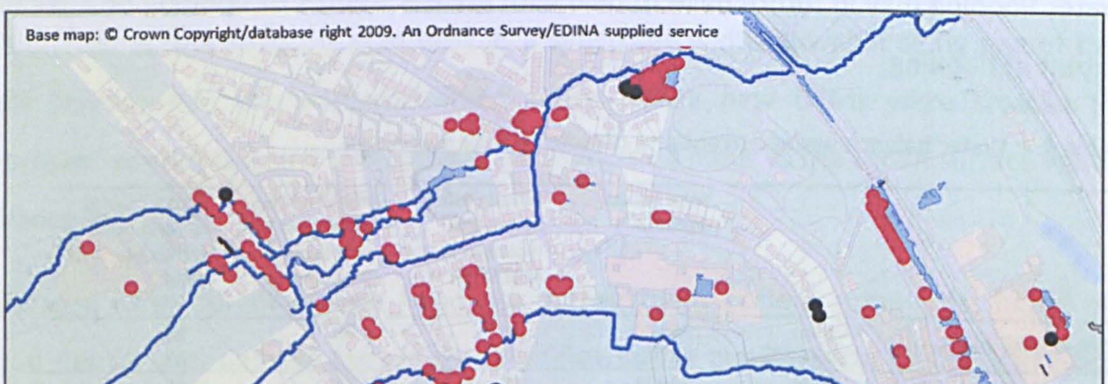

Figure 4.17: Properties at risk of surface flooding for the 1 hour duration, 30 year return period event under baseline (BL) and climate change (CC) scenarios.

Table 4.8: Number of flooded properties and volume of water stored at risk locations under climate change and for the various surface water solutions; scenario 1 (S1), scenario 2 (S2) and scenario 3 (S3) as shown in Figure 4.11.

		Number of flooded properties	Volume of water stored at risk locations, and greater than 50 cm deep water (m^3)
D24RP5 (long duration)	Current	142	3403
	Current S1	-46%	-23%
	Current S2	-46%	-27%
	Current S3	-49%	-30%
	Climate change	+5%	+8%
	Climate change S1	-45%	-15%
	Climate change S2	-46%	-18%
	Climate change S3	-49%	-23%
D1RP30 (short duration)	Current	219	3937
	Current S1	-15%	-14%
	Current S2	-12%	-19%
	Current S3	-21%	-29%
	Climate change	+11%	+19%
	Climate change S1	-6%	+1%
	Climate change S2	-4%	-1%
	Climate change S3	-13%	-14%

In all cases, including with climate change scenarios, the solutions (S1, S2 and S3) reduce the number of flooded properties (Table 4.8). Implementation of the solutions S1, S2 and S3 reduce the number of flooded properties in the long duration event by more than 45% even under climate change scenarios. The reduction is less for the short duration event, and the results range from a 21% reduction under current solutions with solution S3 to a small reduction of 4% under climate change conditions with S2. In terms of the volume of water stored at risk locations, under climate change, solutions S1 and S2 manage to keep volumes comparable to results under current conditions for the short duration event. Therefore, although the solutions are not able to reduce the impacts of climate change, they manage to maintain conditions that are comparable to the current state. Figure 4.18 illustrates that even solution S1, which incorporates storage only at the downstream end of the catchment, leads to a reduction in water stored at risk locations as well as a reduction in the surface water that leaves the catchment. This suggests that the incorporation of the managed flood routes successfully manages to intercept additional existing flood routes which lead to surface water filling depressions at risk locations. Figure 4.19 illustrates that for the long duration event, all three solutions S1, S2 and S3 offer significant reductions in the number of flooded properties (shown in green). There are still however locations which under all scenarios properties are classed as flooded. For example, the properties located in area *a* in Figure 4.19 do not benefit from the solutions because they are upstream of the selected diversion point. The properties located in area *b* of Figure 4.19 continue to be classed as flooded and this is less expected as they are downstream of the selected intervention point which was located on the flood route which drains to that area. This locality was investigated in detail and whereas with no solutions, location *b* has a contributing area of 349191 m^2, it is greatly reduced to only 54621 m^2 under scenario S2 (the reduced contributing area is shown in Figure 4.19). These findings illustrate that whilst the managed flood routes are not sufficient to eliminate surface water flooding at this location, with a smaller contributing area, it is now more likely that local scale and source control approaches may be more effective at dealing with the problem.

In general the solutions are less effective for the short duration event as seen in Figure 4.20. There are many more locations for which surface water flooding occurs under all of the scenarios. Solution S3 is clearly the best option for reducing the number of flooded properties as a result of the short duration event. A reduction of 13% in the number of flooded properties under climate change is achieved, compared to only 6% and 4% with S1 and S2 (Table 4.8). This is also shown by the black stars at locations *a* and *b* in Figure 4.20, which highlight the 28 properties that suffer from flooding under current conditions. Only S3 reduces the surface water flooding at this location. S3 is also the most expensive solution to implement according to Table 4.6, however it is this flow path (which incurs a very steep drop) which intercepts the existing flood routes which lead to the flooding at these locations. This should also be considered in the light that the model has not been validated for this event and that flooding for short duration, intense storms is likely to be much more dependent on the spatial variability of the sewer system performance. In this approach it is assumed that all areas classed as served by sewer can drain rainfall intensities up to 30 mm/hr, however in reality this is likely to vary spatially. The results, and scenario analysis for short duration storms should therefore be treated with caution.

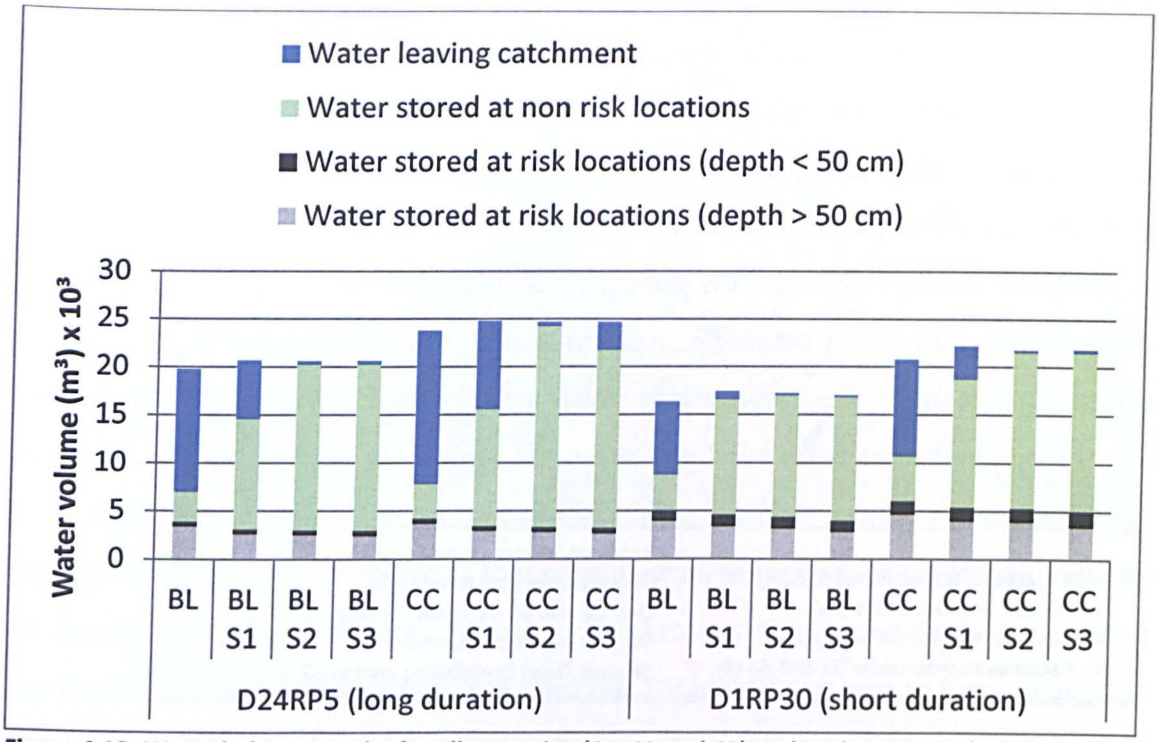

Figure 4.18: Water balance results for all scenarios (S1, S2 and S3) and under current (BL) and climate change (CC) scenarios. (Note: the difference in total excess water within the BL and CC scenarios is due to small changes in the total catchment area as a result of implementation of the managed flood routes).

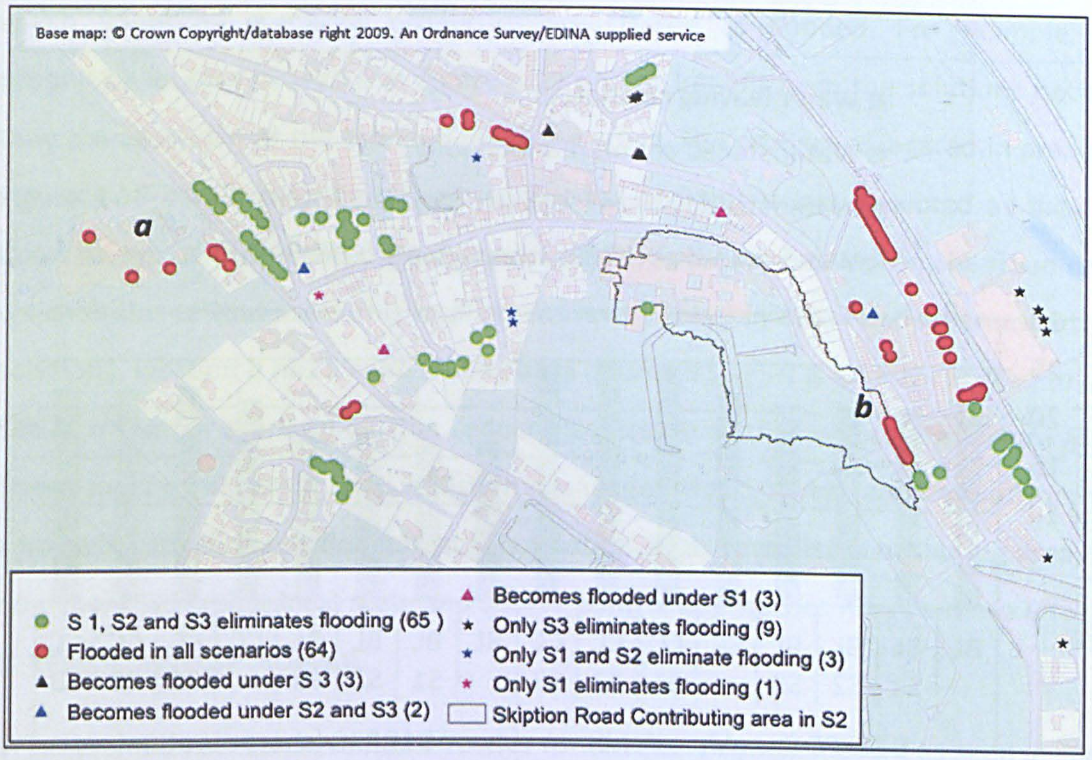

Figure 4.19: Impact of scenarios on the properties classified as flooded for the 24 hour duration, 5 year return period (the number of properties is given in brackets in the legend).

