THE USE OF A RISK BASED APPROACH TO IDENTIFY THE UNCERTAINTIES ASSOCIATED WITH FLOODING OF HIGHWAY DRAINAGE INFRASTRUCTURE

By

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ABSTRACT

The strategic and local road networks are together the United Kingdom's most valuable infrastructure assets. Roads deteriorate over time as a function of traffic and the environment and must be maintained appropriately to preserve their asset value in order to help support the economy. Furthermore, well maintained roads reduce road user costs via lowering vehicle operating costs, reducing accidents, delays and litigation.

Amongst other projections, climate change indicators suggest there will be warmer wetter winters and an increase in extreme weather events such as heavy rains. Increased heavy rainfall events will adversely influence the road infrastructure and place more demands on maintenance.

The inherent risks in highway infrastructure assets and those associated with future climate predictions must be better understood and incorporated within decision support models to enable highway engineers and asset managers make better, more informed decisions regarding infrastructure maintenance.

By combining the risk management process and drainage network analysis this study explored the risks and their potential impacts within a road network. This resulted in a proposed methodology for the identification of parts of a network to be most at flood risk.

Data in respect of the risks and their probability of occurrence, for use within the model was obtained through a questionnaire completed by highway drainage engineers at various locations in the UK.

DEDICATION

For my parents:

David Michael Barnett (1948 – 1994)

Dr Patricia Barnett

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I owe a great deal of thanks to my family. Dad, although you are no longer here, I hope 'your little mate' has done you proud. Mum, you have had to endure me asking countless questions about things you did not understand, but as always you allowed me to talk out a solution. You have supported me through every real challenge I have ever had to face. Finally, Uncle John thank you for your encouragement and the countless cups of tea provided. Last, but by no means least, thank you to Shahad Al-Janabi, Dawn Hurst, and Rebecca Sindall and for their support, motivation and belief in me.

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ACCRONYMS AND ABBREVIATIONS

1D	One Dimensional Model
2D	Two Dimensional Model
3CAP	3 Counties Alliance Partnership
AADT	Average Annual Daily Traffic
BSI	British Standards Institute
CCTV	Close Circuit Television
CIRIA	The Construction Industry Research and Information Association
DCC	Derbyshire County Council
DEM	Digital Elevation Model
DfT	Department for Transport
DMRB	Design Manual for Roads and Bridges
DTM	Digital Terrain Model
EA	Environment Agency
FEH	Flood Estimation Handbook
FHRC	Flood Hazard Research Centre
FSR	Flood Studies Report
FWMA	Flood Water and Management Act
GDP	Gross Domestic Product
GIS	Geographic Information System
GMT	Greenwich Mean Time
HAMP	Highway Asset Management Plan
HAZOP	Hazard and Operability Studies
HGV	Heavy Goods Vehicle
ID	Identification Number
IDF	Intensity, Duration and Frequency
IPCC	Intergovernmental Panel on Climate Change
LA	Local Authority
LASAAC	The Local Authority (Scotland) Accounts Advisory Committee
LCC	Leicestershire County Council
LFRMS	Local Flood Risk Management Strategy
LGV	Light Goods Vehicles
LLFAs	Lead Local Flood Authorities
MADD	Manhole Additional Diameter
MCM	Multi Coloured Manual
MRM	Modified Rational Method
MTU	Mapping The Underworld
NCC	Nottinghamshire County Council
NRP	Non Residential Properties
OFWAT	The Water Services Regulation Authority
OGV	Other Goods Vehicles
OS	Ordinance Survey

PFRA	Preliminary Flood Risk Assessment
PSV	Public Service Vehicles
SWMP	Surface Water Management Plan
TRRL	Transport and Road Research Laboratory
UDRM	Urban Drainage Risk Management
UFCCC	United Nations Framework Convention on Climate Change
UKCIP	UK Climate Impacts Programme
UKCP09	United Kingdom Climate Projections 2009
UNEP	United Nations Environment Programme
URS	United Research Services
WMO	World Meteorological Organization
xref	External Reference

LIST OF NOTATIONS

a	Invert Level
A	Catchment Area
A	Cross sectional area of pipe
b	Soffit Level
B	Width of surface water channel
b_1	side slope of surface water channel
b_2	side slope of surface water channel
c	Crown Level
C_V	Volumetric runoff coefficient
d	Ground Level
D	Duration of rainfall
D	Diameter of pipe
e	margin of error
F	Frequency of rainfall
I	Rainfall Intensity
I	Impact of the event occurring
Ij	the impact of risk j in risk category RCi
j	the number of risks in risk category RCi
k_s	pipe roughness
n	manning's roughness coefficient
P	Probability of an event occurring
Pj	Pj and Ij the probability of risk j in risk category RCi
p	percentage of accuracy required (expressed as a decimal)
Q	Pipe discharge
Q_F	Pipe full discharge
Q_P	Peak Flow Rate
r	Ratio
R	Flood Risk
R_h	hydraulic radius (m)
S	Pipe gradient
T	Return Period
V	Mean velocity
V_F	Full velocity (m/s)
y	Flow depth
y1	Cover depth of pipe
y2	Depth of pipe
z	critical value
ν	kinematic viscosity

CHAPTER 1 INTRODUCTION

1.1 Background

The strategic and local road networks are together the United Kingdom's most valuable infrastructure assets; they play a vital role in the UK economy (Public Accounts Committee, 2014j). With an approximate value of £344 billion, the road networks consist of road pavements, furniture and other infrastructure, including drainage systems. England's strategic road network (4,400 miles) is the responsibility of Highways England, it includes nearly all of England's motorways; and the most important 'A' roads. The network represents about 2% of the whole road network; the other 183,000 miles of local roads are the responsibility of local highway authorities.

The importance of the road network to the UK economy is clearly demonstrated by the fact that currently approximately 60% of all freight moved within the UK is transported by road (DfT, 2015). Between 2012 and 2013, this amounted to 139 billion tonne kilometres of goods being moved within the country by GB-registered Heavy Goods Vehicle (HGVs). The average length of haul for HGVs in 2013 was 94 kilometres and has remained around this length in recent years, however, the amount moved by large rigid HGVs (over 25 tonnes) increased by over 66 % between 1990 and 2013 (Vekaria, 2015). This clear shift towards the use of larger heavier vehicles adversely impacts road surfaces and infrastructure, and consequently has maintenance implications (O'Flaherty, 2008). The trend has been for the amount of freight moved by road to broadly mirror the manufacturing output, and transport and storage output components of Gross Domestic Product (GDP). As the GDP has increased so has the amount of freight moved by road. Consequently as the GDP increased by 2.6% in 2014 this growth is expected to be reflected in a further increase in freight moved by road (Treasury, 2015). However, McKinnon (2007) considered the coupling between GDP

and freight growth was not always directly apparent and de-coupling freight growth and economic growth was a major aim of transport policy making. This view is evidenced by the period 1997 to 2004, which had a stable volume of road freight movement, a 21% rise in GDP, but only experienced a total tonne-kilometre growth of 8%. Two thirds of the decoupling being accounted for by a combination of the increased penetration of the British road haulage market by foreign operators, a decline in road transport's share of the freight market, an increase in goods manufactured abroad and real increases in road freight rates; other contributory factors included road service sector growth, and a reduction in the rate of centralization.

As roads deteriorate over time as a function of traffic and the environment they must be maintained appropriately in order to preserve their asset value. Furthermore, well maintained roads reduce road user costs by lowering vehicle operating costs, reducing accidents, delays and litigation (Robinson et al, 2008).

To this end a large amount of public money is spent on maintaining England's roads, for example in 2012 to 2013 it was £4 billion, with Highways England spending £720 million and The Department for Transport (DfT) providing £779 million towards local highway authorities' road maintenance (DfT, 2014a). The remainder was paid out of other resources by local authorities.

However much money is spent on maintenance it will not be cost effective unless road pavements are adequately drained so that water is both removed from the road surface and prevented from entering the road structure. Drainage also helps improve road safety by ensuring surface water does not accumulate on the carriageway and reduce skid resistance and visibility. It also helps ensure the structural integrity of the road by preventing water

ingress into the pavement structure. Similarly, good drainage helps ensure surface sediments and pollutants are removed by run off (O'Flaherty, 2008).

Furthermore, as recognized by Spink (2014), drainage assets are unlike any other asset in that they have the potential to cause failures and reduce the life of virtually all other asset types. It has been recognized that there is a legacy of poorly performing ageing drainage assets that can and have had tremendous effect on other assets types, with the consequent overall detrimental effect on organisational performance and system resilience. This further emphasizes the paramount need for a good maintenance regime to be in place (Lugg, 2011).

Whilst road drainage design standards help ensure infrastructure is appropriately designed (Volume 4 Section 2 of The Design Manual for Roads and Bridges (DRMB), 2011), the ever expanding number of regulations in respect of individual assets and procedures must become difficult to fully absorb by all those directly involved with managing and maintaining assets. This means that highway drainage engineers need to systematically keep abreast of current standards and guidelines to ensure each drainage asset is maintained to standard and retains functionality (Hassing et al, 2004). This includes designing them to appropriate standards, building them properly and maintaining them as necessary.

Despite the importance of drainage in relation to road safety and the prevention of structural failure, historically highway drainage has been an area which has often been neglected (Public Accounts Committee, 2014a; Lugg, 2012). This situation has very probably been exacerbated by unknown annual budgets and a lack of knowledge as to the uncertainties within a network Lugg (2012).

However, the situation is improving, and local authorities (LAs) responsible for the maintenance of infrastructure assets are gathering the inventory and condition data required for them to be managed more effectively. To this end many local authorities have produced a

Highway Asset Management Plan (HAMP). Although not mandatory, this type of plan incorporates a summary of all highway assets together with a maintenance strategy so enabling a local authority to better comply with legislation and be ready to take advantage of government initiatives which reward good asset management. A current example is the Local Highways Maintenance Challenge Fund which is open to applications from English local highway authorities outside London. Limited extra funding is available if an asset is coming to the end of its lifecycle and needs urgent repair/renewal. Bids must explain why the project has not been undertaken previously and include evidence as to asset history. Crucially bids must draw on an authority's asset management data which must be firmly evidenced (DfT, 2014b).

This task of recording all highway infrastructure (into a HAMP or otherwise) is not completed and Millership (2012) suggested it can be assumed that such plans will never be totally complete due to the logistics involved.

Unlike most other highway assets, inspections of drainage systems are inherently limited as the majority of assets are below ground; this position is compounded as the historical inventory records for highway drainage systems can be poor or non-existent (Lugg, 2012).

Despite the fact that the UK highway drainage infrastructure is designed to national standards with recognized maintenance regimes, flooding still occurs because the capacity of the drainage infrastructure can nevertheless be insufficient. This can result from inappropriate original design, inadequate maintenance, or the occurrence of higher than designed for flows of water which have resulted from changes in land use and climate. The latter has increased the frequency, intensity and duration of rainfall and associated extreme weather events (IPCC, 2007).

The flooding events of the autumn of 2000, and the summers of 2007, 2009 and 2012 are reminders of the impacts caused by flooding in part due to the failure of drainage systems (Millership, 2012). Inappropriate design, poor maintenance and the occurrence of higher than designed for flows of water may be regarded as threats, or risks, to the proper functioning of a highway drainage system and the likelihood and impact of flooding can largely be quantified in terms of such threats.

A viable approach to dealing with threats to a system is the process of risk management which is increasingly recognised as a valuable aid to supporting the decision making process within asset management (Sayers et al, 2002). Given, therefore, the inherent uncertain threats within an ageing highway asset management infrastructure and the uncertain impacts of climate change, risk management may well offer a helpful approach to facilitate the maintenance management of drainage assets. The research described in this thesis seeks to explore such a hypothesis.

1.2 Problem Definition

The threats which individually, or when combined, cause highway drainage infrastructure flooding to occur need to be identified, better understood and quantified in order to help the road drainage asset manager or engineer identify the areas of a drainage network at most risk of flooding, especially in the light of predicted climate change impacts. Where resources are scarce, and the tenet is to make best use of available public funds, this will help the highway drainage engineer allocate funds appropriately and efficiently.

1.3 Aim and Objectives

1.3.1 Aim

To address the research problem, this project explores the use of a risk based approach to better inform the decision making process used by highway drainage engineers when seeking to identify the parts of the highway drainage infrastructure at greatest flood risk.

1.3.2 Objectives

In order to meet the above aim, the research has a number of associated objectives as follows:

1. Explore the current UK design procedure for highway drainage infrastructure.
2. Examine the current maintenance procedures undertaken by highway authorities in respect of highway drainage infrastructure.
3. Explore the uncertain threats associated with highway drainage assets which may cause them to flood.
4. Explore the risk management literature to understand how risk management concepts have been used in disciplines related to that considered herein.
5. Investigate whether, and how, the discipline of risk management could provide a means which can facilitate highway drainage management.

   The framework should enable:

   - The identification of the threats which can cause flooding.
   - In relation to these threats, the quantification of the likelihood of flooding on a highway network.
   - The quantification of the effect, or impact of flooding on a road network.

6. Demonstrate the theoretical risk management framework by means of a case study using data collected from a UK LA.

1.4 Structure of Thesis

The thesis is structured into 11 chapters, a brief description of each is provided below.

Chapter 1 defines the research problem; its aim and objectives. The research problem is defined together with the advantages of the research.

Chapter 2 examines the purpose and types of highway drainage systems. The effects of increasing urbanization and the associated growth in surface runoff are considered. The importance of rainfall analysis and its relationship to estimating surface runoff are considered as it must adequately inform the design of a highway drainage system.

Chapter 3 deals with the maintenance and management issues that impact on highway drainage infrastructure. The importance of the UK road network is recognized both in monetary value and as having a direct impact on the ongoing economy of the country. Despite acceptance of this, the money and emphasis of highway expenditure has historically concentrated on road network construction; little serious consideration has been given to road maintenance. This construction - orientated approach has resulted in a now ageing road network significantly failing through lack of repair, (Public Accounts Committee, 2014j).

The need for this approach to change is recognized as is the necessity for highway infrastructure to be supported by a good asset management system maximizing the potential of the installations throughout life. The need for, and suggested contents of, a HAMP, are considered together with their current development.

The chapter also discusses the concept of a risk management framework that is applicable to any organizational problem. It reviews previous studies associated with the uncertainties within highway drainage systems, flood risk and management, the quantification of an urban drainage risk management system, and how a risk based approach has been used in other sectors.

Chapter 4 provides a summary of the existing UK climate and current rainfall patterns, and briefly examines some findings of the IPCC (2007) and the UK Climate Impacts Programme (UKCIP). The expected increase in rainfall due to climate change, and the potential impact(s) that any increase in precipitation will have on existing Intensity, Duration and Frequency (IDF) curves is discussed together with the resultant impact on highway drainage systems.

Chapter 5 examines the theoretical framework upon which the research methodology is based. The research methodology is detailed and is demonstrated by means of a case study.

Chapter 6 describes the techniques used for data collection and processing; it is structured into six parts:

- Introduction to the study area
- Site layout data
- Development of questionnaire
- Drainage Network Data
- Flood Impact
- Summary

Chapter 7 is concerned with analysing the relevant results of the questionnaire that were required for risk quantification through Monte Carlo analysis.

Chapter 8 models the uncertainties examined, and presents the MicroDrainage results of the flood flow analysis. The potential flood impact results for a variety of climate scenarios were identified.

Chapter 9 quantifies the flood impact using a cost model based on values obtained from the Multi-Coloured Manual (MCM) (2012), and maintenance values allocated by highway

drainage engineers. The probability of each flood impact occurring for all climate scenarios modelled was calculated. Distributions for both the impact and probability were assigned and a Monte Carlo simulation was undertaken to ascertain the parts of the highway drainage infrastructure at greatest flood risk.

Chapter 10 presents a discussion of the results of the research and their implications.

Conclusions and further recommendations relating to the research are shown in Chapter 11.

1.5 Benefits of Research

The outcome of this research was the development of a framework which can be used by highway drainage engineers and asset managers at the strategic and project levels of highway management. The framework can be used to identify the parts of a highway network most at flood risk and hence the location of the assets that should receive prioritized maintenance. The developed framework helps to:

1. Identify and quantify the uncertainties associated with highway drainage infrastructure.
2. Understand the implications of climate change on highway drainage infrastructure.
3. Quantify the risks, in terms of likelihood and impact, of flooding of highway drainage infrastructure.
4. Prioritize maintenance and renewal interventions for highway drainage infrastructure.
5. Understand how commercial network analysis software (MicroDrainage) can be used to help ascertain network exceedance under various climate conditions and uncertainties.
6. Help identify the sections of the highway drainage network which has the greatest impact on the overall risk/cost of flooding.

1.6 Novelty of research

The novelty of the research is associated with the development of a comprehensive novel procedure which combines a drainage network analysis model with risk management techniques to facilitate highway drainage management. Further the procedure utilized:

1. Expert opinion to help:
    a. Identify threats to drainage infrastructure flooding,
    b. Quantify the uncertainties associated with these threats.
2. Commercial network analysis software (MicroDrainage™) as the drainage network analysis model to simulate the identified uncertainties in order to ascertain the degree of flooding.
3. A novel risk-based cost model to establish the impacts of flood risk.

CHAPTER 2 DESIGN OF ROAD DRAINAGE SYSTEMS

2.1 Introduction

A fundamental aspect of road design and construction is the drainage system. The importance was originally identified in 312 BC by the Romans who identified the advantages of installing drainage ditches either side of the constructed elevated carriageway, some still survive today (Davis, 1997). Good drainage design involves finding an optimum balance between the total costs involved (investment costs and maintenance costs) when compared to the possible advantages and disadvantages of road pavement life, traffic safety, easy maintenance and wider environmental aspects (Faisca et al, 2009).

This chapter examines the components of a highway drainage system. Section 2.1 introduces the purpose of such a system and describes the effect water has on the road pavement structure and how increased urbanization adversely impacts the system. Section 2.2 examines the types of highway drainage systems used within the UK. Section 2.3 discusses the rainfall analysis aspect of the drainage design process and Section 2.4 explores how surface runoff is calculated. Section 2.5 identifies the layout and associated components of a typical drainage system and describes the design stages. Section 2.6 introduces the basics of hydraulic modelling. Section 2.7 details the software packages available to analyse drainage networks.

2.1.1 Purpose of a road drainage system

In order for a road pavement to function properly, sufficient drainage provision must be made. According to (Hassing et al, 2004) the main functions of a road drainage system are to:

1. Capture as much surface and ground water flowing towards the road as possible.
2. Transfer water in a controlled way across the road alignment.

3. Carry storm water from the road surface to outfalls.
4. Control the water table level in the subgrade below the road.

2.1.2 Effect of water on the highway

A poorly drained road is a danger to all road users, water on the highway presents many possible adverse consequences to users, including:

1. Friction between tyres and the road surface is reduced; consequently if surface water remains on the carriageway moving vehicles are more likely to skid and the braking distances required to stop increases with speed (Olesen and Rollings, 2012a).
2. Loss of traction occurs at higher speeds resulting in aquaplaning, particularly at exit lanes on high-speed roads, controlled junctions, bends and roundabouts. Full aquaplaning occurs when water depth is greater than 4mm, partial aquaplaning occurs when water depth is 2.5mm, these depths are a function of the surfacing material used on the road (O'Flaherty, 2008; Olesen and Rollings, 2012a; t).
3. In freezing conditions ‘black ice’ can form over the surface; this also increases the risk of skidding (O'Flaherty, 2008).
4. Ponding occurs on the road surface when water cannot drain adequately. Frequently this results from inadequate or blocked drains, or insufficient gradient in the road design to allow water to run to the discharge point.
5. Spray coming from other vehicles affects driver visibility, making road markings and lines difficult to see, if the spray is bad, lines can become invisible due to the accumulation of surface water. Cyclists and pedestrians are in danger as they get splashed by passing vehicles, an event that may cause a lapse in concentration (Olesen and Rollings, 2012a).
6. If water enters the road structure either by surface penetration or groundwater infiltration, the strength and deformation resistance of the pavement and subgrade is

weakened; this increases the susceptibility of the road to more damage from road failure and traffic (Willway et al, 2008b; Willway et al, 2008a)

7. Poor drainage encourages weed and algae growth adding to the disintegration of the surface and increasing consequential maintenance costs (Olesen and Rollings, 2012a).

Figure 2.1 shows an example of water induced disintegration of the surface and subsurface when a large section of road between Moffat and Selkirk (A708) in Dumfries and Galloway collapsed in 2013 as a result of heavy rainfall running off the surrounding hills (Harrison, 2013).



Figure 2.1 - Road failure on A708 (Harrison, 2013)

2.1.3 Legal and environmental aspects of drainage

The Highways Act 1980 (Section 100 and 101) enables the construction, diversion or filling of drains and ditches when necessary to preserve the highway. This also refers to drains on adjacent land which could endanger the highway. The relevant highway authority can fill in a road side ditch if the adjoining land owner agrees, if there is no agreement then the ditch may be piped then backfilled. All highway authorities must ensure they drain their highways and do not allow water to flood onto adjoining land (Olesen and Rollings, 2012a).

2.1.3.1 The Water Regulatory Authority

The Environment Agency (EA) is the water regulatory authority in England and Wales. It has wide ranging responsibilities, which cover water resources, water pollution, water recreation activities, conservation of the environment around watercourses, inland waterway navigation, flood defences and fisheries. If a road scheme may impact any EA interest then consultation must commence at the earliest stage and continue until completion. Discharge of any pollution into controlled waters whether accidental or deliberate is an offence. If there is any need to discharge into controlled waters formal consent from the EA is required. Further information is contained within DMRB HD 216/06 (2006).

2.1.4 The effects of urbanization on drainage

The increase in human population has affected the movement of rainwater. When rainwater falls on land, some evaporates to the atmosphere or transpiration by vegetation occurs; some penetrates the surface becoming groundwater, some runs off the surface. The magnitude of each depends on the type of land surface, and varies with storm duration and the amount of antecedent rainfall; surface runoff increases with ground saturation. Consequently, the volume of water reaching a river during and after rainfall increases; as illustrated in

Figure 2.2 (Ruby, 2011). Over recent years increased urbanization has adversely impacted on the natural water cycle (Butler and Davies, 2011).

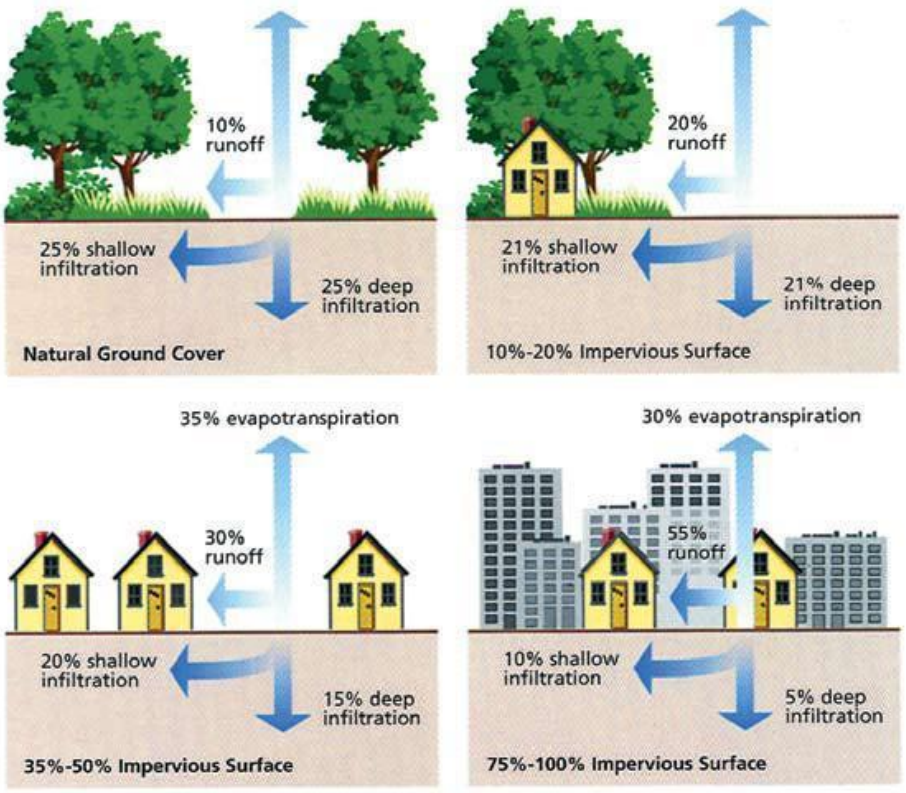


Figure 2.2 - Effect of urbanisation on the fate of rainfall (Ruby, 2011)

2.2 Types of road drainage systems

The type of drainage system installed when constructing a road depends on several factor; road classification, traffic volume, location (rural or populated), the susceptibility of the groundwater and nearby streams, rivers and lakes (Hassing et al, 2004; Faisca et al, 2009)

Whilst surface drainage primarily aims to ensure a road is fully functional, subsurface drains predominately aim to preserve structural integrity (O'Flaherty, 2008). The Design Manual for Roads and Bridges (DMRB) accordingly classifies surface drainage and subsurface drainage (DMRB HA37/97, 1997).

Examples of subsurface drainage include; filter drains (Figure 2.3) and fin drains which are typically situated adjacent to the road allowing runoff to flow to the drain, then percolate the granular material and enter the drainage pipe. CIRIA, 1994 estimated that 25% of all major roads in the UK remove their surface water this way.



Figure 2.3 - Filter Drain (Barnett, 2013a)

This research solely concentrates on surface drainage installations, namely; kerb and gully, combined kerb and drainage blocks, surface water channels and linear drainage channels (sections 2.2.1 to 2.2.4).

2.2.1 Kerb and Gully

The kerb and gully is mainly used in urban areas and rural embankment conditions. Surface water flows over the pavement to a kerb positioned at the road edge, it is collected in gullies connected to subsurface pipes that carry it to the closest outlet point. Subsurface pipes are normally made of concrete or ceramic material and have watertight joints to prevent leakages (The Department of the Environment, 2004). A gully is made from either a clay or concrete chamber, water enters vertically through a grating with bars (Figure 2.4) or laterally through an open side entry (Figure 2.5). Figure 2.6 shows a typical cross section.



Figure 2.4 - Vertical grating (Barnett, 2013a)



Figure 2.5 – Side entry (Barnett, 2013c)

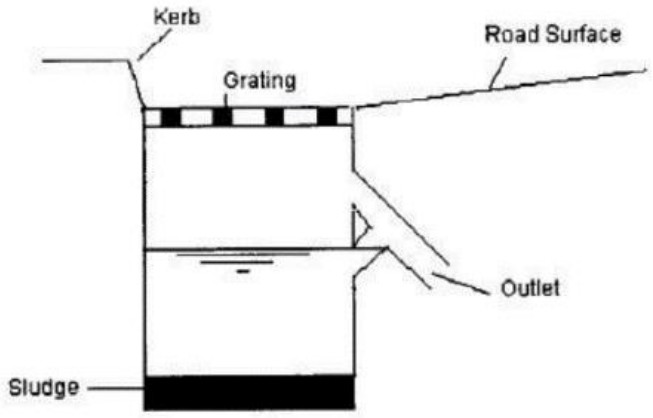


Figure 2.6 – Typical gully pot cross section (Butler and Davies, 2011)

2.2.2 Combined kerb and drainage blocks

Developed in the 1980s these drainage blocks are illustrated in Figures 2.7 and 2.8. These pre-cast concrete units either comprise a top and bottom section or are an all in one section (O'Flaherty, 2008). When blocks are arranged together a continuously closed internal channel section is formed. Part of the block projects above the road surface and looks like a wide kerb, the preformed hole on the front face allows water to flow into the internal cavity and out through the nearest outfall (The Department of the Environment, 2004).



Figure 2.7 - Combined kerb system
(Hynds Pipe Systems Ltd, 2014)



Figure 2.8 - Individual 'Beanie' Block
(Hynds Pipe Systems Ltd, 2014)

2.2.3 Linear drainage channels

Linear drainage channels, as illustrated in Figure 2.9 and 2.10 are precast or formed in situ; they are set level with the road surface and have conduits below their surface allowing surface water to enter through slots. Linear drainage channels are not recommended on shallow gradients as they are prone to maintenance difficulties (The Department of the Environment, 2004). However, the main advantage of linear drainage channels is their ability to remove a convergence of rainfall or snow melt on a carriageway to the U-shaped channel

(Figure 2.10), reducing the length of time water remains on the carriageway and consequently avoiding a short period of water stagnation (Wang and Chen, 2012).



Figure 2.9 - Linear drainage channel

(ACO Technologies PLC, 2014)



Figure 2.10 - ACO Road Drain 100mm

(ACO Technologies PLC, 2014)

2.2.4 Surface water channel

Developed in the 1970s for dual carriageways in a built up area, surface water channels are typically made from precast concrete or made in-situ. The rounded or triangular sections are set against the edge of the road surface or level with the road surface at the central reservation (O'Flaherty, 2008). Surface water channels, as illustrated in Figure 2.11 and 2.12, are quickly constructed and easy to maintain; and are relatively inexpensive due to their long lengths. Outlets are spaced as required and can be connected with existing watercourses. If roads have flat longitudinal gradients then the channel size needs reducing; regular outfalls or parallel longitudinal carrier pipes need installing to allow frequent discharge (The Department of the Environment, 2004).

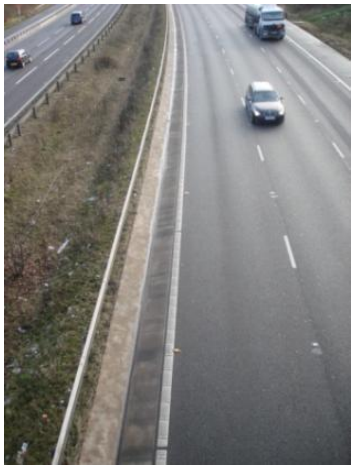
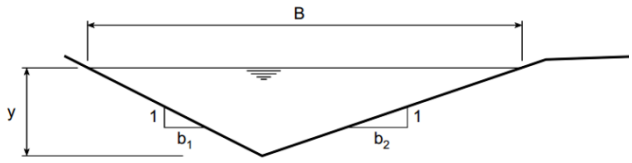


Figure 2.11 - Surface water channel near J28 of M1 (Barnett, 2013d)



Where:
B = Width of channel at water level, y = Flow depth,
b_1 and b_2 = side slope of channel

Figure 2.12 - Surface water channel cross section (triangular) (DMRB HA37/97, 1997)

2.3 Rainfall Analysis

2.3.1 Introduction

The need to predict and record rainfall has long been recognized as crucial to the design, analysis and operation of a drainage system. Observations and rainfall records date from 1766 in the UK. Although records were originally made in varying ways and rainfall was not uniformly measured; records do allow for a derivation of relationships between rainfall event properties particularly intensity, duration and frequency. Rainfall is now measured by either using a rain gauge or radar (Jenkins et al, 2009).

2.3.2 Intensity Duration Frequency Relationships

As discussed in Section 2.1.1, drainage systems are designed to collect and convey surface runoff to prevent flooding; consequently knowledge of local rainfall patterns assists in the design of a network. Network design utilizes the well-established relationship between intensity, duration and frequency (IDF). Rainfall intensity (I) (mm/hr) is defined as the amount of precipitation falling in a given time period (Brommer et al, 2009). Rainfall duration (D) is defined as the time period (minutes) over which rainfall maintains a given

intensity or exceeds a given intensity (Boucher, 2010). The frequency of rainfall (F) (return period) is the likelihood or probability of an event with a specified intensity and duration. An annual maximum rainfall event has a return period of T years if it is equalled or exceeded in magnitude once, on average, every T years. Therefore, rainfall events occurring on average twenty times in 100 years have a probability of being equalled or exceeded of 0.2, and a return period of 5 years. The annual maximum storm events are usually used to establish the return period as currently it is believed that the largest event in one year is statistically independent of the largest event in any other year. IDF curves are used to determine the critical mean rainfall intensity in terms of the duration of this mean intensity (Sanderson, 2010). Figure 2.13 depicts a typical IDF curve.

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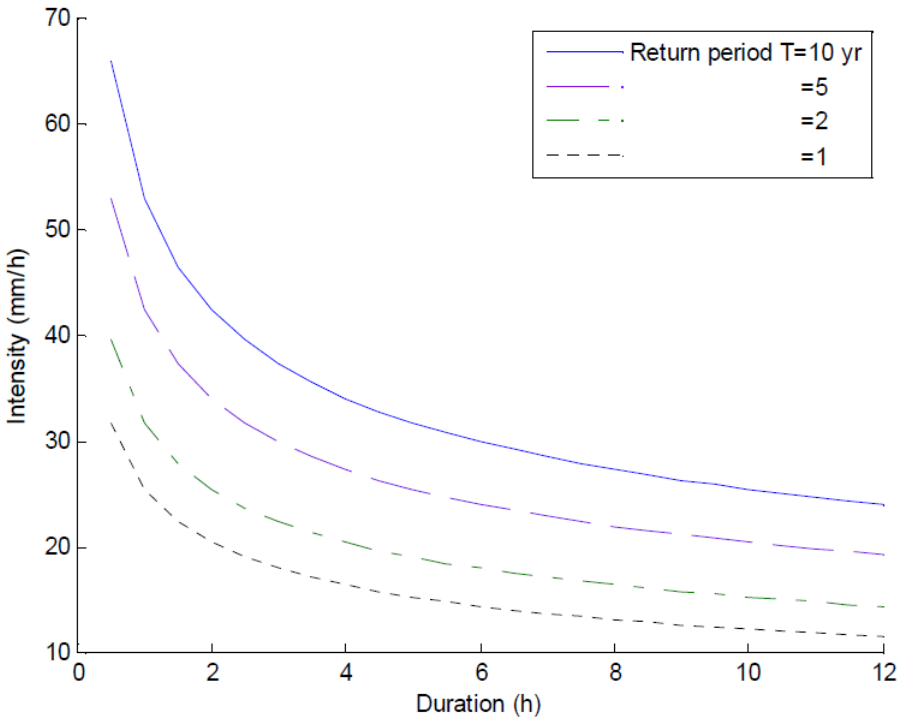


Figure 2.13 - Typical intensity-duration-frequency curves (Butler and Davies, 2011)

The Flood Studies Report (FSR) (1975) and the Flood Estimation Handbook (FEH) (1999) each contain a methodology to create an IDF relationship for use in relation to any ungauged sites within the UK. Sections 2.3.3 and 2.3.4 briefly discuss both methods.

2.3.3 Flood Studies Report (FSR)

The FSR contains a methodology which uses the standard notations when specifying rainfall information. MT-D represents the depth of rainfall (mm) occurring for duration (D) with a return period (T) years. The duration can be specified in hours or minutes, if in hours it starts on the hour, if in minutes at any minute within the hour, if in days it begins at 9am Greenwich Mean Time (GMT) (FSR, 1975g; a; k; d; i). Further information regarding the procedure used to analyse and present the data of the FSR can be found in Volumes 1 and 2 of the FSR (FSR, 1975a; d).

2.3.4 Flood Estimation Handbook (FEH) 1999

This was created to provide an assessment of flood risk which better maximized public protection, it superseded the FSR (FEH, 1999c; a). The FEH combined research on rainfall and flood frequency estimation; it provided updated procedures for application in river and flood defence and used a more recent dataset when compared to the FSR (MicroDrainage, 2012a). However, rainfall frequency estimations using the FSR approach did not encompass all regional and local variations, this can lead to under or over designing in specific areas. The FEH was designed to overcome this problem (MicroDrainage, 2012e).

Allitt (2001) compared 7 UK sites and found that for a 30-year return period event the FSR had always underestimated the 24 hour rainfall depth and occasionally underestimated shorter duration events. A design based on the 30 year FSR storm may, therefore, only provide a less than or equal to 20 year protection.

Butler and Davies (2011) identifies three main limitations of the FEH:

1. Not advised for use on heavily urbanised catchments.
2. Not applicable to catchments of area less than or equal to 50ha.
3. Only utilizes storm duration data ranging from 1hr to 8 days (shorter durations can be extrapolated).

2.4 Estimating Surface Runoff

A fundamental aspect of highway drainage system design is the need to ascertain the runoff entering the system so that adequate storage can be provided within the system. Three factors affect runoff from a catchment namely;

Topographical factors

Surface runoff is greatly influenced by:

The size of catchment

- Catchment shape – rain falling on a circular or square catchment may well concentrate more quickly than in a long and narrow catchment.
- Catchment slope – water flows downhill. The steeper the slope within a catchment the greater the water velocity and potential for flooding.
- Infiltration within catchment - the geology of the catchment influences runoff, as the infiltration rate of a soil decreases as the ground becomes more saturated.
- Attenuation (dips and depressions, puddles and natural lakes) have the effect of reducing the runoff from a catchment (Balmforth et al, 2006; Butler and Davies, 2011; Federal Republic of Nigeria, 2013; O'Flaherty, 2008)

Developmental influences

Land use significantly influences run off. Potential developments within a catchment area need consideration when predicting future runoff as does the attenuation provided by future reservoirs and dams (Balmforth et al, 2006; Butler and Davies, 2011; Federal Republic of Nigeria, 2013; O'Flaherty, 2008).

Climatological factors

The runoff from a catchment depends on the, intensity, duration, size of storm, direction of travel and velocity of the rainfall event. The potential of an increase in extreme weather such as heavy rain on surface drainage systems is discussed in Chapter 4 (Balmforth et al, 2006; Butler and Davies, 2011; Federal Republic of Nigeria, 2013; O'Flaherty, 2008). Table 2.1 shows a summary of 11 methods used to determine runoff volumes and estimate the peak flow rate. Further information relating to each method can be found using the references provided within Table 2.1. The most commonly used methods in the UK are; the Modified Rational Method (MRM), The Transport Road and Research Laboratory (TRRL) Method and Institute of Hydrology Report No. 124 (Butler and Davies, 2011; Russell, 2013; Bache, 2013; Boyack, 2013; Daniels, 2013; Green, 2013; Wells, 2013; Doorman, 2013; Millership, 2013).

Table 2.1- A summary of 11 methods used to determine runoff volumes and estimate the peak flow rate, adapted from (Balmforth et al, 2006).

	Method	Observations	See Section	Reference
1.	Flood Studies Report (FSR), 1975 *Predicts peak flow*	• Parameters are derived from individual catchment characteristics. • Large dataset used to establish the formula.	2.3.3	(FSR, 1975g; a; k; d; i)
2.	Flood Estimation Handbook (FEH), 1999 *Predicts peak flow including hydrograph prediction*	• Needs expert interpretation. • Data set relating to small catchments is not very different to FSR data set. • Needs the related to ascertain the catchment parameters. • Digitally based with digitally pre-defined catchments.	2.3.4	(FEH, 1999c; a)
3.	The Modified Rational Method *Predicts peak flow*	• Used extensively for urban runoff, rarely used for rural runoff. • Need to estimate the runoff coefficient and a calculated time to peak.	2.4.1	(Balmforth et al, 2006; Butler and Davies, 2011; Jiapeng et al, 2003; Watts and Hawke, 2003; Young, 1973; Drainage Services Department, 2013)
4.	The Transport Road and Research Laboratory (TRRL) Method. *Predicts peak flow*	• Parameters easily derived from catchment characteristics. • Correlated against catchment characteristics. • Useful for clay based catchments.	2.4.2	(Balmforth et al, 2006; Butler and Davies, 2011; O'Flaherty, 2008; Young and Prudhoe, 1973; Drainage Services Department, 2013; Kouvelis and Armstrong, 2004)
5.	Institute of Hydrology Report No. 124 *Predicts peak flow*	• Correlation method for small catchments. • Parameters easily derived from catchment characteristics. • No catchment "slope" function. • ADAS and FSR data set for catchments up to 25 km².	2.4.3	(Marshall and Bayliss, 1994; Balmforth et al, 2006; Butler and Davies, 2011)

6.	Report 345 / MAFF Report 5 – (Agricultural Development and Advisory Service (ADAS), 1980). *Predicts peak flow*	• Correlation method for small catchments. • Parameters easily derived from catchment characteristics. • Aimed at defining agricultural land drainage. • Small data set for catchments up to 30 ha.		(Balmforth et al, 2006; ADAS, 1980)
7.	FSSR 6 – Flood prediction for small catchments (IOH, 1978). *Predicts peak flow*	• Correlation method for small catchments. • FSR data set for catchment 50 ha to 25 km² are used. • Parameters are easily derived from catchment characteristics. • Focused on small catchments, minimal improvement on the standard FSR equation.		(Balmforth et al, 2006)
8.	FSSR 16 – (IOH, 1985). *Volume runoff prediction*	Applicable to all catchments. Simple method, only applicable to extreme rainfall.		(Balmforth et al, 2006)
9.	Poots & Cochrane – (1979) *Predicts peak flow*	• Very similar to FSSR 6. • Produced for small catchments		(Balmforth et al, 2006; Poots and Cochrane, 1979)
10	The SCS Method (1985 to 1993) *Predicts peak flow*	• Requires the assessment of a curve number based on vegetation and soil type. • Takes account of increasing soil saturation. • An empirical method well used in USA and New Zealand • Rarely used in UK.		(Balmforth et al, 2006; SCS, 1985; Kouvelis and Armstrong, 2004)
11.	FEH – (IOH, 1999) *Volume runoff prediction*	• Allows for catchment wetness and general use for all rainfall. • Simple to use.		(Balmforth et al, 2006)

2.4.1 Modified Rational Method (MRM)

This is a simplified deterministic method of relating rainfall intensity and catchment characteristics to obtain an estimate of surface runoff. It has formed the basis of most road drainage designs in the past, 0'Flaherty (2008); adjustments are possible in respect of larger catchment areas. In the UK this method (MRM) is recommended by the Wallingford Procedure (Watts and Hawke, 2003; Young, 1973; Jiapeng et al, 2003). The method is widely used internationally, having formed the basis of the design manuals in several countries, for example (Federal Republic of Nigeria, 2013; Austroads Ltd, 2013; Jiapeng et al, 2003; O'Flaherty, 2008; Drainage Services Department, 2013). It is accurate for catchment sizes up to 150 ha.