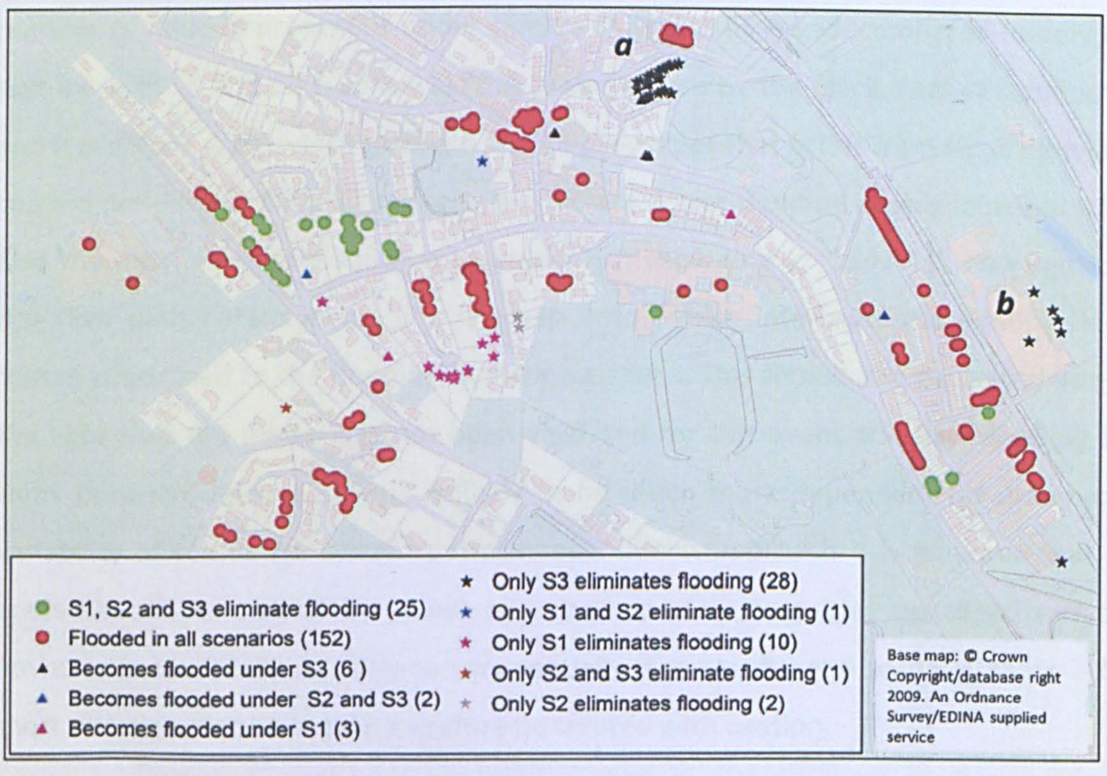

Figure 4.20: Impact of scenarios on the properties classified as flooded for the 1 hour duration, 30 year return period (the number of properties is given in brackets in the legend).

4.4. CONCLUSIONS

The urban surface water balance model has been used to identify surface water flooding under two types of rainfall events; a 24 hour duration 5 year return period event and the 1 hour duration 30 year return period event. By looking at the contributing areas of the flooded locations it was determined that the causes of flooding can be loosely divided into two. There are areas that suffer from flooding due to a very large contributing area made up of a significant proportion of peri-urban natural surfaces, which produce excess water that converges into major flood routes that enter the urban area. And there are areas that have small contributing areas and that suffer from surface depressions filling with surface water. There has been significant research which suggests that considerable reductions in runoff volumes can be achieved with SuDS features. Managed flood routes are now also being advocated but there has been little research into methods for identifying how to best implement these types of solutions. This research developed a least cost path methodology to identify optimal flood routes based on slope and land use. A diversion point was identified along existing flood routes which are causes of flooding in Keighley and the least cost path methodology was applied to identify optimal managed flood routes. Three potential solutions were selected and these were compared on the basis of elevation profiles which reflect the difficulty or ease of implementation. These surface water flooding solutions were used as an input for the water balance model in order to evaluate their effectiveness in reducing surface water flooding in the catchment under current and climate change conditions.

Translating climate change predictions into rainfall scenarios suitable for urban drainage impact studies is an area of on-going development and there is no clear consensus on the most appropriate methodology. In this study climate change factors advocated by UK government (DCLG, 2008) were used as it is a straightforward approach with fewer assumptions. In general, the solutions all reduced the number of flooded properties, and enabled the surface water catchments to retain greater proportions of the excess surface water within the catchment at non-risk locations. The managed flood routes also intercept existing flood routes downstream of the diversion point and transport water to non-risk locations, avoiding risk locations where possible. This is achieved through use of the least cost path methodology which assigns high costs to passing near properties. The selection of an appropriate cost function that best represents the engineering costs associated with re-profiling is an area which deserves more attention. This relationship is critical to the practical application of the methodology.

Incorporation of source management techniques combined with these types of solutions has the potential to reduce surface water flooding and provides potential for adapting to climate change. Significant engineering challenges exist in implementing these types of managed flood routes, especially in a catchment such as Keighley which is characterised by steep and changing slopes, however the scenario analysis has shown that there exists potential for regional scale solutions such as these to build in capacity for coping with climate change. The urban surface water balance model represents how surface water accumulates along the managed flood routes, and therefore reduces flooding. However, since it is not a hydraulic model and nor are the flood channels fully designed at this stage, it cannot be confirmed if the managed flood routes would not be a source of flooding through overtopping. The urban surface water balance model however is a useful high level screening tool that allows many scenarios to be run relatively quickly and comparisons to be made regarding the effectiveness of a range of solutions. Due to the simplicity of the model it cannot substitute detailed hydraulic analysis; it is instead suggested as an initial step to aid in proposing solutions and evaluating their impact.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. WHAT WAS ACHIEVED?

This research set out to develop a method capable of screening for surface water flood risk at a large scale, with minimal inputs and computational effort required, so that it can be used in scenario analysis. To achieve this goal, the hypothesis that a water balance approach can represent the main processes that lead to surface water flooding was tested. The water balance is composed of rainfall inputs, a representation of infiltration and sewer system losses, and the outputs are given in terms of locations and volumes of water that remain on the surface. The model takes the form of a series of transferable ESRI ArcGis toolboxes. It is executed and model results are visualized using GIS. This enables immediate use of the model outputs with existing GIS layers (e.g. spatial queries with land cover data or land use planning data). The conceptually simple model framework, coupled to the intrinsically complex urban surface in terms of dictating water movement, meant that several modelling challenges were encountered such as the treatment of multiple outlet sinks. The concept of catchment nesting was developed in order to accumulate surface water through the urban catchment (as urban sub-catchments do not have the reasonably well defined drainage patterns that natural catchments have).

Chapter 2 described the development of this new approach for modelling surface water flooding, and its sensitivity to the assumptions made. The model is developed in GIS and produces output which is easily visually interpreted and which can be used in spatial queries with existing GIS layers. The model requires as inputs a hydrologically correct DEM, a method for estimating excess surface water according to land cover and an input rainfall amount. The entire model can be run in several hours and for a given input DEM, scenarios can be run in a couple of hours.

Chapter 3 carried out a validation exercise. A measure of model agreement of 30% (Cohen's Kappa) was observed, although the model performed better in some catchments than in others. A detailed, case by case, qualitative analysis of modelled and observed flooding, revealed that many of the major catchment flooding patterns, in terms of the main flood routes and large ponding areas, are represented well in the model. It is therefore concluded that a water balance approach is capable of representing the processes that lead to surface water flooding.

The urban surface water balance model was used as a basis on which to propose solutions for surface water management. The result of the model indicated that the surface water flooding in the study catchments was largely a result of inflows to the urban area from natural areas not served by the sewer system. This points to solutions in the direction of managed flood routes. To the author's knowledge, chapter 4 offers one of the first attempts to propose an objective methodology for identifying optimal managed flood routes through the entire urban area, taking into account the existing built environment. The proposed methodology applies least cost path analysis to multiple criteria that are deemed important in siting flood routes. This exercise further shows the potential value in the surface water balance model as a screening tool, as it enabled these solutions to be evaluated and compared with minimum effort. It also provides a starting point for more detailed analysis.

5.2. CONTRIBUTION MADE

The principal contributions to knowledge made in this thesis are;

- demonstrating that a surface water balance approach is capable of highlighting locations at risk of surface water flooding,
- producing a GIS based surface water balance model that that can be applied to large spatial scales and which requires minimal data inputs and executes with minimal effort and,
- developing a methodology to automate the identification of viable managed surface water flood routes.

Much of the recent model development (that makes use of LiDAR DEMs) is concerned with making improvements to the hydrodynamic representation of interactions of the sewer system with the surface (Boonya-Aroonnet et al., 2007; Leandro, 2008; Leandro et al., 2009; Leitao, 2009; Maksimović et al., 2009). This continues to be an area of much research as illustrated by current projects exploring gulley hydraulics with the aim of better understanding the processes that link the surface to the sewer (FRMRC, 2011). My research approached surface water modelling from a different perspective. An approach was sought that was less computationally demanding and also requiring less data. To this end, the use of a water balance to highlight potential areas of surface water flooding was tested. The water balance approach presented in this thesis avoids the complexities and parameterisation required for hydrodynamic modelling. As has been shown in this research, the water balance approach enables a quick assessment of the main surface water flooding patterns within a catchment, and solutions to be evaluated. The water balance approach is therefore able to highlight areas within a catchment that require further investigation. Due to the conceptual simplicity of the model it cannot highlight areas where the complex interactions of the sewer, surface and fluvial systems lead to flooding, however the approach is able to quickly highlight where there is build-up of surface water. This saves the computational effort and time that would be required to identify such areas using hydrodynamic or hydraulic models. A suggestion for the role of the various modelling approaches is presented in Figure 5.1.