Peak rate runoff (Q_P) in a given area is related to average rainfall intensity and is expressed as:

$$Q_P = 3.61 C_V i A_i \quad (2.1)$$

Where: Q_P = Peak Flow Rate (l/s), C_v = Volumetric runoff coefficient, I = average rainfall intensity (mm/h) and *A* = Catchment area (ha).

2.4.1.1 Volumetric runoff coefficient (Cv)

This is the proportion of rain falling on the catchment area that appears as surface runoff in the drainage system. The coefficient C_v varies depending on whether the whole catchment is being considered, or just the impervious areas alone. A value of 0.75 is usually used within Equation 2.1, the Wallingford Procedure, Volume 4 states: 'An extensive study of the runoff data from sewered urban catchments showed that the volume of runoff was related to the impervious area, the soil type and the catchment wetness. An approximate result may be obtained by assuming that runoff derives from a proportion of the impervious area (paved and

roof), the proportion varying according to soil type. On this basis the overall average value of Cv is about 0.75, ranging from 0.6 on catchments with rapidly-draining soils to about 0.9 on catchments with heavy soils'.

2.4.1.2 Rainfall Intensity

In the UK this is calculated either using FSR/FEH method or by creating site specific IDF curves.

2.4.1.3 Catchment area

The area that receives the rainfall which then flows into the network; it can be pervious or impervious.

2.4.1.4 Limitations

The method is uncomplicated, very widely used and suitable for initial approximations in most situations, and appropriate for full design in catchments of less than 150ha. However, it does not produce a hydrograph of flow against time. The method is based on the following assumptions (Butler and Davies, 2011):

1. The rate of rainfall is constant throughout the storm, and uniform over the whole catchment.
2. Catchment imperviousness is constant throughout the storm.
3. The contributing impervious area is uniform over the whole catchment.
4. Sewer flow at constant (pipe full) velocity throughout the time of concentration.

2.4.2 The Transport and Road Research Laboratory (TRRL), hydrograph method

As the Rational Method does not produce a hydrograph of flow against time, other methods allowing for the production of hydrographs have been developed. This conceptual method comprises a set of methods and models, and relies on a mathematical representation of the critical processes by which rainfall on a catchment is transformed to runoff from the catchment. It is used with a design rainfall hyetograph, specifying the time distribution of rainfall over a catchment. A runoff hydrograph then computes the variations of runoff over time; this allows for peak flow, time of peak, and the associated volume to be calculated.

The hydrograph method, however, assumes a linear flood wave through the catchment with no account being made for any storage effects. It has been and can be adapted for use in different parts of the world to reflect different drainage conditions including for use in tropical conditions; for example, many African countries, the USA and Australia. The major changes incorporated flow from unpaved areas, as this contributes significantly to run-off.

2.4.3 Institute of Hydrology Report No124

It can be necessary to estimate runoff for an undeveloped greenfield site, Balmforth et al (2006) reviewed 11 different approaches (see Table 2.1) and compared their performance, concluding that no one method was correct with the rest incorrect, but added the adjunct that The Institute of Hydrology Report No124 (Marshall and Bayliss, 1994) was good practice for use on small rural catchments, with an adjusted regression equation calculating the mean annual flood. The three most significant variables were found to be AREA, SAAR and SOIL. This method remains widely used in the UK, (Marshall and Bayliss, 1994; Balmforth et al, 2006; Digman et al, 2012).

The following equation was developed to predict the mean annual flood ($QBAR_{rural}$):

$$QBAR_{rural} = 0.00108 \times AREA^{0.89} \times SAAR^{1.17} \times SOIL^{2.17}$$

Where: $QBAR_{rural}$ = mean annual flood for small rural catchments (m^3/s), AREA = catchment area (km^2), SAAR = standard average annual rainfall (mm) between 1941 and 1970, SOIL = soil index, calculated as shown in CIRIA C635, p235. Each of the previous methods was appropriate for use within the research, but the MRM was chosen as it did not necessitate expertise in hydrology.

2.5 Drainage system components and layout

2.5.1 Introduction

A drainage system is made up of three components; inlet, carrier and outlet, Figure 2.14 illustrates an example of these components. The inlet to the system in the example below is a gully, and the gully connector and main pipe are carriers; this is repeated across the whole network. Manholes are positioned at various points throughout the network as access points and to help with storage.

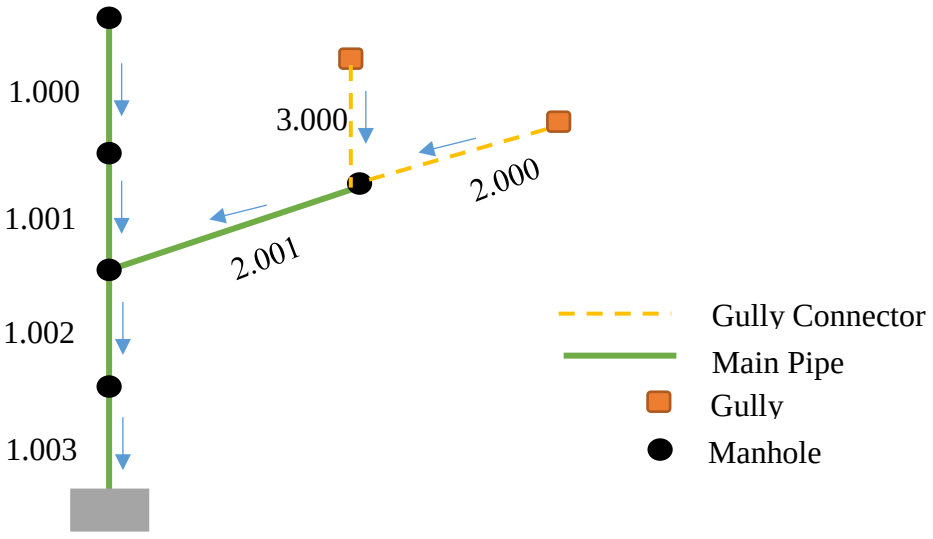


Figure 2.14 - Typical system layout and components (MicroDrainage, 2012a)

2.5.2 System Components

2.5.2.1 Gully Inlets

Gullies allow surface runoff to exit roads and other paved areas; they are always constructed at low points in a road and spaced along the road channel near the kerb. Typically a gully is installed every 200m^2 of impervious area. The top of a gully consists of grating, to help reduce larger debris entering the lower gully pot which collects smaller debris. Precast concrete gully pots are not reinforced but must conform to BS5911-6:2004. Normally gullies must not to be installed near pedestrian crossings, for safety reasons. If this is unavoidable then a pedestrian friendly 'mesh' covered gully must be installed. The number, spacing and size of gullies combine to determine the speed and amount of runoff during storm events and the degree of surface ponding; their installation is governed in DRMB (Highways England102/00). Figures 2.4 to 2.6 provide an example of a typical gully inlet system.

2.5.2.2 Pipes

Pipes are hollow cylinders or tubes used to convey water, they are made from a variety of materials for example; clay, concrete, PVC-U and other polymers. MCHW1 (2008) documents a range of pipes of different material properties suitable for highway drainage works. MCHW3 (2008) provides details of the trench and bedding associated with surface water drainage. Standard pipe details are shown in Figure 2.15 and further definitions are provided in Table 2.2.

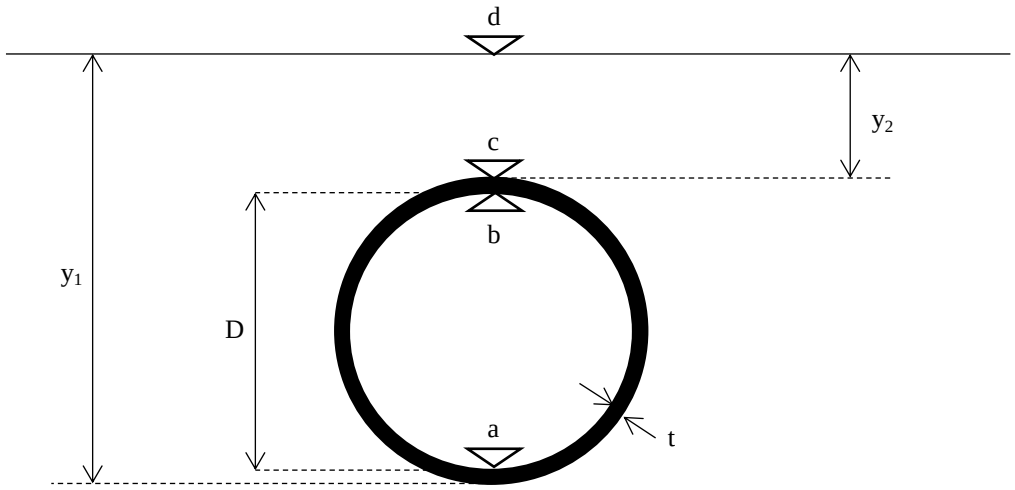


Figure 2.15 – Standard pipe detail definitions

Where: a = invert level, b = soffit level, c = crown level, d =ground level, D = internal diameter of pipe (mm), t = pipe wall thickness (mm), y_1 = depth of pipe and y_2 = cover depth of pipe.

Notation	Description	Definition
a	invert level	The vertical position of a pipe is defined by its invert level (IL). This level relates to the lowest point on the inside of a pipe
b	soffit level	This level relates to the highest point on the inside of a pipe
c	crown level	This level relates to the highest point on the outside of a pipe
d	ground level	The level of the ground surface

Table 2.2 - Pipe level definitions

2.5.2.3 Manholes

Manholes provide an access point from which a pipe run can be inspected and cleaned. In a sewer system they are deeper (greater than 1m) than inspection chambers and wide enough for a person to enter. Spacing is increased to 200m if human access is possible depending on the size of sewer and angles of the various inlets (Olesen and Rollings, 2012a). Usually made of precast concrete (BS EN 5911-3: 2002), the frames and covers are defined by BS EN 124: 1994, an example of a typical precast manhole is shown in Figure 2.16.

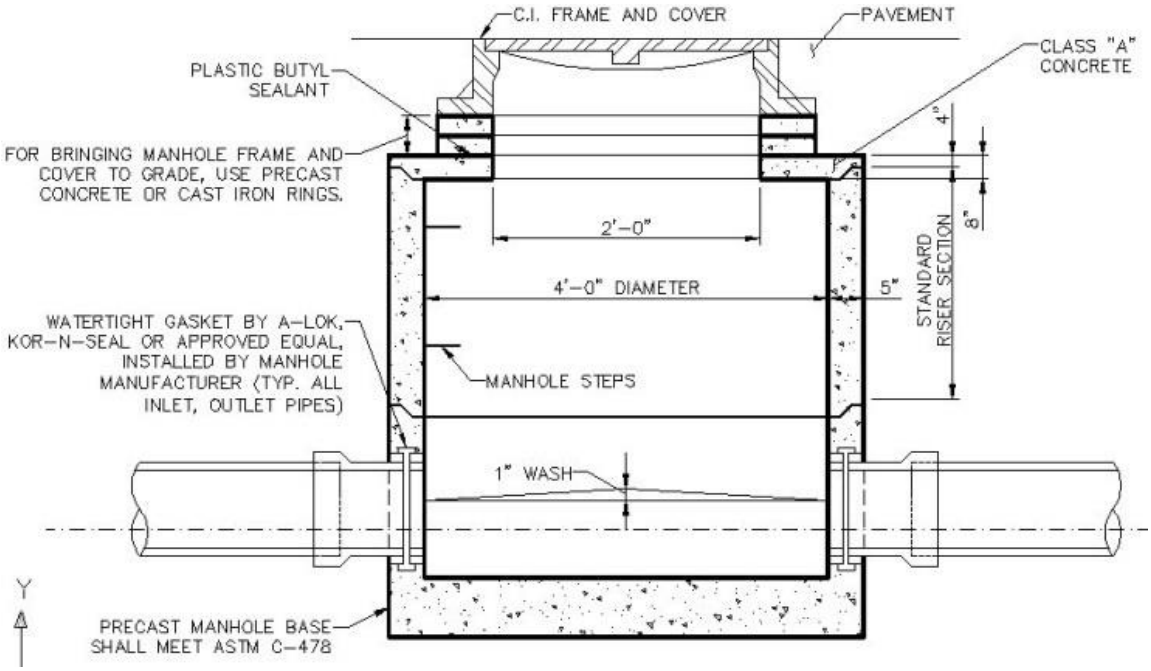


Figure 2.16 - Standard precast manhole (Sewers for Adoption 7th Edition, 2012)

According to Butler and Davies (2011); Sewers for Adoption 7th Edition (2012) manholes must be built:

1. At every change of direction/alignment and gradient;
2. At a maximum distance of 100m
3. At the head of each highway drain;
4. At every change of pipe diameter;
5. At every junction of two, or more, highway drains.

Although Sewers for Adoption 7th Edition (2012) states that manhole spacing cannot exceed 100m, the maximum permitted length of an individual pipe must not exceed 45m.

2.5.2.4 Ventilation

All urban drainage systems need to be ventilated, especially in respect of urban and combined sewers. This helps prevent the formulation of explosive and toxic gases (Butler and Davies, 2011).

2.5.3 Design of system

2.5.3.1 Stages

The recognized UK design procedure for highway drainage infrastructure using the modified rational method is illustrated in Figure 2.17.

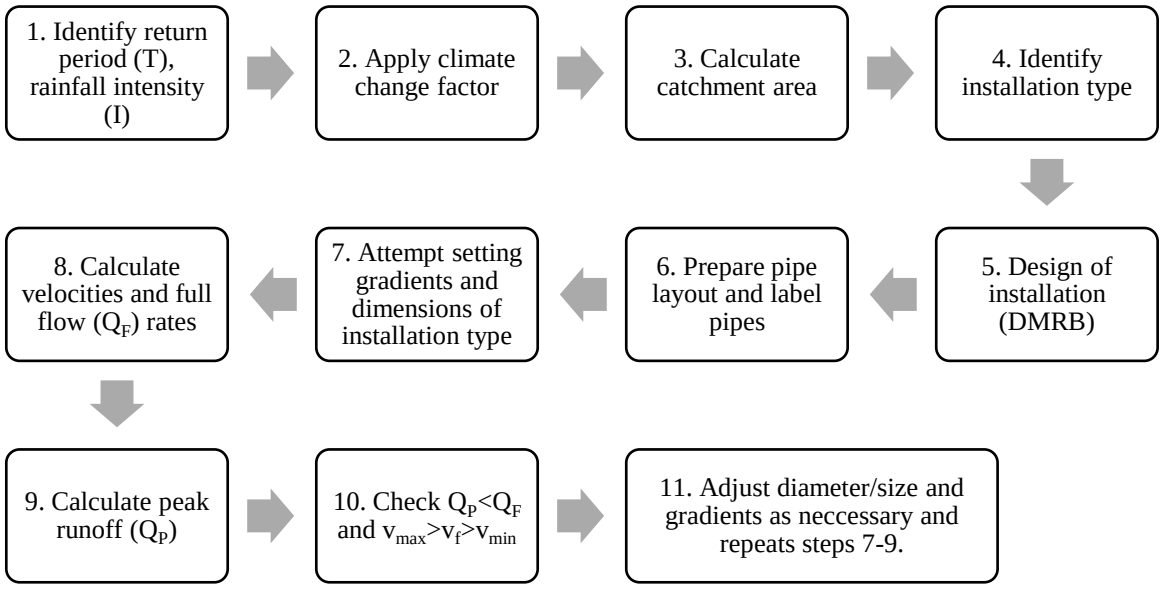


Figure 2.17 - Drainage Design Procedure (based on (Butler and Davies, 2011))

The current standard practice in the UK:

- 1 year return period for steeper schemes or schemes within rural areas.
- 2 year return period for flatter schemes or schemes within residential/city centres, industrial and commercial areas.
- 5 year return period is used for any scheme where properties are in vulnerable areas which would be exposed to substantial flood damage.
- 30 year return period – the system must be designed not to flood, however the system can surcharge above the pipe soffit.
- 100 year return period – the system must be designed so flooding will not cause any property damage, temporary flooding needs retaining on site through attenuation features, for example using Sustainable urban Drainage Systems (SuDS) (Balmforth et al, 2006; Butler and Davies, 2011; BS EN 752:2008, 2008; Sewers for Adoption 7th Edition, 2012).

2.5.3.2 Incorporating climate change

DRMB 33/06 recommends the rainfall intensities used in calculating design storms in the UK must allow for climate change. This is accomplished by adding a factor of twenty percent to rainfall intensities, this percentage factor is widely accepted internationally, for example Federal Republic of Nigeria (2013); (Drainage Services Department, 2013; Austroads Ltd, 2013).

2.5.3.3 Sewers for adoption

New residential areas usually have the drainage in relation to buildings built by the developer, they are usually adopted by the local highways authority and relevant water and waste water authority. A set of design and construction guidelines Sewers for Adoption 7th Edition (2012) covers this process.

Sewers for adoption provide:

1. Engineering specifications
2. Standard details
3. Advice as to design and construction
4. A form of agreement laid down by Section 104 of the Water Industry Act 1991 (Sewers for Adoption 7th Edition, 2012).

2.6 Hydraulic Modelling

Hydraulics is also fundamental to the design of drainage systems to ascertain the most appropriate size of the system components (Butler and Davies, 2011). The basic and relevant equations are discussed below and further details are found in Hamill (2006) and Butler and Davies (2011). In hydraulics there are two main categories of flow; pipe flow and open-channel flow. In pipe flow the liquid flows in the pipe under pressure and always fills the cross sectional area of the pipe. Open channel flow occurs when liquid flows in a channel by gravity. In reality, drainage systems are a combination of the two categories (MicroDrainage, 2012a). The discharge (Q) (m^3/s) of a pipe is calculated using Equation 2.2 where A is the cross sectional area of the flow and V is the mean velocity (m/s).

$$Q = V A \tag{2.2}$$

The velocity of the flow is normally calculated using either Manning's or Colebrook White's equation. The hydraulic performances within pipes are highly dynamic and nonlinear. The steady flow within a pipe can be determined using Manning's equation under free surface condition:

$$V = \frac{1}{n} R_h^{2/3} S^{1/2} \tag{2.3}$$

The Colebrook White equation is used to calculate full pipe flow:

$$V = -2\sqrt{2gSD}\ \log\left(\frac{k_s}{3.7D} + \frac{2.5\nu}{D\sqrt{2gSD}}\right) \tag{2.4}$$

Where:

V = average velocity (m/s)

R_h = hydraulic radius (m)

D = diameter of pipe (m)

ν = kinematic viscosity

n = manning's roughness coefficient

S = hydraulic gradient

k_s = pipe roughness

The roughness of the pipe (k_s) depends on the material of construction and its age, as age increases research suggests pipe roughness may increase due to the accumulation of various elements around the internal surface of the pipe, however, any increase does not occur at a uniform rate and is dependent upon the sedimentation composition (Hamill, 2006). Figure 2.18 illustrates the recommended k_s for a variety of pipe materials and condition. Tables for use in the hydraulic design of pipes, sewers and channels are available to highway drainage

engineers to ascertain the velocity, associated discharge rate, for a given $k_{s,}$ pipe diameter and pipe gradient, Figure 2.19 shows an example of a table for $k_{s,}$ = 0.003mm (Wallingford and Barr, 2006). Butler and Davies (2011) state '…where existing pipe conditions are unknown a value of k_s =0.6 mm is suggested for storm sewers'. This value is similarly augmented by (Sewers for Adoption 7th Edition, 2012). Further information regarding the principles of hydraulics can be found in (Hamill, 2006).