State of the art surface water modelling capabilities that make use of LiDAR DEMs were reviewed in chapter 2. The production and development of surface water models has been fast moving, not least due to changing regulatory requirements for local authorities to produce surface water management plans (SWMPs) (Defra, 2010), but also modellers have been keen to exploit the use of LiDAR DEM technology. Developments continue to be made as illustrated by recent publications such as Fewtrell et al. (2011) which compares various models based on the St Venant equations to simulate depths and velocities from a combined river and surface water flooding event. Most of the models reviewed in chapter 3 (Table 3.1) that used LiDAR DEMs, focussed on modelling small areas in great detail (e.g. producing time variant depth information), and few of these models have been applied for screening large areas for flood risk. In the approach developed in this thesis, the user can screen for surface water flood risk over a large spatial scale in an efficient manner by firstly identifying the major (i.e. largest) surface water catchments, and then the surface water accumulation module is applied to catchment areas where there is scope for build-up of surface water.

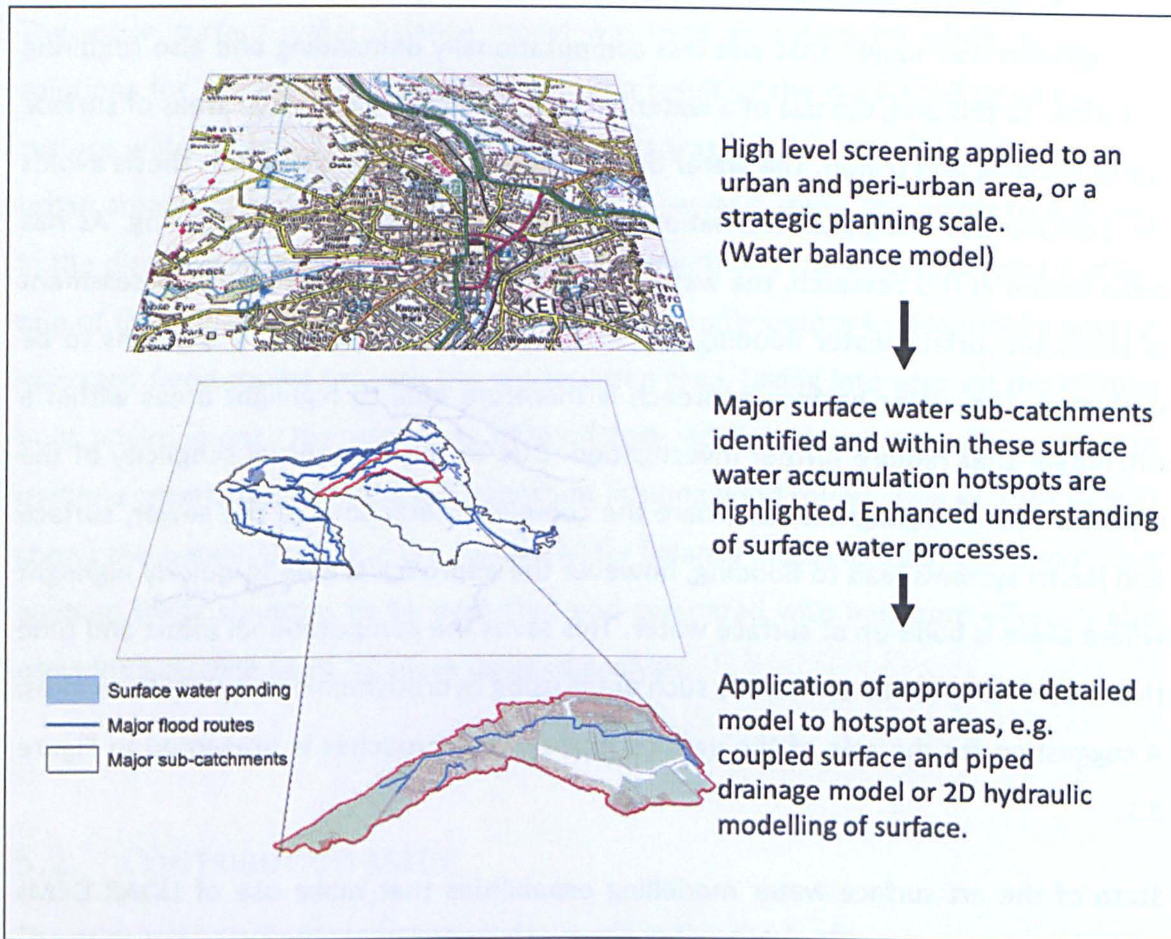

Figure 5.1: Proposed role of various modelling approaches.

Concurrent with the development of this research, in 2009 the Environment Agency released the results of the first major exercise in mapping surface water flood risk at a national scale (Environment Agency, 2010b). A two dimensional model (JFlow) was run on a 5 m grid, as with the water balance model described in this thesis, the 2D model made assumptions regarding the sewer conveyance (a national average of 12 mm/hr was used although how the national average was arrived at is not stated). An average infiltration is applied to rural areas and two values of Manning's n are used to represent rural and urban roughness. With the exception of this national scale exercise, the emerging LiDAR DEM based surface water models that were reviewed, have not been applied to screen for surface water flooding at large scales.

The overarching difference between the surface water balance model and the JFlow model used by the Environment Agency (2010b) is that the latter, whilst it has been developed to reduce typical data requirements, it is still a hydrodynamic model and requires parameterization, including Manning's 'n' which can only ever be estimated. Model output is in the form of gird based time variant surface water depths. Currently the results of this exercise are distributed to local authorities in the form of static GIS layers detailing the extents and depths of flooding as predicted by the model for two events (a 1 in 30 year event and 1 in 200 year event). Results distributed in this format do not lend themselves to providing a deeper understanding of the root cause of surface water flooding as the contributing areas are not easily deciphered. Section 3.3 of this thesis illustrated how it was possible to use the output of the water balance model to gain a greater understanding of the processes leading to surface water flooding. Whilst the Environment Agency model outputs, in the form of static maps, may be used as a basis for surface water management plans, they cannot be used to evaluate the impacts of management solutions unless access to the flow model is provided. The approach developed in this thesis is resource efficient and is executed in software available to local authorities (that may want to explore solutions) and requires competencies that are likely to be already available. The national scale exercise (Environment Agency, 2010a) however also provides an alternative for screening for surface water flood risk, which can also model blocked culverts and watercourses

In contrast to the production and development of models, there is relatively less research in the area of automating, and taking the subjectivity out of the search for viable solutions. With this is mind, it is felt that there is most novelty and greatest potential impact in the development of a methodology that supports strategic planning towards reaching the ideals of sustainable drainage within a highly constrained environment. Development of the methodology based on least cost path analysis, makes it possible to propose catchment wide solutions, in terms of storage and planned flood routes for managing surface water flooding. This is shown in Chapter 4. The least cost path methodology was shown to be able to discriminate between less viable paths (e.g. that would involve significant re-profiling, that go uphill, that involve very steep drops, or that would involve demolition of buildings) and more viable paths. The methodology is also dynamic in that it can be adapted to reflect changes in planning policy, for example if it becomes a viable option to acquire a certain type of land for flood risk management, the costs can be adjusted accordingly and the least cost path method will take this into account. It is envisaged that this type of approach would form the basis for long term strategic planning.

5.3. WIDER IMPLICATIONS OF THE RESEARCH

This research revealed that the lack of observed data is a major problem hindering advances in surface water modelling. Other surface water modelling studies also note the lack of surface water flooding data (Fewtrell et al., 2011; Hunter et al., 2008) and therefore resort to benchmarking exercises in order to gain insight into model performance. Using the data collected as part of this research (as described in Chapter 3), the Kappa statistic was used to measure the strength of agreement between modelled data and observed data and was found to be 30%, which according to a proposed benchmark means that the model has a 'fair' agreement. Although this appears a modest agreement with observed data, a qualitative analysis of the results revealed that many of the patterns, such as flood routes and ponding areas, described by respondents were accurately mapped by the model results. Computing a statistical measure of agreement as part of a validation exercise provides great insight into the model and provides a degree of confidence in the model, yet of the surface water flooding modelling studies that were reviewed, very few provide a measure of agreement. The most frequent approach is to make a visual comparison with scant data that can be obtained on flood extents, depths and locations.

This is a direct consequence of the lack of appropriate data, and this also raises the question of whether complex hydraulic and integrated models that produce time varying depth, extent and velocity data, should continue to grow in sophistication in terms of model output, without having comparable observed data with which to validate such models. Clearly there is a need for both screening models, such as that developed in this thesis, to highlight areas at risk on a large scale, and hydraulic and integrated models which would then be used to further understand the complexities and interactions at a more local scale. Both types of modelling approach require validation data which is currently not available. Perhaps it is worth investing similar efforts (as those invested in model development) into data collection. There are unique challenges associated with data on surface water flood risk locations, the events are short lived and flooding occurs in isolated patches and is widely distributed. A snapshot of the location and extents of a surface water flooding event could be obtained through aerial photography (although the aircraft would have to be on standby or rely on accurate weather forecasting). A further option is the use of CCTV, which would not require deployment as it is always in use and in addition there may be potential to extract time variant depth information which would be of use for time dependent studies.

As part of the validation exercise, locations where the modelled results did not match with the questionnaire responses were looked at on a case by case basis. Many locations were visited in person with the aim of trying to understand the reasons for poor model performance. This process actually revealed some information that is fundamental to urban surface water modelling; that many local features that are important in dictating water movement are not represented in the DEM, and consequently result in inaccurate model predictions. This finding is of relevance for all surface water modelling studies. It raises interesting questions regarding the minimum level of detail that needs to be represented in a DEM for accurate surface water modelling. What are the cumulative effects of small local features that are not present in the DEM? And how much detail should be included? This is likely to vary with the intended use of model results. Temporary features (such as sandbags) will alter the volumes of water arriving at different locations of the catchment. Despite the identified limitations in DEMs, they still offer unprecedented capabilities for surface water modelling in urban environments and Hunter et al. (2008) also concluded that for urban flood wave propagation modelling, a LiDAR DEM was a good choice.

5.4. Transferability of the Methods

The urban surface water balance model adopts two assumptions which determine the transferability of the method to predict locations of surface water flooding under varying wider catchment scale conditions. These assumptions are that a) all the surface water accumulated at the catchment outfall is free to leave the catchment, and b) that the proportion of rainfall that is converted to runoff in areas served by the sewer system can be estimated by allowing a fixed and ubiquitous loss to the sewer system (see section 3.2). The outfalls on the boundaries were identified as the lowest elevations in the LiDAR DEM on the model boundaries (i.e. rivers and watercourses identified using OSMM). The assumption that surface water is free to leave the catchment via these outfalls implies that the water levels of receiving watercourses are below the outfall elevation. In the case of raised river levels or rivers overtopping their banks, surface water discharge rates at the outfall become limited by a complex relationship between the available head of the discharging water, and the head of the receiving water at the outfall. The urban surface water model is non-transient; therefore incorporating these relationships is beyond the scope of the model. It would be possible to represent raised receiving water levels as closing off surface water outfalls by using higher elevations at the boundary to re-calculate the maximum extent and depth of surface sinks. This was not tested as part of the sensitivity analysis, however it is expected that such a scenario would principally alter the potential for surface water ponding near the model boundaries and that changes will be confined to the localities of previously identified surface sinks and major flow paths as these are determined by the topography. In a steep catchment like Keighley, the impact of fluvial inundation, on surface water flooding outside the flood plain will be minimal. Chen et al. (2010) conducted a very detailed modelling study of both a fluvial flood event and rainfall induced surface water flooding event (which also modelled the piped drainage), for an area of approximately 50 ha adjacent to the River Aire in Keighley. This modelling exercise illustrated that whilst the extent and depth of flooding was greater under a combined fluvial and surface water flooding event, there were very few flooded areas that were unique to coincident fluvial and surface water flooding events due to the restriction of the terrain.

Assumption (b) is considered to be more limiting to the wider applicability of the urban surface water balance model. Raised river levels can also impact on surface water flooding by altering the performance of the sewer system further upstream as discharges from the piped system are either contained within the system where flap valves are present (therefore capacity is reduced as the storm progresses), or as river water enters the piped system from the downstream end. The spatial variation of the conveyance rate of the piped drainage system is altered depending on the pipe elevations and the location and availability of storage within the sewer network. For simplicity, and due to the lack of data on the spatial variability of sewer performance, a ubiquitous value to represent loses to the piped urban drainage system was used for all areas classified as 'served by the sewer system'. In reality losses to the piped system will vary spatially and also with the type of rainfall event as well as the conditions at the outfalls. As an example, Allitt (2006) illustrates how flows from highway drainage vary dramatically from one storm event to another, and this could be explained by either the soakaway capacity or the relationship between gully capacity and by-passing water flows. This level of detail is currently very difficult to obtain, given that urban drainage is split between local highway authorities and privatised water companies which do not freely share the results of sewer modelling exercises. Furthermore, as illustrated in the study by Allitt (2006), the relationships between urban overland flows and storm events are not fully understood and therefore accurate modelling is not always possible. Nevertheless, Stovin et al. (2008) propose that, useful spatially distributed data regarding variations in sewer performance can be obtained from the results of hydraulic models produced by water companies, where this information is made available. This could take the form of translating the results of the sewer hydraulic model into a time averaged and spatially interpolated sewer capacity based on a range of storms. The basic assumptions adopted in this study mean that surface flooding is overestimated in areas where the piped urban drainage system has additional conveyance capacity and can absorb incoming overland surface flows, or surface water from a range of rainfall events. Conversely surface flooding is underestimated in areas where the sewer system conveyance rates are highly sensitive to a range of factors such as storm characteristics or the state of the fluvial system.

Whilst it is recognized that a better representation of the performance of piped urban drainage network would be beneficial to the screening tool proposed in this research, representing the effects of coincident sources of flooding is considered beyond the scope of such a tool. The urban surface water balance tool is capable of highlighting areas where there is potential for surface water to accumulate and pond, and therefore where detailed integrated flood risk modelling is required to understand the impacts of flooding from multiple sources. Furthermore by combining the results with local knowledge of surface water flooding (and given the intended users of such a tool would be local authorities), this approach becomes a powerful tool to understand the sources of flooding and eliminate the need for complex modelling where it is not needed. The validation exercise in section 3.3 illustrated how for catchments A and B, the urban surface water balance model is capable of providing a credible and logical explanation for much of the reported flooding without the need for additional modelling (after making an allowance in catchment B for the deficiencies in the LiDAR DEM as shown in Figure 3.15). In catchments C and D, the low agreement statistic and the difficulties in explaining the reported flooding with the model results, point to the need for more detailed modelling to fully understand the source of flooding. It is clear, even only with knowledge of the CBMDC culverts (as shown in Figure 3.16) that the piped urban drainage is critical in understanding the processes that lead to flooding in catchment D. The same may be true of catchment C and hence there is merit in more data hungry and complex modelling for these areas.

Keighley, a town situated in the steep valleys of the River Aire in West Yorkshire, was used as a case study to develop this research. Given that the model requires no parameterization it is expected that it be easily transferable to other catchments. The model is likely to perform to a similar standard in catchments similar to Keighley and where inflows to the urban area are the source of problems. In highly urbanized catchments, it is expected that an improved representation of the spatial variability of the performance of the sewer system will be key in determining where surface water flooding occurs. Flatter catchments may also pose additional challenges as it is expected that urban features, such as dropped kerbs, walls and protrusions will become even more critical in determining the major flood routes. In catchments such as Keighley, although urban features result in local modifications to the surface water movement, surface water accumulation follows the natural topography to some degree. Therefore, where urban features alter flood routes, in general the water eventually finds an alternative path downhill. In flatter catchments it may be the urban features which almost entirely dictate surface water movement (due to the very subdued underlying natural topography). The assumption made regarding the multiple outlet sinks may also have greater implications in flatter catchments for the same reasons.

Regarding the methodology described for finding managed flood routes, in flatter catchments, it will be principally land use that will determine the optimal route. It is felt that the methodology will remain applicable, and maybe even more so. Given that in flatter catchments slope will not be such a limiting factor, a huge number of managed flood routes could be identified using manual techniques. By developing improved methods to assign costs associated with implementing solutions according to detailed land use information, the least cost path methodology can find the optimal route through a highly urbanized and flat catchment (where land use will probably be more influential in determining the optimal routes than overall terrain slope).

5.5. SUMMARY OF MAIN CONCLUSIONS

- A water balance model was produced in GIS which requires minimal computational resources and parameterization.
- A surface water balance approach is capable of representing the main processes that lead to flooding (e.g. catchment scale major flood routes and major ponding areas).

- Less certainty can be attached to local scale (i.e. property level) model predictions as local model results are highly dependent on small scale features that dictate water movement and that are not always represented in the DEM.
- Investigating the sensitivity of the model to the storm sewer behaviour and flap valves on receiving watercourses or the rainfall events simulated was beyond the scope of the present work.
- This omission is likely to be a reason for the poor performance of the model at locations that exhibit spatially and temporally complex interactions with existing urban drainage infrastructure.
- The availability and quality of data for validation of surface water flood risk models is inadequate.
- A questionnaire exercise is a useful method of obtaining data to validate a screening model as developed in this thesis (and lessons were learnt on how to improve the exercise in the future).
- A method that delineates optimal managed flood routes has been developed based on least cost path analysis. This method aids in the identification of high level flood risk solutions.
- Implementation of managed flood routes and storage areas has the potential to reduce surface water flood risk and increase adaptability for climate change.

5.6. RECOMMENDATIONS

This research highlighted the value of using the two methods developed, as a basis for exploring solutions for surface water flooding. Several key areas for further development and refinement of the methods have been highlighted, and it is hoped that with further research these methods will be used in practice. Suggestions for future research are stated below in the proposed order of prioritization.

1. **Validation of optimal flood routes.** Methods are needed to validate that the optimal routes identified by the least cost path methodology are indeed the optimal routes in terms of the costs and difficulties associated with

implementing them. This may be possible by selecting a number of routes of varying relative cost and comparing the actual costs that would be incurred with implementation of the routes. This would take the form of carrying out the detailed engineering design, including all the costings required for the change in land use, materials, structures and earthworks. The results of this exercise would then be fed into the identification of appropriate slope cost functions and land use functions to reflect implementation costs.

2. **Representation of the sewer system for screening approaches.** Further research is required to develop simple methods that can account for sewer performance in screening approaches (without the need for simultaneous hydraulic modelling of sewers). It may be that the results of sewer models can be translated into static layers representing the spatial variability of model performance. This can then be used to derive the rainfall amounts that remain on the surface in urban catchments. Research is needed to identify whether this is possible and the degree of accuracy that can be achieved by simplifying sewer model results in this manner.
3. **Use of design storms.** Questions have been raised as to the appropriateness of using theoretical design storms as a basis for much urban drainage modelling and flood risk studies (Ashley et al., 2007). Although only a limited sample was obtained, the results of this research also point towards the unsuitability of design storms in helping to understand and characterize the events that lead to flooding. An analysis of the rainfall, in relation to the dates given by respondents when surface water flooding was reported, did not present very clear patterns on a type of event that led to flooding. In many respects this is expected as it is not just rainfall that leads to flooding, but a combination of factors including soil moisture for example. This is particularly important where natural surfaces drain into urban areas (and all urban areas have some natural surfaces). The issue of design storms becomes of greater significance under (uncertain) climate change where we cannot be sure that the probability

distributions, on which the intensity duration frequency theory is based, will be applicable (Milly et al., 2008). There have been calls for the use of continuous simulation in urban drainage modelling (Faram et al., 2010), but this may not be the way forward for screening approaches.

4. **Interpretation of model outputs**. The urban surface water balance has been shown to represent the major surface water flooding patterns (flood routes and large ponding areas). In order for the model to be of greater use in surface water management, it would be useful to be able to use model output to prioritize areas for surface water management solutions. In this thesis the model output was used to classify flooded properties. A visual inspection shows that there are clusters of flooded properties and also isolated instances of flooded properties. In terms of finding solutions, priority should be given to areas where greater gains can be achieved. Further research is required to translate model output into measures that can be used to prioritize areas for surface water management solutions. It may be that classifying properties as flooded or not is not the best method, and an alternative that highlights zones with greatest flooding potential, is preferable.

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7. Appendices

7.1. Appendix 1: Modifications to the LiDAR DEM to account for elevated structures

Figure 7.1 locates some of the elevated structures that were identified. Figure 7.2 illustrates the manual modification that is applied to the LiDAR DEM to allow surface water accumulation through elevated structures.