Classification ('Good' and 'Normal' assumed new and clean unless otherwise stated)	Suitable values of k_s (mm)		
	Good	Normal	Poor
Smooth materials (pipes)			
Drawn non-ferrous pipes of aluminium, brass, copper, lead etc, and non-metallic pipes of Alkathene, glass, perspex, PVC-U[#] etc	--	0·003	--
Asbestos-cement	0·015	**0·03**[#]	0·06[#]
Metal			
Spun bitumen or concrete lined	--	0·03	--
# Cast iron, epoxy lining, coupling joints	--	**0·015**	0·03
# Ductile iron, Polyethylene lining, push-fit joints	--	**0·06**	0·15
# Ductile iron, Polyurethane lining, push-fit joints	0·015	**0·03**	0·06
Wrought iron	0·03	0·06	0·15
Rusty wrought iron	0·15	0·6	3·0
Uncoated steel	0·015	0·03	0·06
# Rusty steel	--	0·15	0·3
# Steel, epoxy lining, push-fit joints	0·03	**0·06**	0·15
Galvanised iron, coated cast iron generally[#]	0·06	0·15	0·3
Uncoated cast iron	0·15	0·3	0·6
Tate relined pipes	0·15	0·3	0·6
152mm×51mm corrug'd plate, unpaved circular pipe, running full[22]	50	60	--
76mm×25mm corrug'd plate, unpaved circular pipe, running full[22]	25	30	--
Old tuberculated water mains as follows:			
Slight degree of attack	0·6	1·5	3·0
Moderate degree of attack	1·5	3·0	6·0
Appreciable degree of attack	6·0	15	30
Severe degree of attack	15	30	60
(Good: up to 20 years use; Normal: 40 to 50 years use; Poor: 80 to 100 years use)			
Wood			
Wood stave pipes, planed plank conduits	0·3	0·6	1·5
Concrete			
# Prestressed	0·03	0·06	0·15
Precast concrete pipes with "O" ring joints	0·06	0·15	0·6
Spun precast concrete pipes with "O" ring joints	0·06	0·15	0·3
Monolithic construction against steel forms	0·3	0·6	1·5
Monolithic construction against rough forms	0·6	1·5	--
Clayware			
Glazed or unglazed pipe:			
With sleeve joints	0·03	0·06	0·15
With spigot and socket joints and "O" ring seals			
-- dia < 0·150 m	--	0·03	--
-- dia > 0·150 m	--	0·06	--
Pitch fibre			
(lower value refers to full bore flow)	0·003	0·03	
# Glass reinforced plastic (GRP)	**0·03**[#]	0·06	--
uPVC			
# Twin-walled, with coupling joints	0·003	0·006	
Standard, with chemically cemented joints	--	0·03	--
Standard, with spigot and socket joints, "O" ring seals at 6 to 9 metre intervals	--	0·06	--

Figure 2.18 – Recommended pipe roughness values in respect of pipes made from different materials: extracted from (Wallingford and Barr, 2006)

A1

(p.1 of 6)

k_s = 0·003 mm
S = 0·00030 to 0·00100

ie hydraulic gradient =
1 in 3333 to 1 in 1000

Water (or sewage) at 15°C;
full bore conditions.

velocities in ms^{-1}
discharges in litres/sec

Gradient	(Equivalent) Pipe diameters in mm													
	20	25	30	40	50	60	65	70	75	80	90	100	125	150
0·000300				0·071	0·085	0·097	0·103	0·109	0·115	0·121	0·131	0·142	0·167	0·189
1/ 3333				0·0898	0·1667	0·2755	0·3433	0·4207	0·5082	0·6063	0·8363	1·1145	2·0434	3·3478
0·000320				0·074	0·088	0·101	0·107	0·113	0·119	0·125	0·136	0·147	0·173	0·197
1/ 3125				0·0933	0·1731	0·2861	0·3564	0·4367	0·5275	0·6293	0·8680	1·1565	2·1200	3·4726
0·000340				0·077	0·091	0·105	0·111	0·118	0·124	0·130	0·141	0·152	0·179	0·203
1/ 2941				0·0967	0·1794	0·2963	0·3692	0·4523	0·5463	0·6518	0·8988	1·1974	2·1945	3·5941
0·000360				0·080	0·094	0·108	0·115	0·121	0·128	0·134	0·146	0·158	0·185	0·210
1/ 2778				0·1000	0·1855	0·3064	0·3816	0·4676	0·5647	0·6736	0·9288	1·2372	2·2671	3·7124
0·000380				0·082	0·097	0·112	0·119	0·125	0·132	0·138	0·151	0·162	0·191	0·217
1/ 2632				0·1033	0·1914	0·3162	0·3938	0·4824	0·5826	0·6949	0·9581	1·2761	2·3379	3·8279
0·000400				0·085	0·100	0·115	0·122	0·129	0·136	0·142	0·155	0·167	0·196	0·223
1/ 2500				0·1065	0·1973	0·3257	0·4057	0·4969	0·6001	0·7158	0·9867	1·3142	2·4072	3·9407
0·000420				0·087	0·103	0·119	0·126	0·133	0·140	0·146	0·160	0·172	0·202	0·229
1/ 2381				0·1096	0·2030	0·3351	0·4173	0·5112	0·6172	0·7361	1·0147	1·3514	2·4749	4·0511
0·000440				0·090	0·106	0·122	0·129	0·136	0·144	0·150	0·164	0·177	0·207	0·235
1/ 2273				0·1126	0·2086	0·3443	0·4287	0·5251	0·6340	0·7561	1·0421	1·3878	2·5412	4·1591
0·000460				0·092	0·109	0·125	0·133	0·140	0·147	0·154	0·168	0·181	0·212	0·241
1/ 2174				0·1156	0·2141	0·3533	0·4399	0·5387	0·6505	0·7757	1·0690	1·4235	2·6062	4·2650
0·000480				0·094	0·112	0·128	0·136	0·143	0·151	0·158	0·172	0·186	0·218	0·247
1/ 2083				0·1185	0·2195	0·3621	0·4509	0·5521	0·6666	0·7949	1·0954	1·4585	2·6699	4·3689
0·000500			0·077	0·097	0·114	0·131	0·139	0·147	0·154	0·162	0·176	0·190	0·223	0·253
1/ 2000			0·0546	0·1214	0·2247	0·3708	0·4616	0·5653	0·6825	0·8138	1·1213	1·4929	2·7325	4·4709
0·000525			0·080	0·099	0·118	0·135	0·143	0·151	0·159	0·166	0·181	0·195	0·229	0·260
1/ 1905			0·0562	0·1250	0·2312	0·3814	0·4748	0·5814	0·7019	0·8369	1·1531	1·5351	2·8093	4·5958
0·000550			0·082	0·102	0·121	0·139	0·147	0·155	0·163	0·171	0·186	0·201	0·235	0·267
1/ 1818			0·0578	0·1284	0·2376	0·3918	0·4878	0·5972	0·7209	0·8596	1·1842	1·5764	2·8844	4·7182
0·000575			0·084	0·105	0·124	0·142	0·151	0·159	0·167	0·175	0·191	0·206	0·241	0·274
1/ 1739			0·0594	0·1318	0·2438	0·4020	0·5005	0·6127	0·7396	0·8818	1·2147	1·6168	2·9580	4·8381
0·000600			0·086	0·108	0·127	0·146	0·155	0·163	0·172	0·180	0·196	0·211	0·247	0·280
1/ 1667			0·0609	0·1352	0·2499	0·4121	0·5129	0·6279	0·7579	0·9036	1·2446	1·6565	3·0302	4·9557
0·000625			0·088	0·110	0·130	0·149	0·158	0·167	0·176	0·184	0·200	0·216	0·253	0·287
1/ 1600			0·0624	0·1384	0·2560	0·4219	0·5251	0·6429	0·7759	0·9250	1·2740	1·6955	3·1012	5·0712
0·000650			0·090	0·113	0·133	0·153	0·162	0·171	0·180	0·188	0·205	0·221	0·258	0·293
1/ 1538			0·0638	0·1417	0·2619	0·4316	0·5371	0·6575	0·7936	0·9460	1·3029	1·7338	3·1708	5·1846
0·000675			0·092	0·115	0·136	0·156	0·165	0·175	0·184	0·192	0·209	0·226	0·264	0·300
1/ 1481			0·0653	0·1448	0·2677	0·4411	0·5490	0·6720	0·8110	0·9667	1·3312	1·7715	3·2393	5·2961
0·000700			0·094	0·118	0·139	0·159	0·169	0·178	0·187	0·196	0·214	0·230	0·269	0·306
1/ 1429			0·0667	0·1480	0·2734	0·4505	0·5606	0·6862	0·8281	0·9870	1·3592	1·8086	3·3067	5·4058
0·000725			0·096	0·120	0·142	0·163	0·172	0·182	0·191	0·200	0·218	0·235	0·275	0·312
1/ 1379			0·0681	0·1510	0·2790	0·4597	0·5720	0·7002	0·8449	1·0070	1·3867	1·8450	3·3730	5·5138
0·000750			0·098	0·123	0·145	0·166	0·176	0·186	0·195	0·204	0·222	0·239	0·280	0·318
1/ 1333			0·0695	0·1541	0·2846	0·4688	0·5833	0·7139	0·8615	1·0268	1·4137	1·8810	3·4383	5·6201
0·000800			0·102	0·127	0·150	0·172	0·182	0·193	0·202	0·212	0·231	0·248	0·291	0·330
1/ 1250			0·0722	0·1600	0·2954	0·4866	0·6054	0·7409	0·8939	1·0654	1·4667	1·9513	3·5661	5·8282
0·000850		0·092	0·106	0·132	0·156	0·178	0·189	0·199	0·209	0·219	0·239	0·257	0·301	0·341
1/ 1176		0·0451	0·0748	0·1658	0·3060	0·5039	0·6269	0·7671	0·9255	1·1030	1·5183	2·0197	3·6905	6·0305
0·000900		0·095	0·110	0·136	0·161	0·184	0·195	0·206	0·216	0·227	0·247	0·266	0·311	0·352
1/ 1111		0·0466	0·0774	0·1714	0·3163	0·5208	0·6478	0·7927	0·9563	1·1396	1·5685	2·0863	3·8116	6·2276
0·000950		0·098	0·113	0·141	0·166	0·190	0·201	0·212	0·223	0·234	0·254	0·274	0·320	0·363
1/ 1053		0·0482	0·0799	0·1769	0·3264	0·5372	0·6682	0·8176	0·9863	1·1753	1·6178	2·1514	3·9297	6·4198
0·001000		0·101	0·117	0·145	0·171	0·196	0·207	0·219	0·230	0·241	0·262	0·282	0·330	0·374
1/ 1000		0·0498	0·0824	0·1823	0·3362	0·5533	0·6882	0·8420	1·0157	1·2102	1·6655	2·2149	4·0452	6·6076
		–	0·74	0·74	0·75	0·76	0·76	0·77	0·77	0·77	0·78	0·78	0·80	0·81

$V_{r(0.5)medial}$ for half-full circular pipes.

k_s = 0·003 mm S = 0·00030 to 0·00100

Figure 2.19 – Associated velocities and discharges rates for a variety of pipe diameters and gradient, where $k_{s,}$ = 0.003mm: extracted from (Wallingford and Barr, 2006)

2.7 Software Packages

A variety of software packages exist to design drainage networks. Examples include Infoworks™, MasterDrain™, MIKE URBAN™, TUFLOW™, SOBEK™, and MicroDrainage™. All are compatible with AutoCAD, use the MRM and have large databases containing hydrological data to calculate rainfall intensities (Olesen and Rollings, 2012a). Each of these packages continues to be further developed, including being made more user-friendly. The three main packages used within the UK are; Infoworks™, MasterDrain™ and MicroDrainage™ (Bache, 2013; Daniels, 2013; Doorman, 2013; Russell, 2013; Wells, 2013). These software packages mentioned above all have the facility to utilize storm water models. This type of modelling was first utilized in the 1970s (Zoppou, 2001), a number of methods now simulate overland water flow. Initially, only methods simulating runoff concentration in semi-distributed models were used. The increase in urban pluvial flood events has since resulted in increasingly sophisticated models for exceedance flow. For example, 1-dimensional (1D) and 2-dimensional (2D) models of the urban surface are tightly linked to models of the sewer system (the dual-drainage concept) (Djordjević et al, 2005). Some of the approaches to overland flow modelling are suitable for simulating runoff concentration and exceedance flow; however, some only model one of the stages. Several studies have compared how 1D models of the surface compare to 2D models (Allitt et al, 2009; Leandro et al, 2009; Spry and Zhang, 2006; Mark et al, 2004). A summary of the findings are:

- The results of a 1D model are hard to visualize to a non-technical person.
- The setup of 1D models of the surface is more complex and therefore more time consuming than for 2D models.

- A 1D model gives a good approximation of the surface flow where the flow is well channelled; for example, in a street if the water stays within the street or channel. The accuracy of the model is, however, insufficient in an area where there are multidirectional flow paths, for example in a flat area of a street where the flow goes over the top of a kerb.
- As a real-time application programme functions within a time frame that the user senses as either immediate or current; 1D models have a shorter run time than 2D models, making them more suitable for real-time applications; this is one of the main advantages of a1D model over a 2D model.
- Both 1D and 2D models use a geographical information system to identify surface heights within the catchment surface, including a topographical survey of the existing ground surface and additional information in respect of elevation data for buildings and other protruding features (Butler and Davies, 2011).

Blanksby et al (2007) and Allitt et al (2009) suggested that the two types of models of the urban surface should be combined within a single model to maximize individual advantages, whilst overcoming their shortcomings.

2.8 Summary

This chapter has examined the purpose and components of a highway drainage system. In order for a road pavement to function properly, sufficient drainage provision must be made to keep the pavement clear of water otherwise many adverse consequences may result including flooding. Similarly, if water enters the road structure either by surface penetration or groundwater infiltration the strength and deformation resistance of the pavement and subgrade is weakened, increasing the susceptibility of the road to more damage from road failure and traffic. Increased urbanisation was found to have adversely affected the movement of water; an increased lack of land surface allowing rain to filter easily has meant the volume of water reaching a river during and after rainfall has increased. A description of each type of drainage system used in the UK, and the type of location appropriate for installation is given; suitability is dependent on several factors including location and road classification.

The need to be aware of the intensity (I), duration (D) and frequency (F) of rainfall in a specified area and how network design utilizes the relationship between these aspects of rainfall (IDF curves) is explained. A fundamental aspect of highway drainage design requires the amount of runoff entering the system to be known, as adequate storage needs to be incorporated within the design. A review of the main methods used to estimate surface runoff showed that climate, land use and catchment size each influences the choice of method used. A variety of different methods used in other countries were reviewed, no particular method was deemed the best, each had advantages dependant of several factors. The MRM remains the most commonly used method in the UK very possibly as it does not require expertise in hydrology. A description of the requirements of the formula used to calculate surface runoff using this method was explained. The stages involved in the UK design procedure for highway drainage infrastructure using the MRM was illustrated.

An examination of the software packages available to design drainage networks was undertaken, this showed that three main packages appear to be used in the UK; Infoworks™, MasterDrain™ and MicroDrainage™ each of these packages continues to be further enhanced by their developers. All have the facility to utilize storm water using 1D and 2D engines, although using a 1D model is less time-consuming than a 2D model, a 2D model provides greater accuracy regarding flood flow.

This chapter has discussed the importance of adequate design in relation to highway drainage system, however in order for any system to remain at optimum performance it needs to be maintained. The next chapter examines the importance of asset management and maintenance of drainage systems, with particular reference to highway infrastructure. The concept of risk and uncertainty is discussed in general terms, as is how the risk management process can be incorporated and used to better manage highway assets. The chapter also reviews application of risk management in other relevant sectors.

CHAPTER 3 MANAGEMENT AND MAINTENANCE OF HIGHWAY DRAINAGE INFRASTRUCTURE

3.1 Introduction

This chapter examines the current UK practice regarding highway drainage asset management and maintenance. Section 3.2 discusses what is meant by asset management and the need for asset management plans. Section 3.3 examines why drainage infrastructure assets are different to many other infrastructure assets. Sections 3.4 and 3.5 describe the need for Highway Asset Management Plans (HAMP) together with the current position as to their formulation. Section 3.6 examines the importance of maintenance on highway drainage infrastructure. Section 3.7 discusses how the health of a drainage system can be determined whilst recognising that any decision made is time specific. Section 3.8 discusses the need for remote control monitoring to assist in the identification of asset deterioration and failure. Section 3.9 defines uncertainty and risk. Section 3.10 describes the current approach to flood risk management within local authorities. Section 3.11 introduces the concept of a risk management framework that is applicable to any organizational problem. Section 3.12 reviews previous studies associated with the uncertainties with highway drainage systems, flood risk and management, the quantification of an urban drainage risk management system, and how a risk based approach has been used in other sectors.

Although the importance of the UK road network is well recognized by Government as directly impacting the economy of the country (Section 1.1) historically both money and emphasis have predominantly concentrated on road network construction. This construction orientated approach has resulted in a failure in repairing an ageing infrastructure (Spink et al, 2014; Public Accounts Committee, 2014j).

Each highway asset has a definitive lifespan after which it starts to decay and lose functionality, many of this country's existing highway assets are approaching the more costly stages of their natural life-cycle, with some assets now reaching the end of their serviceable life. Furthermore, the life-cycles of infrastructure assets have deteriorated more quickly than anticipated (DfT, 2014b). This situation has resulted from original under funding of maintenance compounded by recent severe weather events (Public Accounts Committee, 2014a). An ageing asset frequently needs more funding as older infrastructure is more costly to maintain (Spink et al, 2014; Millership, 2012; Olesen and Rollings, 2012a). Consequently, many areas of England are entering an era where a growing proportion of its public highway is nearing the end of its first full life-cycle (DfT, 2014b; Public Accounts Committee, 2014a). A network starts to deteriorate due to one or more factors such as; inadequate construction design standards, poor workmanship, traffic loading and traffic volume. UK highway infrastructure has also recently experienced some longer periods of increased precipitation especially in winter; these have caused major flooding in parts of the country (Willway et al, 2008b). This situation is predicted to get worse as climate change predictions are realized, see Section 4.3.2.

To be effective a road maintenance regime requires good management and consistent adequate funding; both variables impact the final outcome. To facilitate this The Infrastructure Act 2015 turned Highways England into a government-owned company; ‘with the aim of allowing it to work fast and efficiently, provide better customer service and get value for money from investment’ (UK Government, 2015). The legislation provides for stable, long term funding for national strategic road infrastructure projects, to create and repair the motorways and major A routes that support the economy. Pitcher (2015) argued the legislation would improve Highways England’s ability to make long term plans.

Unlike road construction projects which have a defined beginning and end; road maintenance needs to be seen as a continuous engineering management function and not an engineering project management function actioned after a problem has occurred (Spink et al, 2014; Robinson et al, 1998). Agreeing with this latter view; The Right Honourable Margaret Hodge MP, Chair of the Committee of Public Accounts, in September 2014 said, '. … There has been too much reactive work in response to flooding and other events and not enough focus on preventative work that is less expensive in the long-term….' (Public Accounts Committee, 2014j).

Planning the way in which monies are spent on highway maintenance makes economic sense. The Audit Commission (2011) found it cost three times as much to reconstruct a failed road than it does to carry out preventative maintenance. Similarly, Barnes (2000), Olesen and Rollings (2012a) and HMEP (2012) suggested that significant savings were possible if water was prevented from penetrating the road surface and damaging supporting structures and foundations.

Although LAs understand how road surfaces deteriorate over time, similar knowledge does not extend to other types of highway infrastructure (Lugg, 2011). This situation is compounded by a lack of readily available costs associated with specific maintenance activities. For example, neither Highways England nor DfT were able to inform adequately The Government as to the maintenance costs necessary to maintain the UK road networks (Public Accounts Committee, 2014j).