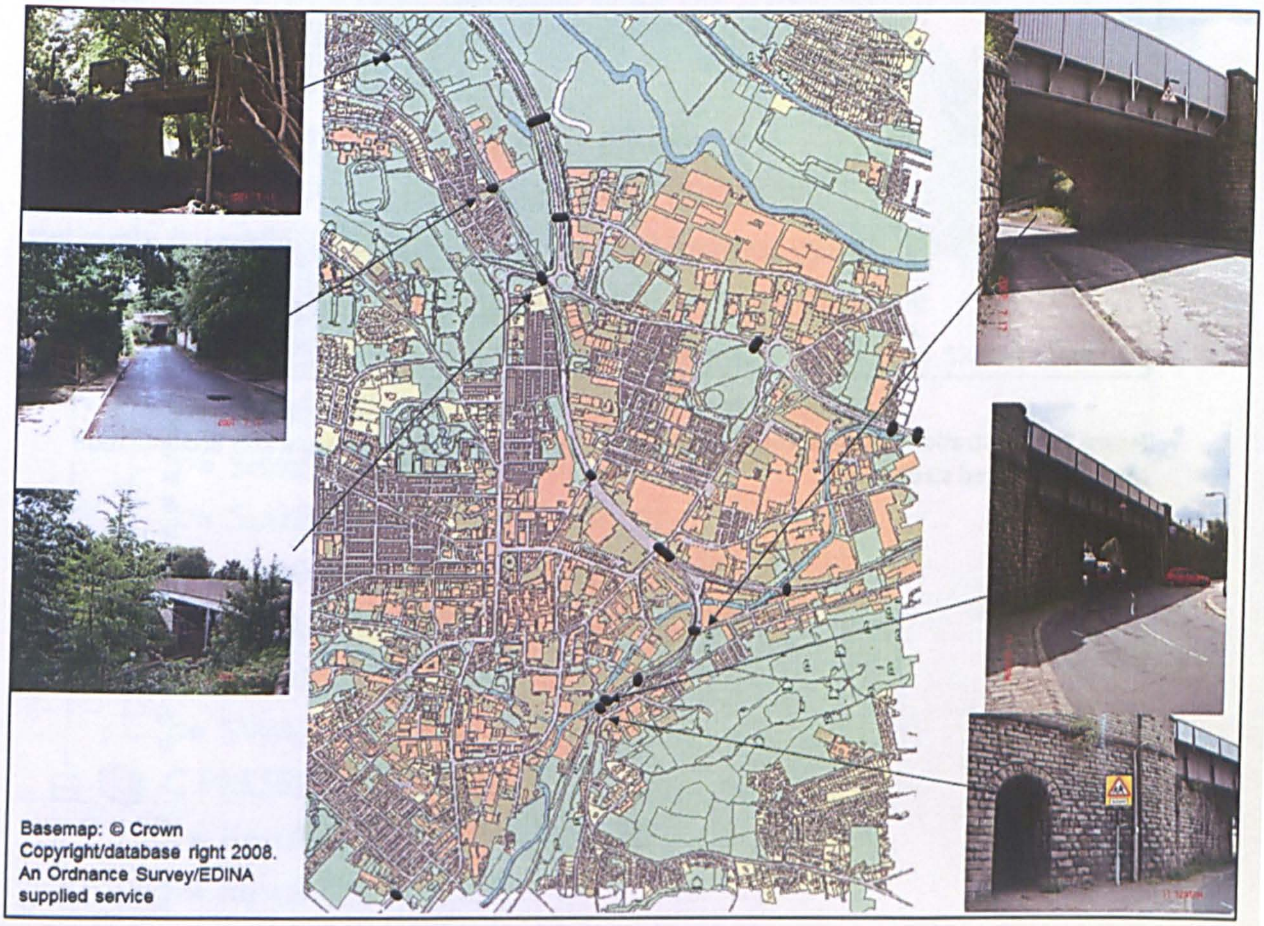


Figure 7.1: Photographs and locations of elevated structures.

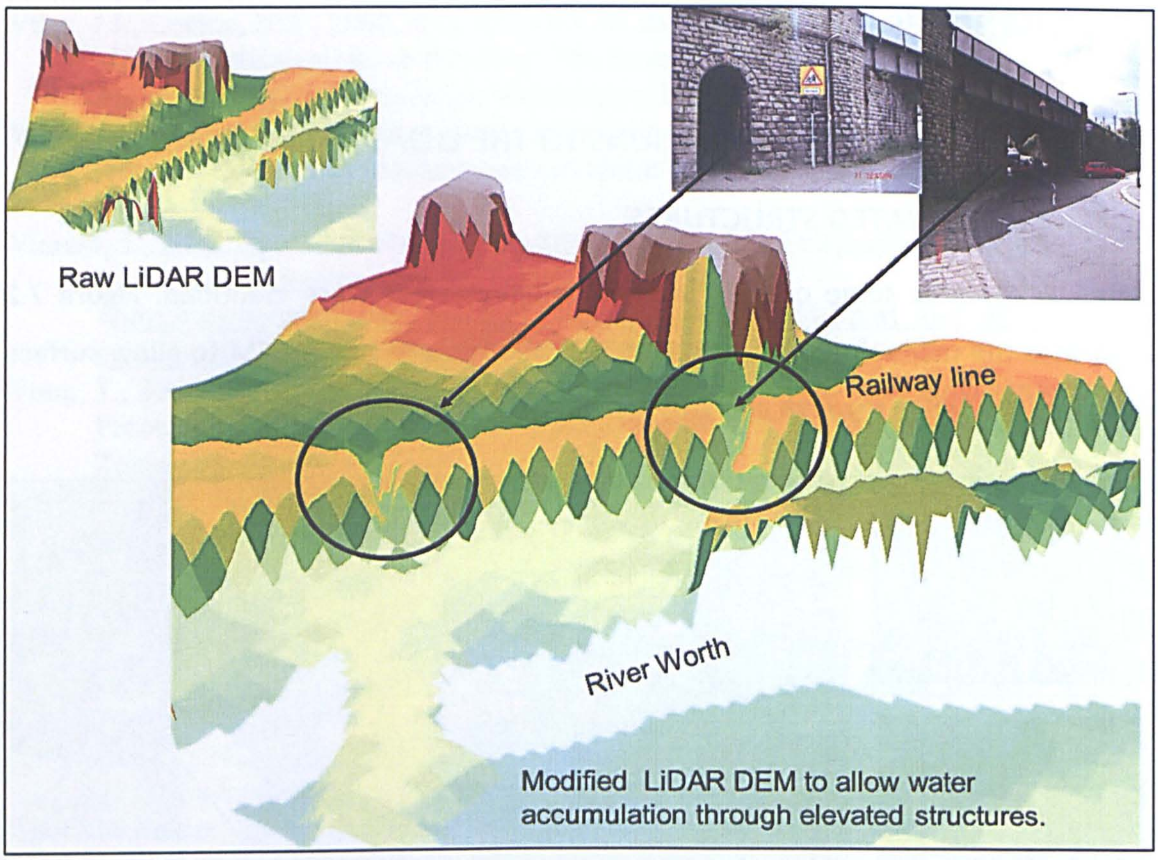


Figure 7.2: Illustration of manual modification to LiDAR DEM to allow surface water accumulation through elevated structures.

7.2. Appendix 2: Description of toolboxes and models that make up the Urban Surface Water Balance Model

Figure 7.3 illustrates the toolboxes and the models that make up the Urban Surface Water Balance Model. The coloured shading in Figure 7.4 shows where each model lies with reference to the model flow chart presented in Figure 2.2. The following account provides a short description of each model and what is achieved. A CD provided with this thesis contains a model manual.

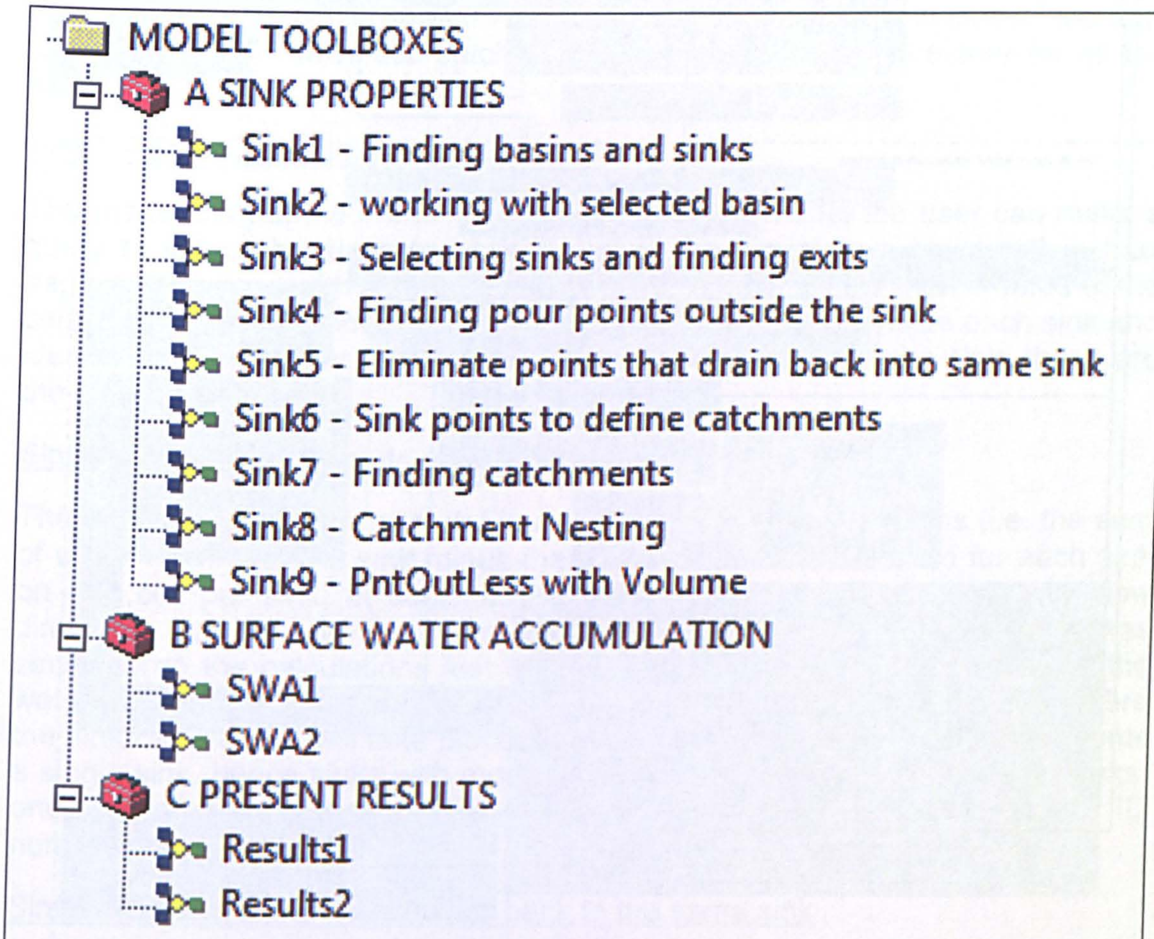


Figure 7.3: Urban surface water balance model toolboxes.

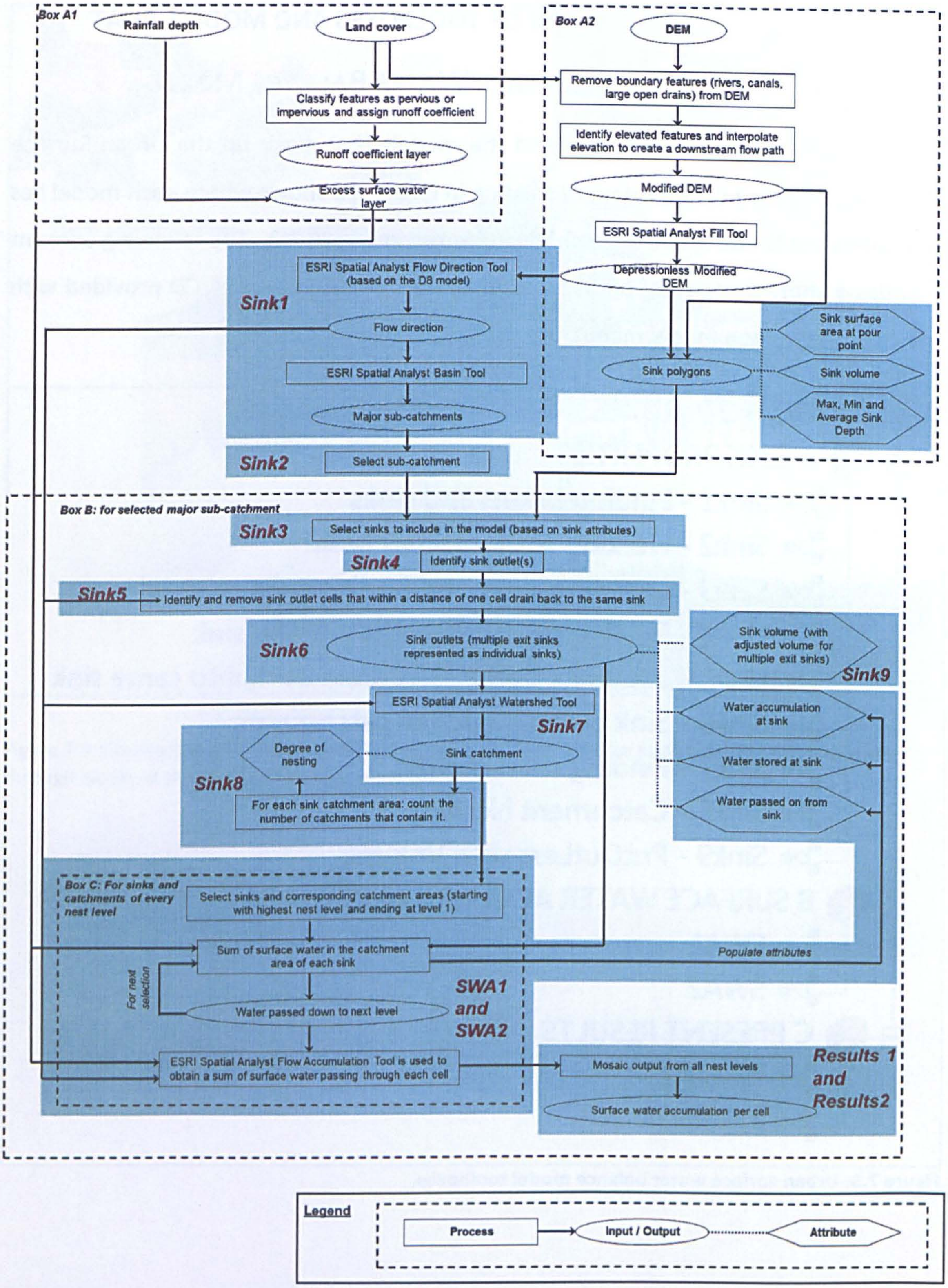


Figure 7.4: Model flow chart shaded to illustrate the models that execute the model processes. Standard ESRI algorithms that directly produce the required model data are preceded by ESRI and the name of the tool (e.g. the ESRI Spatial Analyst Basin Tool which computes catchment areas). All other model processes are computed using a combination of using existing GIS functions and map calculations (e.g. the module Sink4 uses various iterations of the ESRI Data Management Shift function combined with field calculations to compute the sink outlet cells).

TOOLBOX A SINK PROPERTIES

Sink1 – whole raster to get basins and sinks

The model diagram is shown in Figure S3. This model splits the input raster into the major sub-catchments. Each sub-catchment has an outlet that drains to a boundary (i.e. out of the raster or a river or watercourse). The model also identifies the sinks and then calculates sink properties such as maximum, minimum and average sink depth of each sink.

Sink2 – working with selected basin

The model diagram is shown in Figure S4. This model clips and cuts all the data for the selected major sub-catchment and creates a new directory for all the data.

Sink3 – Selecting sinks and finding exits

The model diagram is shown in Figure S5. In this model the user can make a query to select the sinks to be included in the model (e.g. sinks with a max depth > 10cm and with a surface area > 2m²). A new layer is then created of the selected sinks. This model also looks at all the border cells inside each sink and identifies the cells that with flow directions that drain out of the sink; these are the sink outlets.

Sink4 – Finding pour points outside the sink

The model diagram is shown in Figure S6. The model calculations (i.e. the sum of water arriving at the sink minus the sink volume) are executed for each sink on one cell per sink. In some cases there are two boundary cells with flow directions that drain to the same cell just outside the sink. It therefore makes sense to do the calculations just outside the sink in the cell that receives the water leaving the sink. This model identifies those cells. This is the cell where the sink calculations will take place. In essence each of these points represents a single sink, hence sinks with more than one exit point will become split sinks; one sink for every exit point. Every exit cell is linked to the sink by the sink ID number.

Sink5 – Eliminate points that drain back to the same sink

The model diagram is shown in Figure S7. In many cases, according to the cell flow direction, water leaves the sink for one cell then travels back into the same sink (eventually this would create a split sink for cases where this happens). This model therefore eliminates the exit points where this happens (i.e. where water only leaves a sink for one cell then drains back into the sink). This is all done using the flow direction raster which has one flow direction for every cell.

Sink6 - Sink points to define catchments

The model diagram is shown in Figure S8. At this stage a unique number is required for every sink (including a unique number for every sink part of the split sinks) in order to define the sink catchment area. It is not possible to use the exit cells that lie just outside the sink (as these all have unique numbers) because this would delineate a sink catchment that is larger than that of the sink. If the exit cells that lie inside the sink boundary are used, this would result in even more split sinks (even when not required). This would happen where two adjacent exit cells (inside the sink boundary) have flow directions that drain to the same cell outside the sink. This is illustrated in Figure S9. This model assigns each exit cell (inside the sink) the ID number of the cell it overflows to outside the sink. In this way the catchment area for all the cells with the same ID is delineated. The catchment area of each sink part of the split sinks is also delineated (i.e. each sink part has a different ID).

Sink7 – Finding catchments

The model diagram is shown in Figure S10. This model uses the unique sink exit ID numbers to delineate each sink catchment in turn.

Sink8 – Catchment nesting

The model diagram is shown in Figure S11. This model calculates the nest level of each sink catchment. The model takes each of the catchments and counts how many other catchments contain it. A nest level of 1 means the catchment is only contained in its own catchment (and is therefore equivalent to the major sub-catchment boundary).

Sink9 – PntsOutless with volume

The model diagram is shown in Figure S12. This model assigns a volume to each of the exit points (where the calculations will be done). In most cases this is equal to the sink volume but where sinks have been split due to multiple exits it assigns a portion of the total sink volume to each exit. The model currently uses the total volume of the sink divided by the number of exits so that each exit has the same volume.

TOOLBOX B SURFACE WATER ACCUMULATION

The model diagram for the surface water accumulation algorithm is shown in Figures S13 and S14. The SWA1 and SWA2 models are almost identical but the SWA1 just produces some of the input files needed to run the accumulation algorithm for the first time. In the highest level (to start the model) there is nothing carried over from nested sinks, so it starts by creating a layer with no carry over. Model SWA2 then continues the same process that is run in SWA1. It is fully automated, the user simply inputs the number of levels in the major sub-catchment and it keeps running until it gets to level 1. As the model progresses it uses the outputs from the previous level calculations as inputs. Each nest level is calculated in turn, i.e. the model runs once for level 10, then runs again for level 9, then level 8 etc.. The model sums the surface water from all the cells in the catchment area of each sink. Any portions of the sink that have already been accounted for in higher nest levels are not included. Only the carryover of the nested sinks is included for these portions.

The surface water is accumulated for each sink by a summation of all the excess surface water values of each cell inside the catchment area of the sink. This is much quicker that the flow accumulation tool and provides the output that is needed for the exit cell of each sink. Given that the calculations are made on the cell outside the sink boundary (i.e. the cell that receives the water leaving), if the ESRI Flow Accumulation tool were used, the value given for that cell would be the total water arriving at the exit cell, which might be more than that entering the sink. Since there are sometimes several cells inside the sink which have flow directions that drain out, it would be trickier to use the flow accumulation value of each exit cell inside the sink boundary. This is why it was therefore more appropriate and faster to use the summation of all the excess surface water values inside the catchment area of the sink.

The ESRI Flow Accumulation tool is not used for the purpose of the calculations; however it is run simultaneously to get an indication of the surface water flow paths. If this is omitted, the model runs even quicker providing the user with the volumes stored and passed down at each of the sinks.

TOOLBOX C PRESENT RESULTS

Results1

Given that the surface water accumulation calculation are made at one point (cell), for the purpose of presenting the results, the values are illustrated on the sink polygon. This model transfers the data obtained at the sink points to the sink polygons.

Results 2

This model produces a mosaic of all the flow accumulation results. When the SWA2 model is run a raster of the flow accumulation for each nest level is also produced. This model mosaics the flow accumulation output for all the nest levels to produce one raster file for the entire sub-catchment area.

7.3. Appendix 3: Surface water flooding questionnaire

The University Of Sheffield.

Catchment Science Centre

PENNINE WATER GROUP

Flooded or not?

Surface water flooding is where large volumes of water pond or collect following heavier rainfall events. We are working on reducing surface water flood risk. To do this we need to locate the areas that have suffered or currently suffer from surface water flooding and also locate areas that are not affected by surface water. The data we collect is confidential and will be used anonymously to test and validate our research. If you would like to know more about this research please visit **www.flood.group.shef.ac.uk** or contact Jacqueline Diaz-Nieto by email at j.diaz@sheffield.ac.uk

Please help us by completing this questionnaire and returning to us by the **25th of September** and you will be entered into a prize draw for a **£25 gift voucher** for the store of your choice. You can also complete the questionnaire online at **www.flood.group.shef.ac.uk/quest.html** or you can email your answers to **j.diaz@sheffield.ac.uk**

The winning reference number will be published on the webpage in October and can also be requested by email.

Reference number : ______

1) Has this property or have the streets next to this property been flooded or affected by surface water? (this includes large puddles of water which are an inconvenience)

No ☐
Please answer **questions 2 & 3** and return the questionnaire in the envelope provided. This information will be very useful to our research. Thank you very much for your time.

Yes ☐
Please answer **questions 2 to 6** and return the questionnaire in the envelope provided. This will be of great value to our research. Thank you very much for your time.