3.2 Asset Management

3.2.1 General Definition

BS ISO 55000 (2014) defines 'asset management' as the 'coordinated activity of an organization to realize value from assets'. Assets are defined as follows: 'An asset is an item, thing or entity that has potential or actual value to an organization'. 'This definition is deliberately wider than physical assets but these form an important focus for more organizations'. Asset Management involves the balancing of costs, opportunities and risks against the desired performance of assets, to achieve the organizational objectives. This balancing may need to be considered over different time frames. Several organizations interested in highway networks have offered definitions for example; OECD (2001); Road Liaison Group (2005a); BSI (2008). These definitions varyingly describe a process concerned with looking after assets with a view to maximizing the use of the money available (Robinson et al, 2008). Only 11 years ago The County Surveyors Society, (2004) commented that the term 'asset management' was used increasingly in relation to the management of highway networks. 'However, no common understanding of what asset management is and what can be achieved through its application exists'. It offered the following thoughts 'Asset management means different things to different people….. Asset management represents more than simply an integration of existing management systems and data. It builds on existing processes and tools to form a continuous improvement framework that complements and supplements existing practice'. PAS 55 (BSI, 2008) summarized the concept and included aspects from other definitions, as well as incorporating the element of sustainability; 'asset management is the systematic and co-ordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over the life cycle for the purpose of achieving its organizational strategic plan'. Logically, every organization would

benefit from having a complete, up to date record of all the assets under their control, including their condition. This information would help prioritize expenditure, including maintenance expenditure.

3.3 What makes drainage infrastructure assets different?

Historically highway drainage has suffered financially and from sub-optimum management; a contributory factor is reflected in the fact that unlike other highway assets visual inspections of drainage systems are inherently limited as they are invariably below ground. This position is compounded as very frequently the 'as built' records for highway drainage systems have been found to be inadequate or non-existent (Millership, 2013; Lugg, 2012; Spink et al, 2014). The problem was further evidenced by the finding that Highways England did not possess information relating to 70% of its drainage systems, Department for Transport (2011). Similarly, many local highway authorities did not have a complete inventory of their bridges, drains, footways and street lighting (Public Accounts Committee, 2014j; a). This problem is not confined to the Highways England or local authorities, potentially all owners of a large number of assets face similar problems. Potentially, a complete asset inventory may never be achieved due to the logistics of the task, especially for larger infrastructure owners (Millership, 2013). For example, to demonstrate the enormity of the task, Highways England has responsibility for some 300,000 gullies, 16,000km of pipes and culverts and, 11,000km of filter drains (Spink et al, 2014). Table 3.1 shows UK infrastructure asset owners' estimates regarding the extent and condition of their drainage assets (%).

Table 3.1 UK Infrastructure asset owners' estimates regarding the extent and condition of their drainage assets (%) (Spink et al, 2014)

Organization	**Approximate network coverage of drainage asset knowledge - 2013**			
	Inventory		**Condition**	
	Historic records	Field surveys	Asset level	Defect level
Highways Agency	95	85	15	15
Network Rail	30	100	60	15
London Underground	15	85	80	80
Transport for London	10	3	3	2

3.4 The need for highway asset management plans (HAMP)

The Prudential Framework (2004) was implemented to improve LA service delivery by supporting strategic planning for capital investment, it resulted in LAs being given more control over expenditure so they could set their own borrowing limits (LASAAC, 2004). Following the Government decision to implement resource accounting and budgeting, each highway authority had to identify, quantify and value their assets by 2009/10, as the allocation of public funds became increasingly rigorously policed. The justification of expenditure is now based on evidence, need, performance and risk (Bache, 2013; Daniels, 2013; Doorman, 2013; Green, 2013; Wells, 2013; Department for Communities and Local Government, 2013). HAMPs or another form of asset inventory together with the associated costs and maintenance plans, are a pre-requisite to justifying requested levels of Government funding (Department for Communities and Local Government, 2013; Public Accounts Committee, 2014a). Similarly, Government schemes such as the Local Highways Maintenance Challenge Fund encourage good asset identification/recording/management by rewarding applicants with the chance of obtaining extra funding (DfT, 2014b).

Robinson et al (2008); Hooper et al (2009); Spink et al (2014), each considered that the most successful plans provided a link from the organizational mission statement through to the implementation of works.

3.4.1 Drainage infrastructure records

Currently, all UK drainage infrastructure owners have inadequate records (Lugg, 2012), the reasons for this are:

- Despite being informed it was necessary to record all highway assets together with the maintenance received (most usually by a HAMP) (Public Accounts Committee, 2014j), no national standards exist in relation to the condition of non-pipework drainage assets; although BS EN13508-2:2003+A1:2011 relates to recording the condition of pipework and associated chambers. The lack of relevant drainage infrastructure national standards mitigates against the acquisition of useable reliable data (Bache, 2013; Daniels, 2013; Green, 2013). According to Spink et al (2014) the following reasons also apply:
- Most condition surveys are carried out using Closed Circuit Television (CCTV); the most expensive type of survey, this coupled with the fact that so few sub-surface surveys have taken place in relation to the extent of the network, the overall number of surveyed assets remains small (Public Accounts Committee, 2014j).
- CCTV surveys are frequently used to examine a current problem but once fixed survey details are often disregarded.
- The development of low cost, walk over the ground, survey methods that do not use CCTV are in their infancy.
- A survey represents the position at the time of doing; old surveys may not be relevant, however, they could help indicate areas having recurring problems.

Despite the problems relating to recording assets, progress continues and LAs gather more data. For example Coventry City Council (2008) included a detailed drainage life cycle plan in their HAMP, which included the following:

- Balancing Ponds
- Carriageway Gully
- Connections
- Culverts <1.3m
- Ditches
- Drainage Channel
- Drainage Pipes
- Headwalls
- Footway Gully
- Interceptors
- Kerb Drainage
- Manholes
- Soakaways
- Swales
- Trash Grids

A group of readily available parts helps support a quick efficient maintenance regime; it is necessary to balance the cost of stock retention, delivery times, and the cost of asset failure. A lack of salt played a major part in necessitating roads and airports to close during the winter of 2009/2010. This example clearly indicates how failure to adequately stock sufficient materials can quickly cause sustained public inconvenience, and have significant financial implications.

Suggested content of a HAMP (Spink et al, 2014):

- The scope and extent of the plan.
- The number of inventory and condition inspections undertaken, including measurement against previous plans.
- A summary of interventions and investment carried out in the previous period.
- The current condition of the drainage network and changes in the condition resulting from investment or deterioration – when compared to the previous plan.
- The required and/or desired condition and/or performance of the drainage asset.

- Performance gaps, for example if the drainage is not meeting requirements, evidenced by flooding.
- The risk assessment details which influenced the prioritization of proposed works.
- The prioritized programme of inspections and funded and/or proposed interventions to meet the plan.
- The future monetary investment required to meet the necessary performance or increased demand.
- The consequences and mitigation measures required if recommended works cannot be undertaken.
- A review of how effective the plan has been and the positive action taken, for example record the frequency of drainage related incidents.

3.4.2 Drainage surveys and recording

DMRB BD63/07 (2007) describes the inspection and reporting requirements for highway structures on motorways and trunk roads. General inspections must be scheduled every 24 months to ascertain the physical condition of all visible elements. Comprehensive principal inspections are required every 6 years to ascertain the physical condition of the parts that can be inspected. IAN 147/12 (2012) defines 3 types of drainage surveys and how to upload the information to the drainage data management system.

- **Asset inventory surveys:** are unlikely to encompass all assets in an area; they identify the location of priority assets or confirm existing records.
- **Asset condition surveys:** assess the condition of all drainage assets in a defined area, but exclude a complete record of defects. If an asset has not previously been recorded the survey captures the basic asset inventory, but not full asset attributes. Records detail asset connections and directions of flow.

- **Detailed defect surveys:** record all condition defects; pipework assets require an internal CCTV survey, non-pipework assets necessitate a detailed inspection including the selective excavation of some sub-surface assets. If the asset inventory has not previously been recorded, or not recorded in detail, then a detailed inventory needs compiling. These surveys concentrate on particular assets experiencing performance problems, although they can include all drainage assets, in which case a record of asset connectivity and directions of flow is included. Each asset type is classified based on its geometry and representation within the software, namely:
    - **Point items:** outfalls, chambers, gullies, soakaways, flow controls such as valves and weirs.
    - **Continuous (linear) items:** channels, ditches, culverts and pipes.
    - **Region (polygonal) items:** balancing ponds and infiltration basins.

This method has improved the cost effectiveness of asset recording for Highways England; the inventory contains a schedule of each highway drainage asset, their component parts, materials and dimensions, and asset connectivity (IAN 147/12, 2012). Currently an assessment of highway drains is carried out every 10 years using CCTV or manual techniques to identify structural failures, additionally reactive assessments are undertaken if blockages/ build-up of debris requires immediate treatment (DMRB BD63/07, 2007).

3.4.3 The need to allocate a monetary value to each asset

The need to allocate a monetary value to each asset is necessary to establish where efficiencies can best be made. It also helps in acquiring an appreciation of the savings for comparative purposes and enables informed choices as to where to spend money; with an audit trail discovering and tracking what happened to any savings (Robinson et al, 2008).

Robinson et al (2008) also argued that for an asset management system to function effectively; continuous asset monitoring was required, with asset status constantly being fed into the system; this emphasizes that asset condition is known to constantly change.

3.5 Highway Asset Management Plans - current position

The first UK local authority HAMP was produced by Hertfordshire County Council in 2003, by 2011 numerous plans were available but they remain at various stages of refinement (Lugg, 2012). Highways England completed its first plan in 2011, (Department for Transport, 2011; Public Accounts Committee, 2014j). In 2014, 45 local highway authorities had not completed a plan (Public Accounts Committee, 2014a).

Derbyshire County Council (DCC), Leicestershire County Council (LCC) and Nottinghamshire County Council (NCC) formed the 3 Counties Alliance Partnership (3CAP) together with business consultants in 2007, aimed at improving the delivery of highway and other professional services by joining resources to make cost and efficiency savings. Two thirds of local authorities have now formed alliances in an attempt to reduce costs (Public Accounts Committee, 2014j; a).

Software packages, for example Confirm®, allow organisations to record an asset inventory of all known infrastructure assets under their jurisdiction, for example, location and maintenance history of each asset (Pitney Bowes, 2014).

3.5.1 Management process

In relation to highway management there are four basic levels of management, as shown in Figure 3.1.

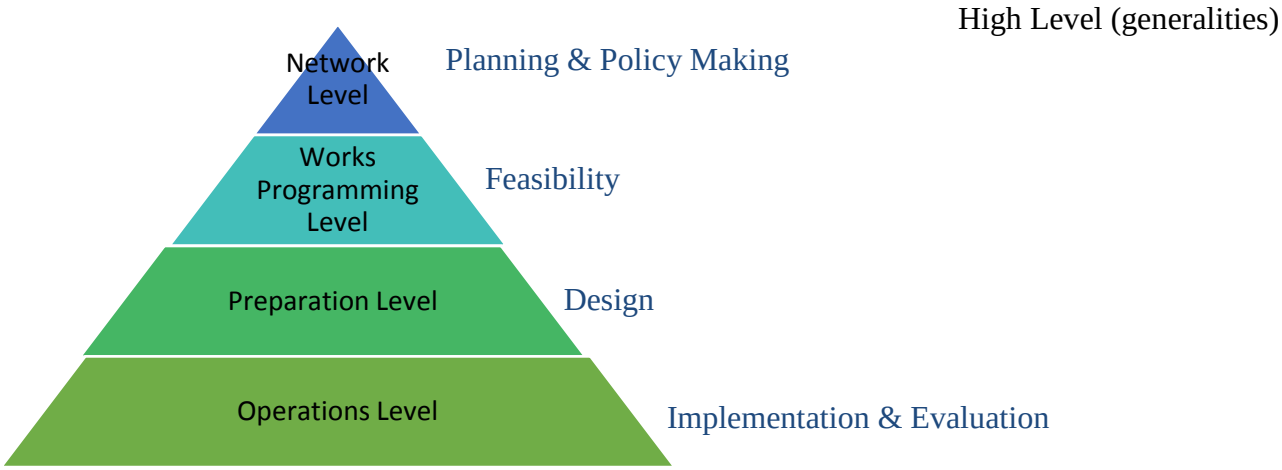


Figure 3.1 - The 4 basic levels of management (Robinson et al, 1998)

Network Level: (Strategic level) – An asset management policy, together with the organizational strategic plan, drives the asset management strategy and specific asset management objectives, targets and plans to be produced (IIMM, 2011).

This strategic level involves project identification, planning and policy making, as well as making long term decisions in respect of the whole network. Estimates relating to highway development and maintenance are produced for various budget heads and economic scenarios. The highway is defined as proportions of the network or lengths of road, in various categories; for example, by the degree of congestion, road classification, actual physical condition, pavement type, or the amount of traffic using it (Robinson et al, 1998).

Programming Level – the project is reviewed. This includes all basic requirements and a consideration of alternative projects including the recommendation of the preferred option.

The economic feasibility of each works is considered following a cost benefit analysis. Work that take several years, together with expenditure programmes relating to sections of the network likely to need a variety of maintenance, including new construction, are identified. Ideally a feasibility study should be done for each possible option. The road network is considered by section, and described in terms of its physical components. Estimates of expenditure are produced and allocated to a range of different budget heads; for example different years and the proposed work to be done (Robinson et al, 1998).

Preparation Level: (Project level) – the preferred project is prepared for implementation. Very detailed designs are drawn and construction appraisal contract strategies formulated, detailed costings are prepared, together with contracts, each requiring specialist training to implement. The cost benefit analysis needs to be reviewed prior to finally validating the overall feasibility of the proposed scheme (Robinson et al, 1998).

Operations Level: the approved project is implemented, a detail design prepared, tender enquiries are made and assessed, contracts signed, followed by construction, final completion and commissioning. This stage is managed by work supervisors, technicians or clerks of works depending on function. The time horizon is reduced from years to the current budget year, reducing to a week, then a day. The skills of the staff in charge similarly changes, (Robinson et al, 1998). Finally, the performance of the new asset and the whole project should be evaluated (Spink et al., 2014).

3.6 Maintenance of drainage assets

Maintenance is necessary to ensure each asset remains working efficiently it can be broken down into non-cyclical, cyclical and emergency activities as shown in Table 3.2.

Table 3.2 - Maintenance Categories

Type of Maintenance	Work undertaken
Non-cyclical	This refers to minor work that does not change the infrastructure. Examples include work required following a condition appraisal; removing roots or general debris.
Cyclical	Includes regular scheduled maintenance for example cleaning out gully pots and manholes.
Emergency	Work responding to a particular incident such as flooding or fix any safety related problem e.g. displaced manhole cover.

Historically, drainage maintenance was based simply on a condition appraisal. A better method considers the importance of asset functionality in the network as well as the predicted performance of the asset type. The decision as to which assets receive maintenance and their priority must be viewed in the context of drainage networks performance and the whole life costs of keeping the network performing at a satisfactory level. The extended life of an asset is generally proportionate to the amount spent on repairs (Spink et al, 2014). Table 3.3 shows how refurbishment and renewal costs are spent.

Table 3.3 Refurbishment and renewal costs

Costs	Work carried out
Refurbishment	Necessary non- routine work to restore the asset to its original performance level; for example repointing a manhole.
Renewal	If the asset is past repair, and other alterations to the network to accommodate its loss are not possible then it needs replacing.

Apart from historical poor recording of asset locations there are problems associated with maintaining (and installing) urban drainage assets closely situated to other sub-surface assets belonging to other utilities. Many pipes and cables frequently run across the same site and it is a common occurrence not to know which are live and which have been abandoned; this problem aggravates the laying of new pipes, as space may be very tight. Ownership disputes regarding sub-surface assets further exacerbates the situation (Spink et al, 2014; Olesen and Rollings, 2012a; t).

Table 3.4 shows the different maintenance options available in respect of a variety of problems and assets.

The management of highway infrastructure maintenance has been shown not to be a straight forward process that allows for easy quantification and prioritization. Management maintenance should be seen as an ongoing engineering management function that is necessary for continuous success. It is not an engineering project management function with a start and completion date (Road Liaison Group, 2005b). Unexpected situations and major events occur which change planned priorities, with each such uncertainty impacting on highway infrastructure maintenance schedules.

The increase in serious flooding events over the past decade has concentrated interest in urban flooding and the best ways to manage it. Extreme rainfall has seen highway drainage infrastructure overwhelmed and the resultant increased pressure from the public to minimize flood incidents in areas with failing assets and poor network capacity (Kellagher et al, 2008).

Table 3.4 The different maintenance options available in respect of a variety of problems and assets types.

Asset type	**Problem**	**Cause**	**Potential remedy**
Channel and ditches	Blockage	Debris entering.	Remove.
	Vegetation	Growth.	Remove.
	Collapse	Unstable bank. Animals burrowing.	Bank erosion methods. Control vermin.
Catchpits and manholes	Silting	Near proximity to ploughed fields or adjacent to land drainage problems.	Mechanical jetting /vacuuming. Hand excavation.
	Blockage various material blocking or chambers buried or filled	Damaged or missing covers Poor maintenance	Increase frequency of cleaning.
	Collapse	Damage by ground movement or vehicle load.	Rebuild asset.
Gullies	Blockage	Grating blocked by litter of debris.	Clean by hand.
		Sump blocked by sediment of debris.	Clean by vacuum suction.
	Collapse	Broken gate or brickwork.	Replace or repair.
		Failed pavement due to vehicle load or material wash-out.	Remove loose material, fill and patch surfacing.
Pipes	Silt and debris accumulation	Standard deterioration.	Routine cleaning: Rodding/dragging Pressure jetting Flushing
	Root obstruction	The close proximity of various vegetation.	Root cutting using a jetting required with a flail.
	Partial collapse	Major pipe cracking or deformation.	Local open cut repair/replacement. Patch repair or local relining.
		Holes and collapses of less than one pipe length.	
	Complete collapse	Structural failure of more than one pipe length.	Excavate a trench and insert new pipe section.

3.7 Health of a highway drainage system

An asset management plan is developed usually to plan incremental change to organisational assets. A good up-to-date asset management plan does not however provide a comprehensive picture regarding the health of the drainage system but can provide some indicators. Although no definitive content requirement exists for such a plan, Spink et al (2014) proposed items for inclusion (see Section 3.4.1.). To formulate a comprehensive method of defining the health of a highway drainage system each highway authority would need to record accurately all relevant assets (Public Accounts Committee, 2014a), Highways England has already improved asset recording (Section 3.4.2).

A logical way to record assets is through the formation of an inventory database, to include:

- Asset specification, including the material of construction and its monetary value. Problems may become associated with certain types of installations; such details allow for the checks to be made.
- Age of asset.
- Likelihood of an issue occurring that could adversely impact the asset, for example subsidence.
- Type and date of scheduled maintenance surveys undertaken together with findings.
- Type and date of necessary maintenance was identified, together with an appropriate timescale for action.
- Type and date of unscheduled completed maintenance in respect of each asset including the reasons for the maintenance.
- Likelihood of subsidence occurring and adversely influencing the drainage infrastructure.

- Information as to current/redundant subsurface highway drainage infrastructure and current/redundant infrastructure installed by other services, would assist when planning asset installations (Muggleton et al, 2014; Metje et al, 2007; O'Flaherty, 2008). In practice many such assets are only identified when new assets are installed, however, other utility providers make subsurface details available if a record exists. A joint database of all subsurface assets would be mutually beneficial, furthermore, routine co-operation with other utility providers regarding scheduled subsurface interventions may reduce excavations, costs, ground disturbance and inconvenience to the public (Russell, 2013).

The compilation of accurate information relating to assets that form a drainage system would greatly help when gauging the health of the system. However, any system review is time specific, and a healthy prognosis would not guarantee the system is not completely devoid of near term problems. Remote control monitoring could help inform the health of surface and sub-surface assets.

3.8 Remote control monitoring of highway drainage systems

A labyrinth of drainage pipes and cables providing essential services lies under the surface of most UK roads. Ageing infrastructure coupled with building expansion means there is an urgent need to establish the position and condition of these forgotten assets, particularly as new technologies continually emerge, for example broadband placed more demand on sub-surface space. Every hole dug by a utility company (around 4 million annually) carries an associated public disruption cost, and the probability of causing damage to existing assets.

McMahon et al (2005) concluded that the UK's utility industry bill for street works construction was some £ 1.5 billion annually with £150 million spent on third party damage.

A permanently installed unattended drain condition monitoring system, capable of detecting problems needing immediate treatment would potentially assist in maintaining pipe functionality, reduce road maintenance costs and inconvenience to the public (Metje et al, 2007; Muggleton et al, 2014; Hao et al, 2012; Brennan et al, 2006; Berz et al, 2001; Browering et al, 2003; Drobot et al, 2007).

Various detection techniques exist in respect of pipe lines including, electromagnetic line locators, magnetometers, infrared thermography, acoustic location systems and ground penetrating radar (Harrington and Iaquinta, 2012). Currently to be effective a variety of the techniques have to be used in conjunction, dependent on the location and site condition. The material of pipe construction, contents, pipe diameter, depth and the ground type/conditions surrounding the pipes all influencing the technology efficacy. Reviewing the locating technologies Costello et al (2007) concluded no single technology was currently capable of locating all underground utility services with complete certainty or provide a generally applicable means of condition assessment. Advantages relating to one technique frequently disadvantage another, however, the development of a multi-sensor approach remained the best way forward (Hao et al, 2012). The 'mapping the underworld' (MTU) project being undertaken at The University of Birmingham continues to research the feasibility of a range of potential technologies that can combine into a single device to accurately map underground utilities.

Kellagher et al., (2008) recognized that the probability of flood was dependent on the performance of a highway drainage infrastructure network under various conditions including; increased rainfall, further climate change, urban growth, asset deterioration, the local topography and pipe failure. 'The contribution towards risk from different flooding

sources and the components of flooding pathways, including infrastructure components is critical information to support risk-based decision making'.

3.9 Uncertainty and risk

3.9.1 Definitions

3.9.1.1 Uncertainty

Making a decision is a mental/cognitive process which follows a review of possible alternatives and then choosing one. Consequently, there must be very few decisions made with absolute certainty, as total knowledge as to all available alternatives in any situation is rare; therefore, an evaluation of uncertainties also contains inherent uncertainty (Toma et al, 2012). In this sense, 'decision making is sometimes also defined as a process of sufficiently reducing uncertainty and doubt about alternatives to allow a reasonable choice to be made from them.' (Infrastructure Risk Group, 2013). Merrett and Sykes (1983) similarly considered that 'uncertainty exists when there is more than one possible outcome to a course of action but the probability of each outcome is not known'. Ansell and Wharton (1992) described 'uncertainty' as 'not knowing what is going to happen next, and having no idea what the possible distribution looks like'. These opinions are not dissimilar and all reflect there being more than one possible outcome to an event with the output being uncertain. Individual opinion has been found to influence a view as to whether a situation will occur or if it needs action taking (Jordaan, 2005f; Wilson and Shlyakhter, 1997; Vose, 2010).

Uncertainty has also been called 'fundamental uncertainty', 'epistemic uncertainty' and 'degree of belief' it is by definition subjective, as it is a function of the assessor (Vose, 2010). Vose (2010) further argued that 'uncertainty is the assessor's lack of knowledge about the parameters that characterize the physical system being modelled' although stating that sometimes it is possible to minimize this for example; using further measurement, study, or

by consulting more experts. According to Vose (2010); Jordaan (2005f) a mathematical language is usually needed to encode uncertainty, with probability being traditionally seen as the best way and the best understood.

3.9.1.2 Risk

Increasingly the management of risk is being recognized as part of the decision making process. Various definitions of 'risk' exist including those by (Ansell and Wharton, 1992; BSI, 2010; Huntingdon and MacDougall, 2002; Jordaan, 2005a; Merna, 2008a; Vlasta Molak, 1997; Rodger and Petch, 1999; Smith, 2003; Tahmasebi Birgani and Yazdandoost, 2014; Vose, 2010). Jordaan (2005a) suggested that a 'decision is said to be subject to risk when there are a range of possible outcomes which could flow from it, and when objectively known probabilities can be attached to these outcomes'. Vlasta Molak (1997) defined risk in the context of disease as 'a measure of the probability of the introduction of an exotic disease and the seriousness of such an outcome in the context of the importation of animals or animal products. Vose (2010) described organizational risk as 'a random event that may possibly occur and, if it did occur, it would have a negative impact on the goals of the organisation'. He also considered a risk was composed of three elements:

- The scenario
- Its probability of occurrence
- The size of the impact if it did occur (either a fixed value or a distribution.

Vose (2010) also suggested that, 'An opportunity is also a random event that may possibly occur but, if it did occur, it would have a positive impact on the goals of the organization. Thus an opportunity is composed of the same three elements as a risk'. Although expressed slightly differently each of these definitions is similar in sharing the common elements of

probability and unknown outcomes. V Molak (1997); Vlasta Molak (1997); Jordaan (2005a); Vose (2010); BSI (2010) considered risk was based on a well-established relationship:

$$Risk = Probability\ of\ event\ occuring \times Consequence\ of\ event\ occuring \quad (3.1)$$

Risk is therefore distinguished from uncertainty where there is a plurality of outcomes to which objective probabilities cannot be assigned (Vose, 2010).

3.10 Flood Risk Management

3.10.1 Introduction

Flood risk management is a major topic of growing importance, and is governed by multiple legislation and regulations both at national, regional and local level (Kundzewicz et al, 2012; Plate, 2002). The recognition of its importance has escalated since the impacts of climate change have become more apparent (IPCC, 2007).

The Floods Directive (2007) defines 'flood risk' as the combination of the probability of a flood and its potential adverse consequences in relation to human health, economic activity, the environment and cultural heritage'. Floods have occurred naturally since time immemorial; and their consequences are known to be wide ranging. As it is impossible for engineers to eliminate all flood risk, engineers can only try and manage the risk in the best possible way (Huntingdon and MacDougall, 2002). The risk assessment process described in Section 3.11.2 needs to incorporate economic, social/ environmental, and all technical issues and uncertainties, relating to the extent of flooding and the damage caused by it.

Figure 3.2 shows the factors affecting flood risk (Huntingdon and MacDougall, 2002). A well-recognised approach to understanding the connection between hazard and risk is the source-pathway-receptor model as shown in Figure 3.3.



Figure 3.2 – The factors affecting flood risk: adapted from (Zevenbergen et al, 2010)

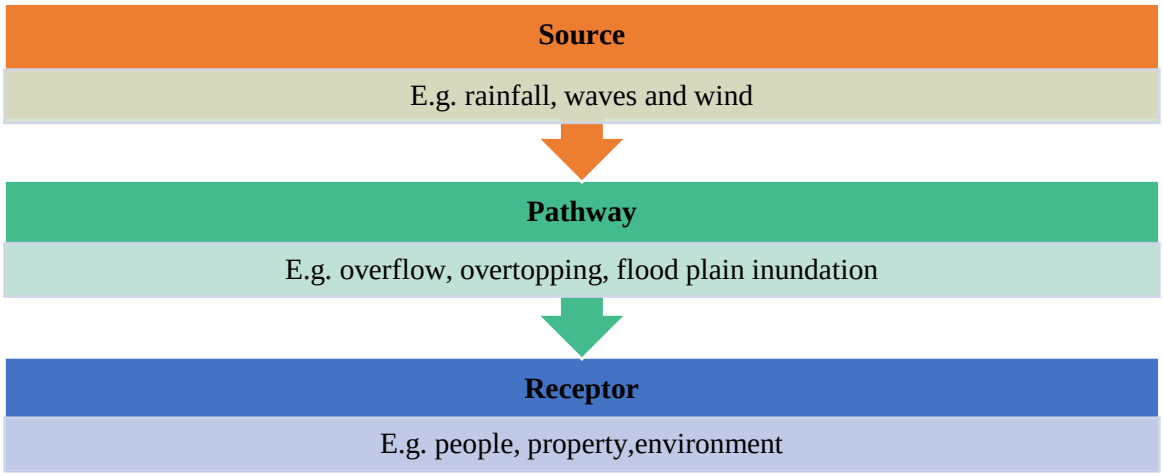


Figure 3.3 - Source, pathway, receptor model : adapted from (Zevenbergen et al, 2010)

In relation to flooding, the management of risk is heavily biased to the receptor end of the scale. As precipitation (source) cannot be controlled, and whilst there is scope to manage the pathway (land and watercourses) ultimately people, and property (the receptor) are the most controllable parameters in this system (Zevenbergen et al, 2010). One of the key aims of flood risk assessment is to have the best possible understanding of the complexities of the situation (Plate, 2002). Flood risk is dynamic both in space and time, and the risk assessment must reflect this (Huntingdon and MacDougall, 2002).

3.10.2 Legislation

The Pitt Review (2008); the Flood Risk Regulations (2009) and the Flood & Water Management Act (2010)(FWMA) were introduced to gain a better understanding and ability to manage flooding, the new legislation was enacted against the backdrop that each highway authority, and local authority has a duty of care to maintain the highway in a condition fit for purpose under the Highways Act 1980.

3.10.2.1 Flood and Water Management Act 2010

The legislation presented new duties for upper-tier and unitary authorities regarding flooding from surface water, it designated them as LLFA for their area. Each LLFA must produce a Local Flood Risk Management Strategy (LFRMS) and ensure it is compatible with other risk management authorities, including highway authorities. All local authorities are required to produce a surface water management plan (SWMP) detailing the risk of surface water flooding.

3.10.2.2 Flood Risk Regulations 2009

The Flood Risk Regulations 2009 were established to make the EU Floods Directive (2007) into domestic law in England and Wales. The EU Floods Directive provides a framework to evaluate and manage flood risks in order to reduce adverse consequences for economic activity, the environment (including cultural heritage) and human health. The Flood Risk Regulations 2009 require all LLFAs to carry out a Preliminary Flood Risk Assessment (PFRA) in order to identify important flood risk area.

3.10.2.3 Preliminary Flood Risk Assessment (PFRA)

This involves collecting information on past and future (potential) floods, assembling the information into a Preliminary Flood Risk Assessment report, and identifying Flood Risk Areas, this process is ongoing across all local authorities. This research is not concerned with the larger implications of flood risk management at the LLFA or higher level; it is only concerned with the theoretical risk of flooding in highway drainage infrastructure due to a number of defined uncertainties.

3.10.2.4 The management of urban surface water drainage in England and Wales

Following the UK flooding events of 2007 a number of reports were produced aimed at developing urban surface water management to reduce flooding incidents and pollution impacts within England and Wales, current administrative, legislative, institutional and structural practices were addressed. Reviewing these reports Ellis and Revitt (2010) concluded that the relationships between flood risk management and water quality must be considered at local, area and regional levels, and legislative clarification on surface water discharges need further examination. The review further considered new modelling approaches were required to predict flood risk at both catchment and local level, with improvements to communication systems and tools needed to ensure effective stakeholder participation. There was a clear need to disaggregate and quantify the various components of surface water flooding so that appropriate and cost-effective drainage options could be identified. Interestingly, the major impediment and barriers to integrated urban drainage management was found not to depend on technology but was institutional and social, neither parameter has been well addressed to date, this was explained by technology and planning issues within the water industry being frequently led by legal and market led targets. Flood risk management has been discussed; it utilizes the concept of the risk management framework, discussed in Section 3.11.

3.11 Risk Management Framework

Risk management is a methodical process comprising of communicating and consulting, establishing the context, identifying, analysing, evaluating, treating, monitoring and reviewing a risk Figure 3.4 shows the risk management framework.

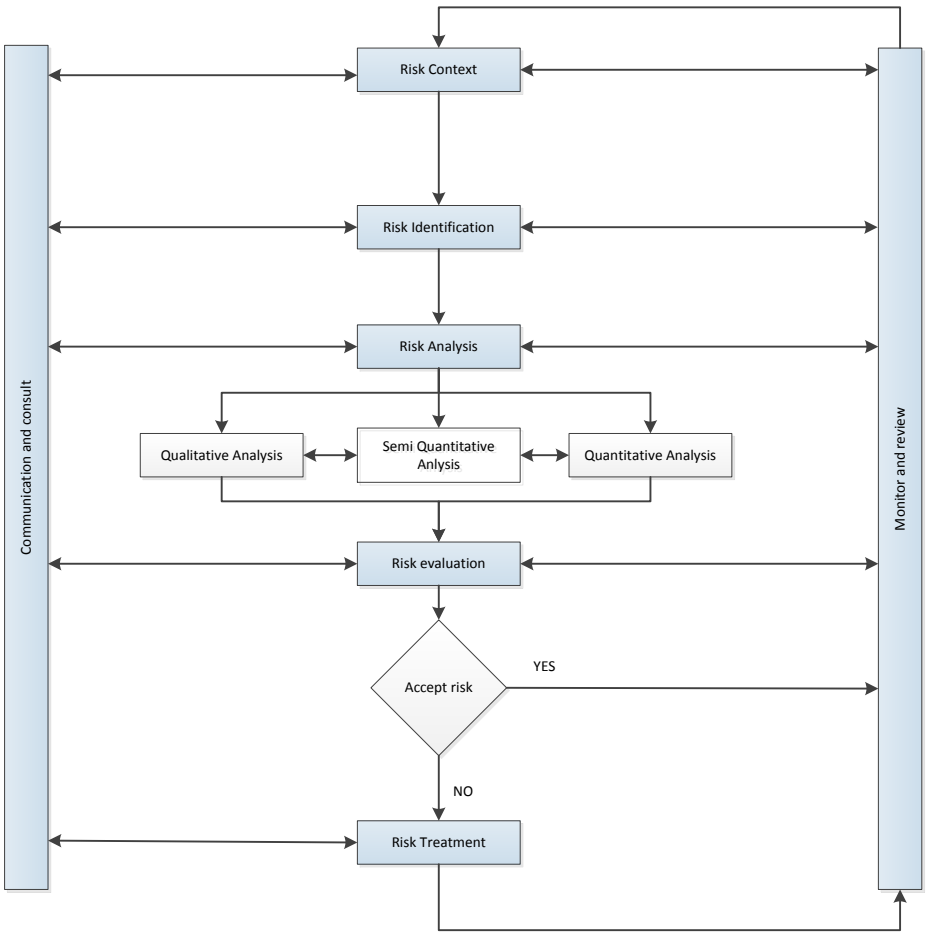


Figure 3.4 - Risk management framework (BSI, 2010)

3.11.1 Risk Context

The risk context needs to define the scope of the risk management process so that the criteria against which the risks are to be assessed can be judged. All risks carry an uncertainty as to how they will contribute to the process under examination (BSI, 2010). This research is concerned with the uncertainties that individually and collectively contribute to the flooding of highway drainage infrastructure.

3.11.2 Risk Assessment

This refers to a process that encompasses; risk identification, risk analysis and risk evaluation. The contribution of risk assessment to the risk management approach is shown in Figure 3.4. Each stage is described further in Sections 3.11.2.1 to 3.11.2.3.

3.11.2.1 Risk Identification

This is considered the most important stage of the risk management process as all subsequent stages relate back to the risks initially identified; if they are incorrect so is any work based on them (Ayyub, 2003a; Merna, 2008b); it is about discovering, recognizing and recording risks (BSI, 2010). It is necessary to identify what might occur or which situations already exist, and consider how they might impact on any particular system or achieving the organizational objectives. Once recognized, all existing controls such as design features, processes and systems need identifying and associating to each individual risk (Merna, 2008b).

There are different ways to identify risks; examples include:

1. Reviewing: evidence based methods such as check-lists or historical data, for example; the location of frequent fatal accidents and a repetitive set of circumstances.
2. Brainstorming: this involves an individual or a group of interested people generating spontaneous ideas that may help to solve a particular problem. Potential risks and

their probability together with the degree of impact on a situation is recorded (Smith, 1999).

3. Use of expert judgement: this is a systematic approach used to identify the risks using a structured set of questions or prompts aimed at analysing what can occur; the idea is that utilising subjective judgements may discover issues likely to trigger a risk (Vose, 2010). The increasing complexity of some problems has led to an expansion in the use of expert opinion to help analyse and ascertain a meaningful understanding of some situations; this has included an emphasis on empirical analysis, (O'Hagan, 1998).

   The size of the sample affects the probability of obtaining certain results, generally the larger the sample means that the results are less likely to deviate from the mean (Mukhopadhyay, 2000). Even if a sample is small 'people expect a sample from a population to represent all the essential characteristics of that population' (Garthwaite et al, 2005). However, practical issues can influence the final sample size obtained for analysis, for example the costs involved (budget) in relation to interviewing or circulating possible respondents, their geographical location in relation to the researcher and the willingness of suitable respondents to participate. Samples used in qualitative studies are generally much smaller than those used in quantitative studies (Ritchie et al, 2013) as the concern is with meaning, and not making generalized hypothesis statements (Crouch and McKenzie, 2006). Crouch and McKenzie (2006) suggested that a qualitative sample reaches a point of diminishing return; more data does not necessarily lead to more information. This is because one occurrence of a piece of data is all that is necessary to ensure that it becomes part of the analysis framework, frequencies are rarely important. Consequently, the sample size in the majority of qualitative studies should generally follow the concept of saturation

(Glaser and Strauss, 2009). However, Green and Thorogood (2013) and Guest et al (2006) suggested that while saturation is a convincing concept, it has a number of weaknesses including the limitation of time and resources.

Within any field of research participants may well offer diverse opinions. Consequently, qualitative samples must be large enough to assure that most or all important perceptions are discovered. The aims of the study being the ultimate driver of survey design and, therefore sample size (Charmaz, 2014). Other factors that might influence the potential sample size, include the scope of the study, the nature of the topic and the quality of the data required (Ritchie et al, 2013). Ultimately, many researchers avoid suggesting what constitutes a sufficient sample size. Guest et al (2006) suggested that although the idea of saturation is helpful at the conceptual level, it offers no practical guidance for estimating sample sizes for robust research prior to data collection. However, Charmaz (2014) suggests that 25 participants are adequate for smaller projects (without defining what constitutes 'smaller') and according to Ritchie et al (2013) qualitative samples often 'lie under 50'. Green and Thorogood (2013) found that 'the experience of most qualitative researchers is that in interview studies little new came out of transcripts after interviewing 20 or so people'. While some researchers offer guidelines for qualitative samples, there is evidence that suggests others do not strictly adhere to them. Following a review of fifty research articles Thomson (2004) found sample sizes ranging from 5 to 350 with 34 percent using samples between the range of 20 and 30, a number suggested as suitable by (Creswell, 2012), however, a study by Scott et al (2005) suggested that only 10 informants were needed to reliably establish a consensus.

4. Interviews: respondents are asked a series of questions which are recorded and used as a basis for further analysis. Questions can either be structured or unstructured. All participants should have knowledge and experience of the subject matter, ideally participants should be interviewed on a one to one basis to obtain a greater depth of understanding of each risk identified (Smith, 2003).
5. Questionnaires: the use of questionnaires to obtain information is well understood by many people. They are relatively easy and inexpensive to design and circulate. Unlike the interview technique they do not allow participants to discuss the answers given or raise other issues and are consequently relatively hassle free to use and can potentially widen the response (Vose, 2010). Similarly a questionnaire is less time consuming than using the Delphi technique, discussed in item 7 below, and not as likely to suffer such a high drop off rate once a respondent has agreed to participate.
6. Hazard and Operability Studies (HAZOP): this inductive reasoning open-ended and exploratory method has the aim of finding firm evidence, but not absolute proof of, the truth of the conclusion reached. The technique attempts to consider possible deviations from the expected or intended (BSI, 2010). It often occurs that when a task is examined in detail previously unidentified risks become apparent, particularly to management (Merna, 2008b).
7. Delphi Technique: developed in the 1950s, this is a very well established structured communication process that offers subjective judgements on a collective basis. The technique collects, groups, sorts and ranks data with the aim of reaching a consensus from a group of people with expertize to influence complex problems; it is of particular use when explicit problem solving techniques are not appropriate (Linstone and Turoff, 1975).

There are three aspects to the technique namely: sequential questionnaires, regular feedback to participants and participant anonymity. The questionnaires can be distributed by email, post or fax as respondents do not have to meet. Seaver et al (1978) and O'Hagan et al (2006) considered the undesirable effects of personalities and reputations to be unavoidable in a group interaction setting. Anonymity helps participants avoid any possible temptation to instantly agree with the majority without having properly considering the issue. It also prevents the ready reiteration of views offered by a senior participant present who occupies a position of influence (Linstone and Turoff, 1975; Rowe et al, 1991; Rowe and Wright, 1999; BSI, 2010).

A first questionnaire is circulated and summarized, then used to develop a second questionnaire which is circulated to the same group including aspects of the responses initially received. The second questionnaire asks participants to review their initial responses in view of the responses given by other experts. This process can be repeated until ultimately a consensus view as to what is agreed is reached and no new ideas emerge (McKinnon, 2000). However, most improvements of estimates were found to take place between the first and the second iteration (Woudenberg, 1991).

As with all techniques, Delphi has disadvantages including:

- It can be difficult to maintain active participation with the experts throughout the process, and there can be a large drop off rate; far more so than if respondents are asked to complete a one off questionnaire (BSI, 2010).
- The process is time consuming to manage. Dunham (1998) states that 'coordination of the Delphi technique using email with 20 participants and the processing of three questionnaires could utilise 30 to 40 hours of the coordinator's time'.

- The decision-making process is not as transparent as when at a face to face meeting, consequently it can be easier for the coordinator to influence the outcome. This fact can be recognized by the participants and may lead to less trust in the process and subsequent outcome (Rowe and Wright, 1999).