2) How many years have you lived at this address? (this is for us to know what heavy rainfall events you would have experienced at this address)

______

3) Can we contact you if we have any further questions?

Yes ☐ I am happy for you to contact me by *(please provide details where applicable)*:

Name: ______

Email: ______

Telephone: ______

Post: ______

No ☐ please do not contact me.

4) Can you remember the dates and details of when this property or the streets next to it have been flooded or affected by surface water? (please complete the table below)

Date (or approximation e.g. *summer 1989*)	**What was affected or flooded?** (e.g. back garden, street in front of house, front drive) and any additional information about the flooding or affected area (e.g. how deep was the flooding)

5) Do you have any additional information that you think would be of interest to us?
For example do you know of other areas in the neighbourhood which are affected by surface water flooding (properties, streets, parks etc..), do you have any additional comments to make about the flooding suffered at this property, or do you have any photographs of flooding incidents?

6) Do you give us permission to notify the City of Bradford Metropolitan District Council of these flooding incidents?
All responses are confidential and will not be disclosed unless you tick the **Yes** box below.

Yes ☐ No ☐

WHAT COUNTS AS SURFACE WATER FLOODING?

If the presence of rain water is disrupting everyday life then it can be considered surface water flooding. It is important to remember that surface water flooding occurs during or immediately after heavy or prolonged rainfall. It is sometimes difficult to decide whether flooding is due to surface water, river flooding or sewer flooding and in many cases it might be a combination of various sources. The list below provides information about the types of flooding we are interested in hearing about.

Examples of surface water flooding:

- Flooding that is a direct result of heavy or prolonged rainfall (this type of flooding is usually very localized and only affects certain streets or properties in the area).
- A large ponding area which leads to a road being closed.
- A very large puddle that you would rather not drive through.
- A surface water flow path that runs through a property.
- Surface water that enters a property and causes damage.
- Large puddles that restrict access to a property.
- Flooding due to blocked gullies (rain water cannot drain into the gully and so there is flooding on the surface).
- Heavy or prolonged rainfall events that lead to flooding from sewers (when water pushes manhole covers open and water exits the sewer system onto the surface).
- Localized flooding from small streams or watercourses (it is sometimes difficult to decide whether this is river flooding or surface water flooding. As a general rule of thumb if the flooding affects a small area and occurs during or shortly after the rainfall that fell in the same place as the flooding location then we can say it is surface water flooding).

What is NOT surface water flooding:

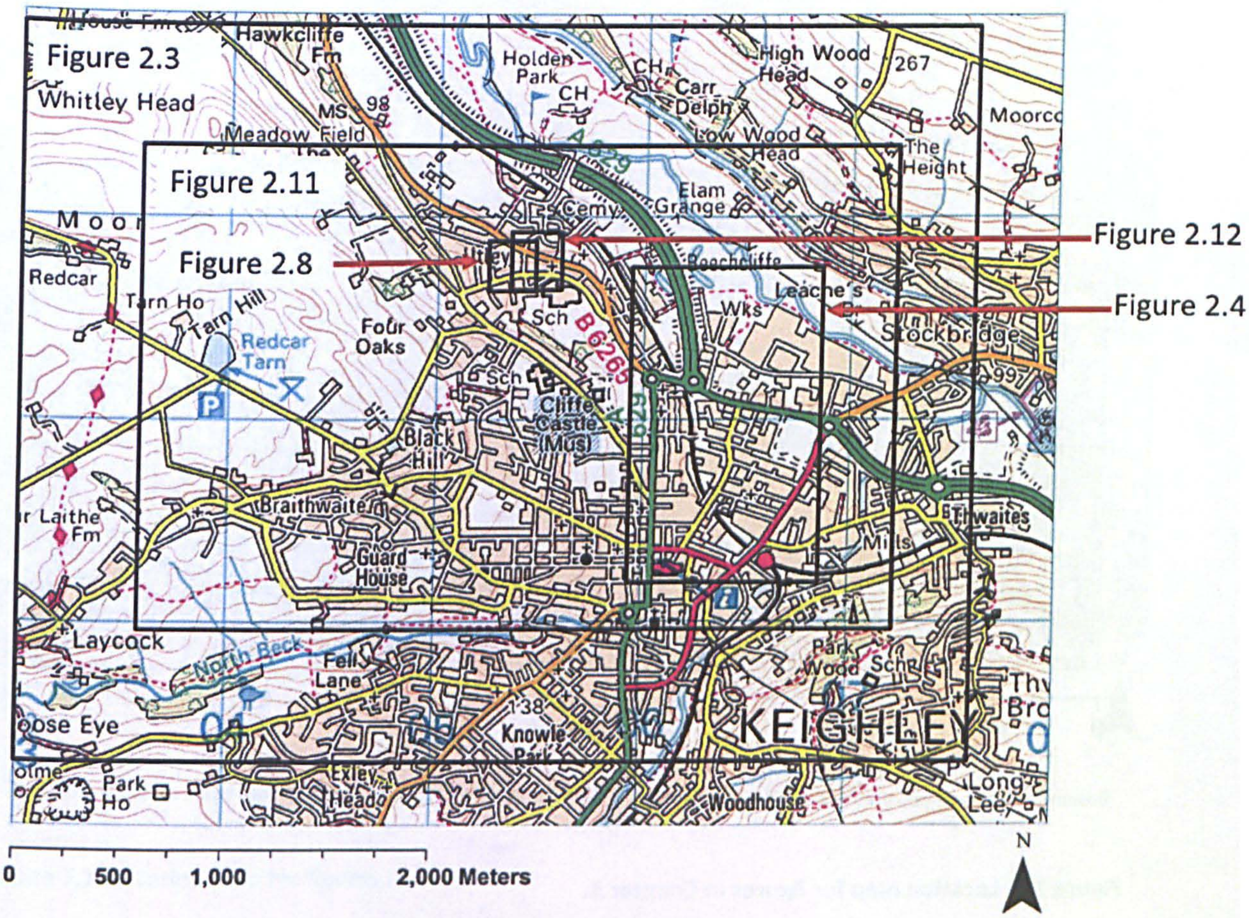
- Flooding from rivers that overtop their banks (this type of flooding usually affects very large areas).
- Flooding from water that seeps from the ground (groundwater flooding).
- Flooding from burst water pipes and sewers (when it has not rained).
- Flooding from leaks in the roof.

7.4. APPENDIX 4: TABLE OF MISCLASSIFIED PROPERTIES AND REASONS ATTRIBUTED FOR THE MISCLASSIFICATION

Label	Reported and Modelled	Catch-ment	Visi-ted	Proposed explanation for misclassification	Summary reason
1	Y,N	A	Y	The resident reports a large ponding area near the property. Ponding occurs due to the presence of a wall which is not picked up the by LiDAR DEM.	Limitation with DEM
2	Y,N	A	Y	The resident mentions a flow path which washes out the drive. This flow path is in fact represented in the model but it is approximately 15 metres from the property and so the selection criteria fail to highlight the house as at risk.	Selection criteria
3	Y,N	A	Y	The resident mentions that there is an underground beck and also CBMDC records also show a culvert near the property. It is likely that the flooding is related to the culvert	Drainage assets
4	Y,N	A	Y	The residents mention that water accumulates in their drive. The model shows the water running straight down the road in front of their property. Having visited the site the property has a very low curb and it's likely that some water enters the drive as well as flowing along the road	Limitation with DEM / Flow direction algorithm
5	Y,N	A	N	The resident mentions significant ponding in the street in front of the property causing problems entering property. The model represents a sink with a maximum depth of 19 cm in front of the property. The treatment of multiple exit sinks means that this sink doesn't fill, furthermore the sink is approximately 3 metres from the property so wouldn't be included in the selection criteria.	Treatment of multiple exit sinks / Selection criteria
6	Y,N	A	N	The resident did not provide any details regarding the flooding. The model does pick up a sink in the road in front of the property but it only has a maximum depth of 16 cm. Furthermore the sink does not fill in the model because its contributing area (which is 1085 m^2) is entirely classified as served be sewer which for the event used in the model test produces zero excess water.	Selection criteria / Excess water method
7	Y,N	B	Y	The resident did not provide details regarding the flooding. The model does not represent any sinks or flow paths near thie property. The site was visited and it was not possible to make any clear conclusions regarding why this property might flood. It is known that upstream of this property one of the mayor flow paths locations is wrongly modelled and it may be that this has cumulative effects downstream.	No obvious reasons / Limitation with DEM
8	Y,N	B	N	The resident specifically mentions flooding on only one event in 2003. On this event the back yard flooded. The model indicates the presence of a large sink to the rear of the property with a maximum depth of 61 cm but in the model test run, the sink doesn't fill as its contributing area (10382 m^2) is entirely classed as served by sewer and therefore the excess water produced is zero.	Event that lead to flooding is different to the event used to test the model / Excess surface water method
9	N,Y	B	Y	Having spoken to a neighbouring resident, it was confirmed that there is a culvert that starts upstream of the property and is likely to intercept the modelled flow path that leads to this property being classed as flooded.	Drainage assets
10	Y,N	B	N	The resident reports flooding of the tennis court. The model also represents a sink in the location of the tennis court which fills to a water depth of 10 cm, however the property is not highlighted as at risk because the water depth is too shallow and the sink is more than 2 metres away from the property.	Interpretation of flooding
11	N,Y	B	Y	The resident provided no further details. The model represents a flow path across the road in front of the property which then flow along the side of the property. Having visited the site there are 3 gullies in the road in the approximate location of the modelled flow path. Furthermore there is a small stretch of culvert with would drain the flow path in front of the property away from the property itself.	Drainage assets / Limitation with DEM / Flow direction algorithm.
12	Y,N	B	Y	The resident reports flooding on the road in front of the property and also water entering the cellar. The model represents a flow path 7 metres in front the property. therefore it is not highlighted as at risk. The model also highlights a full sink adjacent to a contiguous property to the rear - it may be that this is the source of flooding in the cellar but the property in question is not highlighted.	Selection criteria