Although many Delphi studies aim at consensus among participants there is a need to account for the inherently high degree of uncertainty and equivocality which can result in an inevitable level of dissent, (Klenk and Hickey, 2011; Woudenberg, 1991). If a plurality of opinions and the underlying arguments attached to them exists, then they should be made visible (Pill, 1971; Landeta and Barrutia, 2011). Furthermore, the diversity of any underlying arguments based on substantial disagreements in expert opinions needs careful examination as they have proved more insightful than the evaluation of projections reached by consensus. The problem under examination has been found to be better served by striving for a stability of group opinions for a single projection, for example by identifying a number of consensus clusters, rather than seeking an overall participant consensus, (Gordon and Pease, 2006; Tapio, 2003).

3.11.2.2 Risk analysis

The purpose of risk analysis is to help managers better understand the risks and opportunities they face and to evaluate all options; it is directly concerned with having an input into risk assessment (Vose, 2010). There are several definitions as to the purpose of risk analysis (ISO 31000, 2009; Ansell and Wharton, 1992; Ayyub, 2003c; Jordaan, 2005a; Merna, 2008b; Rodger and Petch, 1999; Vose, 2010), these definitions and others are basically similar in content and refer to the estimation of uncertainties and consideration of the impact if the risk occurs; followed by stating that an appropriate management response needs to be made.

There are three methods to analyse risk: qualitative, semi-quantitative and quantitative analysis (Ayyub, 2003c; BSI, 2010; Vose, 2010). Risk analysis provides an input into risk assessment and hence which risks should be reacted to, together with the most appropriate strategies and methods to apply (BSI, 2010).

Qualitative analysis

Qualitative risk analysis is a descriptive process used to define the probability of each identified risk occurring and their related consequences, an example is shown in Table 3.5.

Table 3.5 - Example of descriptors used in qualitative analysis (Vose, 2010).

Category	**Probability**	**Impact**
Very High	Highly likely to occur.	Severe influence on impact types
High	Likely to occur.	Considerable influence on impact types
Medium	Possible to occur.	Notable influence on impact types
Low	Most likely will not occur.	Minor influence on impact types
Very Low	Highly unlikely to occur.	Negligible influence on impact types

Qualitative analysis investigates the why and how of decision making, not just what, where, and when. Frequently, smaller samples are used rather than large samples. Qualitative methods produce information only in respect of a particular case study, with more general conclusions being only informed assertions (Ayyub, 2003c; Spiggle, 1994). Qualification is used when these two parameters are described using words. For example, the impact might be described as high, low or moderate, with the likelihood of probability as probable or not very likely. Descriptive words are used because it is extremely difficult to assign an actual value. Although descriptive classifications are usually easier to assign their usefulness is limited (Ayyub, 2003c; Spiggle, 1994).

Semi-quantitative analysis

Semi-quantitative analysis does not seek a precise answer, it looks for an approximation; the method allows analysts to apply quantification such as using a predetermined scale. Numerical scales are used for consequences and probability and combine to form the level of risk. This type of analysis is particularly useful in cases where quantified data might fluctuate periodically (BSI, 2010), it is generally used before quantitative analysis (Aven, 2008). Table 3.6 provides an example of the typical scaling factors (Vose, 2010).

Table 3.6 - Example of semi quantitative scale

Category	Score
Very high	5
High	4
Medium	3
Low	2
Very low	1

Quantitative analysis

Quantitative risk analysis further refines the scores identified through semi quantitative analysis; the accuracy of the scores is further improved by a more in depth evaluation of the data. Quantitative research relies exclusively on the analysis of numerical or quantifiable data. Quantifying the probability of a risk occurring is frequently more subjective than when attributing a score to an impact. In an ideal world, the probability could be derived statistically from historical data. This is frequently not available or not in a form or quality to be able to make statistical comparisons. In the absence of good historical data a subjective assessment has to be made; this can utilize any historical data available as well as experience and opinions (Vose, 2010).

There are a variety of techniques which enable quantitative risk analysis, such as; decision tree analysis, sensitivity analysis, Monte Carlo simulation and Markov analysis (BSI, 2010).

Decision Tree Analysis

Decision trees are a simple but powerful form of multiple variable analysis; it gets its name from the structure that can be drawn from a possible decision having alternatives and these in turn having further possible alternatives (Godfrey, 1996). The tree structure when drawn shows all possible paths (branches) that can be taken towards making the decision. If it is possible to evaluate the probability and impact of every option either by assigning values subjectively or in some other way, then an expected value helps to define the level of risk applicable to each option.

Sensitivity Analysis

Most decision analysis has numerical inputs that are not completely certain (French et al., 1998). As the output from using a decision model critically depends on the data used as input parameters it is necessary to understand the effect that the uncertainties have had on the inputs. Uncertainty can emanate from several aspects such as numerical failure to calculate a parameter correctly, inaccuracy with making a judgemental estimate, imprecision and/or ambiguity of meaning. Consequently, the effect that the almost inevitable present uncertainties have on how a decision is ranked needs consideration, as does the changed values and outputs from the model (Insua and French, 1991; Jessop, 2004).

Sensitivity analysis involves establishing the size and significance of risk to various input parameters; it identifies the variables that must be accurate and those that have less importance on the size of the risk Vose (2010). Although a very commonly used technique it only allows the variable under consideration to change and yet it is commonly used in conjunction with Monte Carlo simulation which allows every variable to vary simultaneously (Flanagan and Norman, 1993). The findings from a systematic review should be independent and not based on arbitrary decisions, as sensitivity analysis involves a repeat of the primary

analysis or substitution of alternative decisions/ranges of values for decisions that were arbitrary (BSI, 2010). Many issues suitable for sensitivity analysis are only identified during the review process when any peculiarities of the studies under consideration are identified. When sensitivity analyses show that the overall result and conclusions are not affected by possible different decisions made during the review process, the review results offer a higher degree of certainty (Vlasta Molak, 1997). Sensitivity analyses are sometimes confused with subgroup analysis. Although some sensitivity analyses involve restricting the analysis to a subset of the totality of studies, the two methods differ in two ways. First, sensitivity analyses do not attempt to estimate the effect of the intervention in the group of studies removed from the analysis, whereas in subgroup analyses, estimates are produced for each subgroup. Secondly, informal comparisons are made between different ways of estimating the same thing, whereas in subgroup analyses, formal statistical comparisons are made across the subgroups. The findings of sensitivity analysis are best presented in a summary table (Ayyub, 2003c).

Monte Carlo Simulation

Monte Carlo simulation involves the random sampling of each probability distribution within the risk model to produce a specified number of simulations; each probability distribution is sampled in a manner that reproduces the distribution shape. Monte Carlo simulation can be applied to any deterministic problem which contains variables; it allows distributions of any shape to be defined for those variables. There are many types of probability distributions, namely; discrete, binomial, triangular, normal, PERT, Poisson, and beta (the most commonly used is the triangular distribution) and some examples are shown in Figure 3.5 (Vose, 2010).

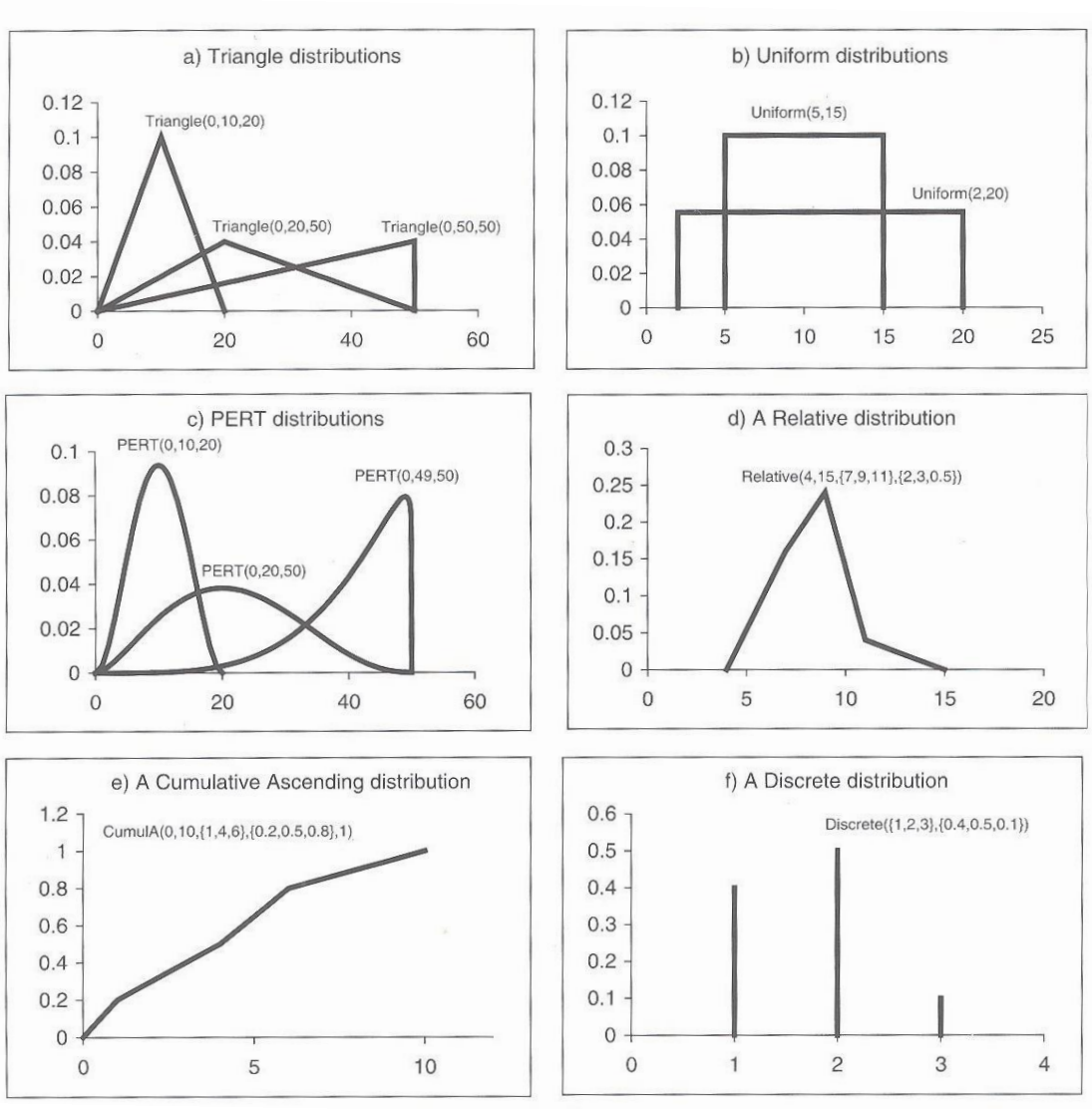


Figure 3.5 - Examples of probability distributions (Vose, 2010)

Monte Carlo simulation is computerized, there are two methods by which the numbers can be produced; either by using generated random numbers or using a stored table of random numbers. Monte Carlo simulation is excellent at estimating the mean and standard deviation of a distribution, but very inaccurate at estimating the unlikely extremes (the tail of the distribution) (Williams, 2014). Despite this problem, Monte Carlo simulation is one of the major analytical tools used in quantitative risk analysis (Coleman and Litterman, 2012).

Monte Carlo simulation offers several advantages over other modelling techniques:

1. It is widely recognized, so as a consequence its results are likely to be accepted.
2. Changes to the model are easy to make and the results compared easily with previous models.
3. The simulation only requires a basic level of mathematics to perform, with readily available software able to complete the simulations specified.
4. The distributions of each input variables do not have to be approximated.

Markov Analysis

Markov analysis is a method for forecasting random variables. This type of analysis provides a means of analysing the reliability and availability of systems which have strong dependencies. Many other system analysis methods assume component independence which can lead to optimistic predictions for the reliability parameters. Markov analysis assumes that the future is independent of the past given the present. The random variable is recorded in time; and can either be discrete or continuous. It is used in accounting to estimate bad debt. It can also be used in modelling the future brand loyalty of consumers, based on their current rate of purchases and repurchases. In quality control, Markov analysis is applicable to common problems and other sequence dependent events (Ayyub, 2003c; Jordaan, 2005a; Merna, 2008b). A typical use of this model is the analysis of common spares with a limited on-site stock. The major problem with this method is that Markov diagrams drawn in relation to big systems are very large and complicated to construct Merna, (2008b).

The Markov model and the Monte Carlo simulation are both stochastic modelling techniques, namely; they can deal with events having an element of chance and hence a set of

possible outcomes as opposed to a deterministic model where a single outcome is derived from a defined set of circumstances. They are both statistical techniques used in forecasting the future behaviour of a variable or system whose current state or behaviour does not depend on its state or behaviour at any time in the past.

3.11.2.3 Risk Evaluation

Risk evaluation concerns comparing the modelled measures of risk with the risk criteria initially established. The evaluation determines the significance of the level and type of risk. The understanding of the risk obtained during risk analysis helps to make more informed decisions as to what action to take. Legal, financial and ethical considerations, and the perception of risk can also be inserted into the decision (BSI, 2010).

3.11.2.4 Risk Treatment

Risk treatment involves selecting one or more options for modifying the acknowledged risks, and implementing those options. Once a treatment has been implemented, it becomes a control or it modifies existing controls. There are many treatment options for example, removing the source of the risk, avoiding the risk, reducing the risk, modifying the consequences, changing the probabilities; it is also possible to simply retain the risk or to increase it (BSI, 2010).

3.11.2.5 Communication and Consultation

This is a dialogue between the stakeholders and the organization, this two way process should be iterative and continuous. Information is received and shared about how to manage the risk. Once the process is completed decisions are made by the organization alone (ISO 31000, 2009).

3.11.2.6 Monitor and Review

Some risks will no doubt change over time; some may even change to the extent that they invalidate the risk assessment, such factors need to be identified so that a continuous monitoring and assessment process can be implemented. Similarly the data associated with each risk needs monitoring and reviewing. The effectiveness of the controls similarly needs to be monitored and documented. A system whereby the risks are periodically reviewed needs establishing, such a system needs to be supported with a proper level of documentation and accountability (BSI, 2010).

3.12 Review of previous studies

3.12.1 Identifying the uncertainties within highway drainage systems

Identifying uncertainties that influence the functioning of a particular drainage system is a complex issue, as it varies from country to country and can be affected by a variety of factors including rainfall and materials of construction. Consequently, no universal framework or methodology exists for categorising and assessing modelling uncertainties (Walker et al, 2003). Montanari (2007) suggested uncertainty assessment in hydrology lacked coherent terminology, and this factor influenced the lack of a systematic approach. However, Butts et al (2004) listed model parameters; input data and calibration data and model structure as the sources of uncertainties.

A variety of highway drainage models have been constructed involving the inclusion of identified uncertainties, each with the aim of better understanding the system to improve operational performance. Benzerra et al (2012) developed a model to achieve sustainable management in respect of the drainage systems installed in Jijel, Algeria. The installations comprised numerous separate stand-alone systems constructed with the sole objective of

transporting storm water and wastewater. None of the schemes benefitted from being part of an overriding strategy or had consideration to any of the other schemes. As a consequence future service provision and managerial constraints were not accounted for with other issues ignored or neglected, such as management information, the lack of inclusion of environmental protection, future maintenance, and regulations applying to the installation of the systems (including design standards). The methodology for sustainable management aggregated the performance of indicators and assigned a performance score. Questionnaires were used to ascertain scores attributed to each criterion, together with the perceived impact on identified objectives. A performance score was produced for each element studied at each level, however, due to some incomplete questions the methodology was not validated. The model outcomes demonstrated that difficulties associated with acquiring precise data relating to drainage networks does not prevent the development of a predictive model. Deletic et al (2012) aimed at developing a common terminology used within modelling of highway drainage uncertainties, stating that the model parameter development and calibration process needs to strongly relate to the model application, further stating that uncertainties could be estimated if unknown, with Monte Carlo simulations often used to propagate input data uncertainties. Furthermore, each uncertainty was highly interlinked, suggesting that assessing the impact of a single parameter was inadequate and a simultaneous propagation of key sources of uncertainties is needed. Deletic et al (2012) concluded that knowledge regarding uncertainties in urban drainage was poor.

3.12.2 Flood risk analysis and management

Apel et al (2004) investigated the complete flood disaster chain of events involved with flooding, namely:

1. Precipitation
2. Runoff
3. Catchment concentration
4. Flood routing in the river network
5. Possible failures of flood protection measures
6. Economic damage

The above processes were represented by spatially distributed models, however, these models were not suitable for risk analysis as they were complex and necessitated a large amount of processing time. Consequently a simplified model was developed and analysed using a Monte Carlo framework. The probability of occurrence of events of different magnitudes, together with their predicted economic damage were calculated. The model allowed for the identification of the contribution of individual sources of uncertainty. The developed model was applied on the river Rhine near to Cologne. The research concluded this risk based approach could be successfully used to perform a quantitative flood risk analysis including the effect of levee failures. Additionally it could be used as a decision support system for operational flood control and as a cost benefit analysis of flood protection measures.

Kellagher et al (2008) developed a systematic risk based approach which assessed and managed sewerage systems based on probability and hazard impact. This approach described work undertaken in association with the Department of Trade and Industry, System-based Analysis and Management project (DTI SAM) aimed at developing a procedure, together with supporting tools, enabling decision-makers to account for both probability and

consequences of flooding by allocating proportionality to assets associated with causing floods. The methodology included a process-based quantified assessment of flood risks in an urban area, an essential requirement for flood risk management. The developed methodology was intended to support asset managers in the prioritisation of intervention works and in making the most cost effective use of available funds.

Escuder-Bueno et al (2012) developed a risk based approach to integrate social research data into flood risk analysis, this aimed to support decision making on non-structural protection measures. The approach involved the quantification of flood risk in urban areas and evaluated the different scenarios comparing them to the impact of non-structural measures on risk reduction. The main advantage of the developed methodology was the provision of a quantitative estimation of flood risk before and after investing in non-structural risk mitigation measures. Smith (2003) discussing flood defence designs believed it 'completely unethical and irresponsible' for designers to ignore uncertainties in the design process. Similarly, Chang et al (2013) considered flood defence systems should have all uncertainties incorporated into the design process; as without this them the decision maker could not consider all the risks. The increased incorporation of uncertainty within the design process was recognized by (Spink et al, 2014).

3.12.2.1 Quantification of an urban drainage risk management (UDRM) system

Despite remarkable advances in highway drainage systems designs and urban flood management techniques, flooding remains an international inconvenient expensive issue to cope with. This is partly attributed to uncertainties in rainfall events which can disrupt the normal performance of an urban drainage system and eventually lead to inundations and damages. Tahmasebi Birgani and Yazdandoost (2014) argued that the conventional urban drainage management approach, which tends to focus on system security in the face of extreme rainfall, needs to be modified. The study emphasized the need to address both the

level of drainage security and the consequences of flooding in an urban area (Tehran in Iran). Based on the concept of risk management, 'persistence' for an urban drainage system was consequently based on the joint consideration of resistance and resilience. 'Persistence' was defined as 'the ability of a disturbed system to resist, buffer the effects of variable disturbances and return to a recognized level of performance after disturbances'. The study included four indicators within the model namely; the magnitude of reaction, the resistance capacity, recovery capacity and a graduation level representing the proportionality of the damages (extracted from other studies). The study concluded that analysing an urban drainage system in the modelled way demonstrated that the ability of a drainage system to return to a normal level of performance can efficiently enable managers and urban planners to further appreciate the impacts of different urban drainage measures on the behaviour of the urban drainage risk management system faced with extreme rainfall events. However, the study did not investigate which measures had specified impacts and further research based on these findings is required to ascertain the impacts associated with a variety of interventions.

As a case study, Tahmasebi Birgani and Yazdandoost (2014) analysed part of the urban drainage system of Tehran, Iran using the proposed scheme. Four urban drainage measures including three best management practices and a conventional system were added to the current urban drainage system to assess the performance of various measures in improvement of the persistence of UDRM systems. Results indicated that the analysis of the systems persistence can efficiently enable urban planners to select measures with an insight into the behaviour of the UDRM systems faced with disturbances.

3.12.3 The use of a risk based approach in other relevant sectors

Highways

Decò and Frangopol (2011) utilized a quantitative risk assessment in relation to highway bridges under multiple hazards. The consequences associated with structural failure or malfunction was associated with the probability of bridge failure. The estimation of the effects of numerous common hazards, for example abnormal traffic loads were included in the model as was the probability of failure associated with the hazards. The research showed that time dependant total risk profiles of a bridge under multiple hazards can be predicted, assisting in the decision support framework.