Label	Reported and Modelled	Catch-ment	Visi-ted	Proposed explanation for misclassification	Summary reason
13	Y,N	B	Y	The resident reports flooding in the road in front of the property and blames it on blocked drains. The model represents a sink along one side of the road but it is only 17 cm deep and furthermore does not accumulate any surface water for the model test event as its contributing area (794 m^2) is entirely classed as served be sewer.	Selection criteria / Excess water method
14	Y,N	C	N	The resident reports flooding in the street in front of property and into the drive. There is a flow path along the back of the semi-detached properties on the opposite side of the road - many of these properties seem to have canopies in-between the properties. It may be that in reality this flow path flows under one of these canopies, across the road and into this property.	Limitation with DEM
15	Y,N	C	N	The resident reports flooding along the road and a large puddle on the road. The model does not represent a sink or a flow path in this location. Furthermore this property is very near to the catchment boundary and therefore there is little scope for surface water to build up. It may be that the catchment has been delineated incorrectly.	Limitation with DEM
16	Y,N	C	N	The resident reports a flow path along the road in front of the property. The model produces a flow path along this road when run using 1 hour rainfall duration of a 30 year return period. The flow path is 6 m from the property.	Selection criteria / Event
17	Y,N	C	N	Resident mentions flooding specifically in Summer 2008, when water came down the road in front of property. The model produces a flow path along this road when using 1 hour rainfall duration event of a 30 year return period.	
18	Y,N	C	Y	The residents mention ponding near the properties. The model represents a sink in this location, however the contributing area of the sink is mainly classed as served by sewer and therefore very little water accumulates in the location in the model test event. In a 1 hour 10 year return period event, a water depth of 15 cm is modelled in the sink and in a 1 hour, 30 year event results in 50 cm water depth	Event / Selection criteria
19	Y,N	C	Y	As above (the properties neighbour the same sink)	Event / Selection criteria
20	N,Y	C	N	The property is highlighted as at risk because it is less than 2 m away from a sink with a water depth greater than 50 cm. The sink is not on the curtilage of the property but on a neighbouring field.	Selection criteria
21	N,Y	D	N	The property is highlighted as at risk because it is adjacent to a sink with a water depth greater than 50 cm and also a flow path flows very near to the property. It may be that the flow path has been incorrectly delineated in this location.	Limitation with DEM
22	N,Y	D	N	As above (the properties are neighbours)	Limitation with DEM
23	Y,N	D	N	The resident mentions a flow path in the road in front of the house approximately 1 inch deep. The model does indeed show a significantly high volume flow path in the road, but the property is not highlighted as at risk because it is approximately 10 m from the property.	Selection criteria
24	N,Y	D	N	The property is highlighted as at risk because it has a sink with a water depth of 50 cm. Furthermore the contributing area of the sink is largely pervious and for this event results in significant accumulation of water in the sink. Water enters the sink from an adjacent road, however it may be that the water continues to flow along the road rather than diverting into this property.	Limitation with DEM
25	Y,N	D	Y	The resident mentions water flooding the neighbour's garden and then running into this property. Upstream of this property (20 m), the model identifies a large sink which stores all the water from an incoming flow path. Having visited the site it does appear the upstream sink may exist but it could not hold water 50 cm deep as the retaining wall is approximately 25 cm tall. It may be that this sink does not hold as much water as represented in the model and therefore water continues to flow downhill into the misclassified property.	Limitation with DEM

7.5. Appendix 5: Figure location maps



Basemap: © Crown Copyright/database right 2008. An Ordnance Survey/EDINA supplied service

Figure 7.5: Location map for figures in Chapter 2.

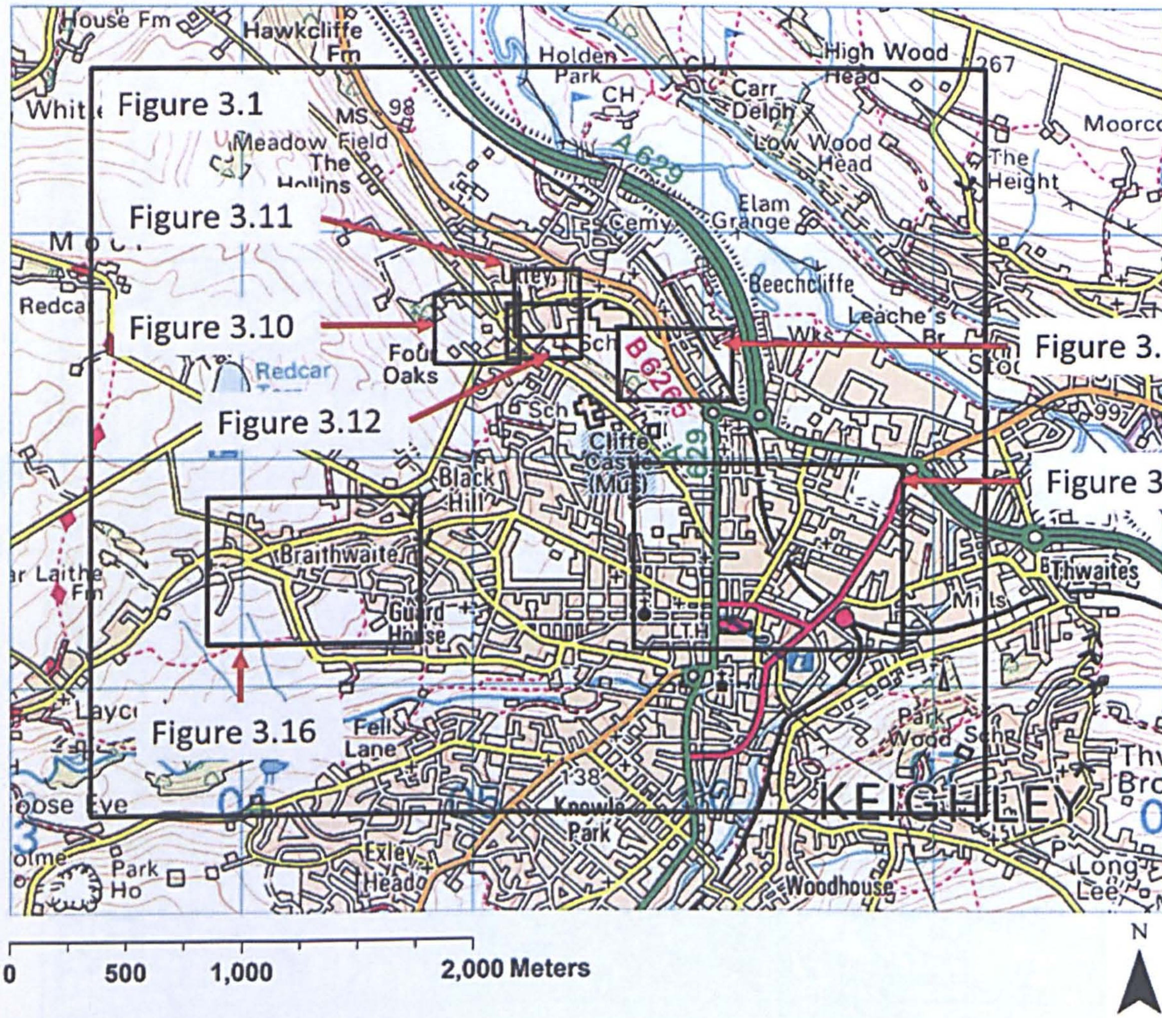


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Figure 7.6: Location map for figures in Chapter 3.

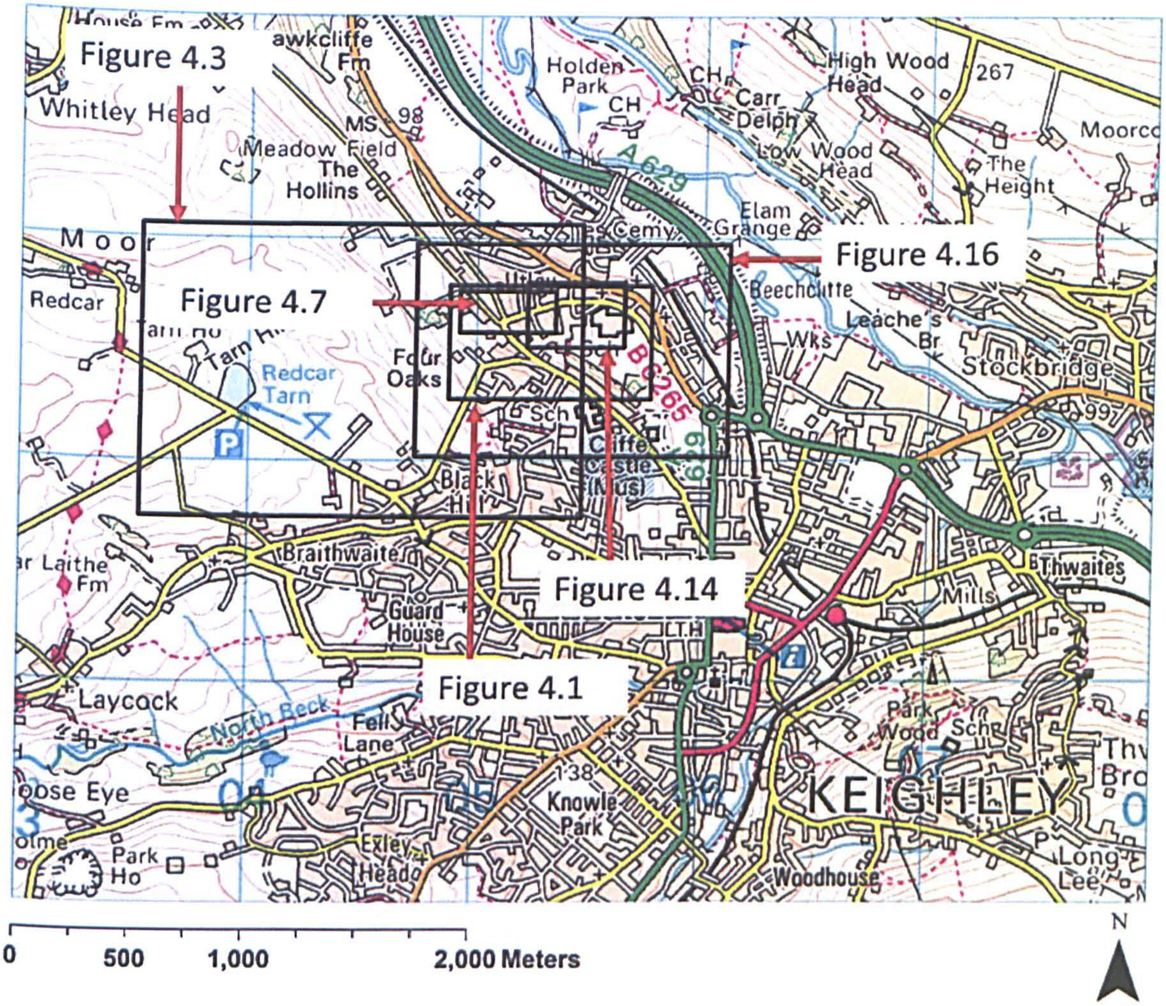

Figure 7.7: Location map for figures in Chapter 4.

7.6. APPENDIX 6: CONTENTS OF THE CD

MODEL MANUAL

A word document with instructions on how to use the urban surface water balance model.

SWMB (Folder)

A folder containing the ESRI toolboxes that make up the urban surface water balance model. Contained in this folder is the original LiDAR DEM used in the study.