Evdorides et al (2013) developed a verified analytical methodology for a qualitative and quantitative assessment of the reliability of pavement-performance models linked with the variability of the data considered in the models. The developed models identified the mostly influential parameter on pavement performance expressed in terms of roughness. The methodology utilised the Monte Carlo data generation technique to develop appropriate performance models enabling the effects of the variability of the model parameters of the performance predicted to the analysed. The prediction of performance made by the models were assessed quantitatively, they showed that they were in close agreement with the progression of historical data.

Schlotjes et al (2015); Schlotjes et al (2013) developed a method to predict the probability of structural failure of road pavements utilizing information obtained from New Zealand road data sets. The method was based on using expert opinion to develop failure charts in relation to the predominant types of failure on a road pavement which could be used in the identification of contributing factors to pavement failure. The probabilities obtained for each failure type were used to determine an overall probability of pavement failure.

Railways

Decisions need to be made in a robust transparent way and demonstrate the viability of an investment to satisfy the need of stakeholders. They need to be taken in an objective manner after recognizing the uncertainties, and with the least possible subjectivity. The inaccurate forecasting of project capital costs and the associated need to make a return on investment is a worldwide issue. The removal of as many uncertainties as possible from the forecasting process attached to the establishment of project capital costs is consequently a factor that could reduce the threat of a project becoming unviable. This is a recognized problem as large infrastructure costs have been found to be inaccurately forecast within the UK by on average 20.4 percent for roads and 33.8 percent for tunnels and bridges (Flyvbjerg et al, 2004).

With a view to helping better identify how to improve the forecasting process attached to the establishment of project capital costs within the rail industry and consequently help reduce the threat of a project becoming unviable, a study by El-Cheikh et al (2013) developed a new mathematical model. The model was based on fuzzy sets theory to address the limitations inherent in traditional methods used to select the preferred investment option. The developed method demonstrates that fuzzy set theory is a good tool to use to overcome subjectivity and support economic analysis. Another approach developed by Usman et al (2015) to understand the causes of drainage related railway track failure combined the use of cause and effect analysis allied to fault tree analysis. This two stage approach initially developed fault trees from a cause and effect analysis that was informed by expert opinion and the literature. The Fault Trees can be used by railway asset managers to isolate or influencing failure factors, identify associated failure paths and linkages between these and the influencing factors, and; assist in diagnosing the cause of failure leading to the identification of remedial action.

3.13 Summary

Chapter 2 identified that in order to function properly sufficient drainage provision must be made to keep a pavement clear of water; the UK drainage design was illustrated. In order for a designed system to remain at optimum performance it has to be managed and maintained. To this end, this chapter has considered management maintenance in the context of highway infrastructure aimed at retaining functionality.

The need for a highway authority to construct an up-to-date comprehensive asset management plan has been clearly established as is its relevance to the acquisition of funding. Despite the importance of such plans their formulation remains at varying stages of development and sophistication, however progress continues, possibly partly influenced by access to funding and partly by the increased realization that quick access to asset details assists in prioritizing and scheduling maintenance and reducing costs. The lack of historic data regarding sub-surface asset condition surveys was found to contribute to the overall inadequacy of asset records, however, IAN 147/12 partly addresses this problem, having introduced more cost effective methods of determining drainage inventory condition. A more comprehensive way of ascertaining the health of a drainage system is considered with the appreciation that a diagnosis will always be time-specific. Whilst a need to physically inspect assets, wherever possible, may always remain, a need for more research investment into remote control monitoring capable of assessing the health of assets is recognized.

Flood risk management was found to be governed by multiple legislation and regulations applicable nationally, regionally and locally, with flood risk identified as dynamic both in space and time, with both aspects needing to be reflected in associated risk assessment. Flood risk management was found to utilize the risk management framework recommended by BSI (2010).

The theoretical concepts of risk and uncertainty were explored, with the literature reflecting that the management of risk in industry is increasingly recognized as an important part of decision making. The purpose of risk analysis is to help managers better understand the risks and opportunities they face and to evaluate the options available. A probability of possible occurrence, together with its consequence, is then attached to each identified risk; semi quantitative analysis frequently uses five categories (highly likely to occur to highly unlikely to occur) which are assigned to each probability and consequence, the multiplication of probability and consequence identifies the hierarchy of risks. A review of various quantitative analysis techniques was undertaken in order further investigate the highest risks identified through semi quantitative analysis. Monte Carlo simulation was found to offer several advantages over the other modelling techniques reviewed. It allowed for distributions of any shape to be defined for the variables modelled.

A review of previous studies relating to the use of a risk based approach was undertaken. It was identified that a variety of drainage models have been constructed with a view to better understanding a system and so improving operational performance. Identifying the uncertainties influencing the functionality of a particular drainage system is a complex issue which varies from country to country, with no universal framework, terminology or methodology for categorizing and assessing modelling uncertainties in existence. No research was found specifically relating to the uncertainties associated with highway drainage infrastructure flooding.

The use of expert opinion was found to be increasingly used to help analyse and ascertain a meaningful understanding of some complex problems. Although the literature review provided a variety of opinion as to the minimum number of experts it was necessary to involve in a qualitative survey no definitive minimum number was ascertained, although the numbers suggested were generally small.

This chapter has examined the current maintenance procedures undertaken by highway authorities in relation to highway drainage infrastructure (Research Objective 2). It has also explored the uncertain threats associated to highway drainage assets which may cause them to flood (Research Objective 3). The discipline of risk management has been identified as a suitable framework to facilitate highway drainage management (Research Objectives 4 and 5). Another issue of major importance to potentially affect road drainage infrastructure maintenance and management is the potential impact of climate change.

The following chapter is concerned with climate change; a summary of the existing UK climate and current rainfall patterns is provided as are some findings of The Intergovernmental Panel on Climate Change (2007) and the UK Climate Impacts Programme (UKCIP). How current rainfall patterns may change in the future and how any increases in precipitation may potentially impact on existing Intensity, Duration and Frequency (IDF) curves is discussed together with the possible resultant consequences for highway drainage systems.

CHAPTER 4 IMPACT OF CLIMATE CHANGE ON SURFACE DRAINAGE SYSTEMS

4.1 Introduction

This chapter is concerned with climate change; it focuses on its potential impact on rainfall intensity, duration and frequency, and associated IDF curves and their influence on the design of highway drainage systems. Section 4.2 provides a summary of the existing UK Climate and current rainfall patterns. Section 4.3 briefly examines some findings of The Intergovernmental Panel on Climate Change (2007), the UK Climate Impacts Programme (UKCIP), and other relevant research. Current rainfall patterns and frequency of extreme events are explored in Section 4.4. Section 4.5 identifies the impact of climate change on local authorities; predicted increases in rainfall could increase the vulnerability of highway drainage systems due to lack of capacity.

4.2 Existing UK Climate

'Climate' refers to a region's long-term weather pattern, it is measured in terms of maximum and minimum temperatures together with average precipitation across the seasons. Precipitation includes rainfall, fog, mist and snow.

The overall climate in the UK is officially described as 'temperate maritime' having mild temperatures usually not much lower than 0ºC in winter and rarely higher than 32ºC in summer. The UK weather is known for its variability as it can change on a daily basis; month by month, and year by year, and across the counties (Jenkins et al, 2009).

The North Atlantic Drift is the main ocean current that effects the country, warming it by 5 to 8C. However, the air that comes across the Atlantic Ocean is quite moist and helps bring some wet weather. Changes in topography and land use over relatively short distances,

together with the long coastline and numerous islands, helps explain the variety of weather experienced. The south and east are usually drier, and warmer, having more sunny days and less wind than the north and west. These favourable weather conditions usually occur more often in the spring and summer than autumn or winter (Murphy et al, 2009).

4.2.1 Current rainfall pattern

The UK Met Office has been responsible for recording rainfall for many years and has used a variety of different recording stations; this fact, taken together with the fact that a variety of methods were used to record the rainfall, has meant that until the process was regularised a lack of consistency existed across the sites, aggravating the interpretation of some historic data (Met Office, 2013c). Jenkins et al (2009) examined trends in rainfall and found that the annual mean rainfall over England and Wales had not changed significantly since records began in 1766. However, the proportion of winter rainfall falling in heavy rainfall events has increased over all UK regions since 1965. In summer, rainfall decreased in all regions except north-east England and northern Scotland. The annual rainfall (1910-2014) for England is shown in Figure 4.1. It can be seen there is a good consistency of precipitation over the recorded period (Met Office, 2013a).

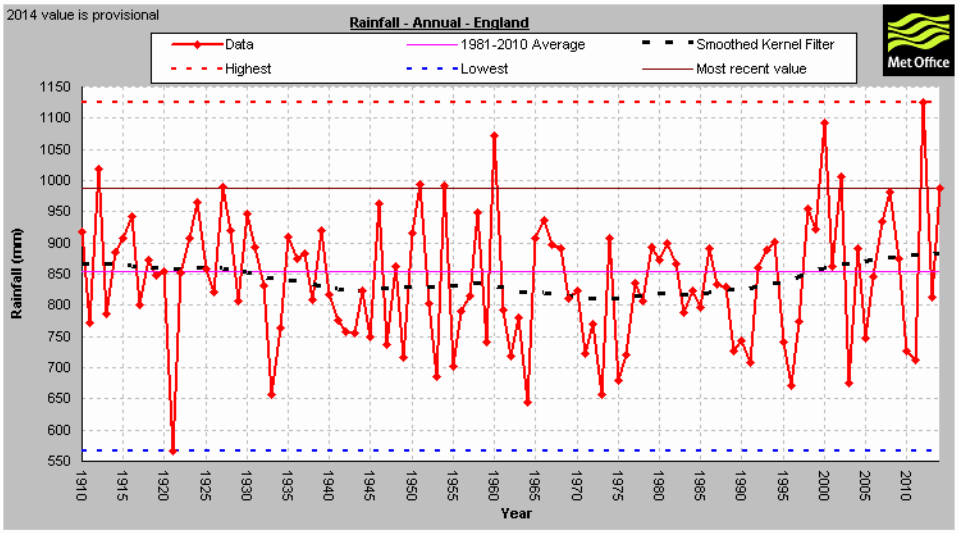


Figure 4.1 - MET Office England Annual Rainfall (1910-2014) (Met Office, 2013a)

4.3 The changing climate

4.3.1 IPCC approach

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the United Nations Environment Programme and the World Meteorological Organization (WMO); scientists from many countries offer contributions (IPCC, 2014). IPCC (2007) defined 'climate change' as 'A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer'. Climate change in IPCC usage refers to any change in climate over time, whether due to natural variability or resulting from human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UFCCC), where 'climate change' refers to 'a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which in addition to natural climate variability is observed over comparable time periods (IPCC, 2007). Although the definitions vary slightly UNFCCC and the IPCC concluded that the climate is changing, with the findings of the IPCC accepted by many scientists and governments including the UK Government. Their basis for explaining future climate changes is related to an increase of greenhouse gases in the atmosphere allowing direct sunlight to reach the earth's surface unimpeded. The degree that such gases can influence climate change depends on its concentration, length of stay in the atmosphere and ability to impact global temperature (EPA, 2015).

4.3.2 The UK Climate Impacts Programme (UKCIP)

The UK Climate Projections (UKCP09) is a service offered by UKCIP (Murphy et al, 2009), it uses projections based on a Met Office methodology and reflects current understanding of how the climate system operates and incorporates likely future changes.

Appropriateness and limitations of using data provided by UKCIP

The details provided are the most up-to-date currently available, and although climate models will never be able to exactly reproduce the real climate system enough similarity exists between current climate models and the real world to give confidence that they provide plausible projections of future climate changes (UK Climate Projections, 2014). The probabilities provided represent the relative degree to which each climate outcome is supported by the evidence currently available, taking into account current understanding of climate science and observations, and using expert judgement. A good degree of confidence exists in climate projections; however, future improvements in understanding, modelling and statistical capability mean that the projections may change.

Limitations of using the UKCIP data

All climate change projection methods incorporate a range of assumptions. The modelling and statistical framework developed by the Met Office Hadley Centre to produce UKCP09 includes consideration of the drivers of uncertainty known to be important; and sufficiently well understood to be included in the climate models used to make the projections. However, not all forcing processes and feedbacks are included either because their importance is thought to be small or because they are currently too poorly understood to be included in a credible way (such as the

feedback between climate change and the methane cycle). The effects of known but poorly understood processes imply a component of uncertainty which is currently unquantifiable, and consequently not included in the data. Further limitations on the overall accuracy of the data are provided at (UK Climate Projections, 2014).

Projections show there are likely to be hotter drier summers; warmer wetter winters, sea level rises; and an increase in extreme weather events such as heavy rains and heat waves. The long-term severity of these changes depends to some extent on the international success in reducing carbon emissions. UKCP09 climate projections are available for high, medium and low emissions scenarios, 5km and 25km gridded resolution for each emission scenario are also available. The central estimates predict the mean annual precipitation for the UK will remain the same, estimates at the 10% probability level show maximum annual regional increases of 14% with decreases of 16% in some areas, shown in Figure 4.2 (Murphy et al, 2009).

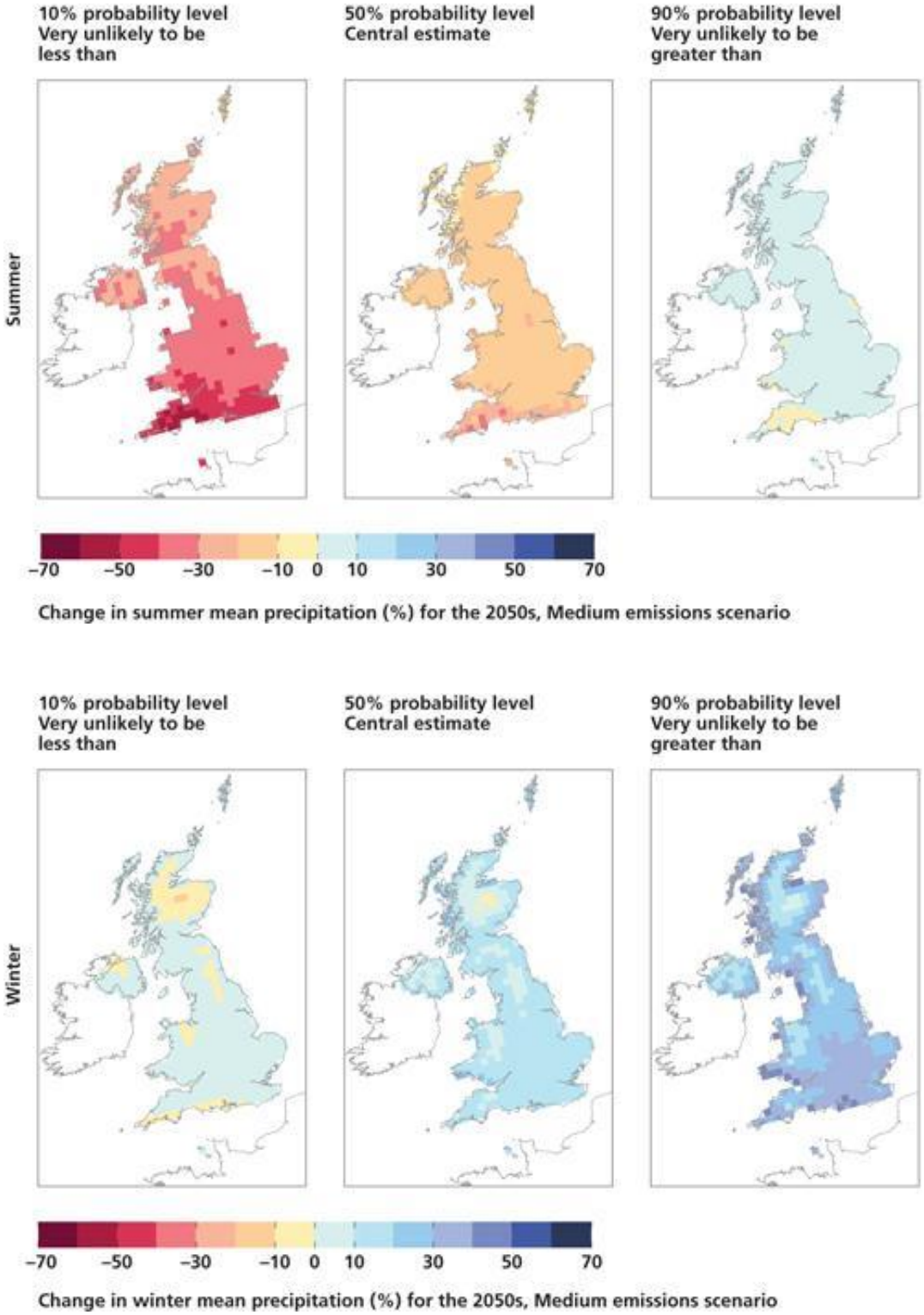


Figure 4.2 - 2050s, medium emissions scenarios estimated percentage change in mean summer and winter precipitation (Murphy et al, 2009).

4.3.3 Other research on climate change

Stern (2007) took an international perspective when examining the scientific evidence, and concluded that a powerful body of evidence indicated climate change was a serious and urgent issue, with more research being needed. The causes and consequences of climate change globally were considered, with the conclusion that the resultant problems necessitated deeper international co-operation. Climate change was also considered the greatest ever challenge to economics. Murphy et al (2009) similarly accepted the urgent need to adapt to the developing situation and minimize the worst consequences whilst maximizing any opportunities. Bours et al (2013) also concluded that climate change adaptation policies, programmes, and projects need to effect change from international governance down to changes in individual behaviour, with issues needing addressing urgently.

Alternative views are normally associated with any area of research and climate change is no exception; not all scientists view climate change in exactly the same direct way. For example, Lomborg (2010) accepted global warming but considered the current policies instigated to curb pollution as expensive, with little ability to curb economic growth and development. A small minority, claim climate change is explained by sun variability, with future warming quite possibly being moderate (Lockwood and Fröhlich, 2007; Zastawny, 2006). Mountford (2010) reviewed the work of the IPCC and concluded 'the public has been fed a particular variant regarding the climate change story with many of the caveats removed'. However, the overwhelming consensus indicates global warming is an ongoing phenomenon that will continue for decades, whatever strategies are implemented, and it will create numerous environmental problems including changes to the hydrological cycle (Trenberth et al, 2006; Holman, 2006; IPCC, 2007; Milly et al, 2005;

Dragoni, 1998). A very large consensus of research supports the view that anthropogenic activity remains the major factor causing current global warming, for example, (Kerr, 2007; Trenberth et al, 2006; IPCC, 2007).

4.4 Changes in Frequency (Return Periods)

As previously noted in Section 2.5.3 highway drainage systems are designed to a return period or a rainfall event (the frequency of the rainfall occurring), calculated using historic data (Butler, 2010). For example, using 100 years of daily rainfall data, an event with a 1 in 20 year return period would be expected to occur 5 times in a dataset and on average once every 20 years (Sanderson, 2010). Consequently, any increase in the frequency of extreme events will adversely impact the ability of highway drainage infrastructure to perform as intended.

Heavy rainfall events occurring in winter have increased for all areas over the past 45 years (Sanderson, 2010). For example, 2012 was the second wettest on record with 486,000 flooded property claims made by UK residents; approximately half of the reported damage related to pluvial flooding on a floodplain. At the end of 2012 accumulated insured flood losses reached £1.2 billion, the second highest amount recorded (Harrabin, 2012). Paul Mustow (2012), head of flood management at the Environment Agency stated 'We have to get our heads round the possibility now that we're going to have to move very quickly from drought to flood - with river levels very high and very low over a short period of time. The massive variation of weather in 2012 clearly demonstrated UK drainage installations need the capacity to deal with a diverse precipitation range in order to protect a road and minimise runoff to surrounding areas'.

In 2010 OFWAT commissioned the Met Office to present guidance on future daily rainfall return periods for England and Wales, this resulted in future daily rainfall return periods

being calculated for 40 towns and cities in England and Wales for 1 in 5, 10, 20, 30, 50 and 100 years using observed rainfall amounts for winter (December, January and February) and summer (June, July and August) under the climate scenarios 2040, 2060 and 2080. The calculations utilized an 11 member ensemble of regional climate projections alongside the UKCP09 climate projections, the projections used are classified as medium emission scenarios (Sanderson, 2010). Utilizing the 10th, 50th and 90th percentiles of future rainfall distributions, for both winter (December-February) and summer (June-August) rainfall for the 2040s (2030-2059), 2060s (2050-2089) and 2080s (2070-2099), estimated changes in return periods for rainfall events currently having return periods of 1 in 5, 10, 20, 30, 50 and 100 years, were calculated for 40 locations (Sanderson, 2010). Further information as to methodology used to produce future daily rainfall return periods can be found in (Sanderson, 2010).

Figure 4.3 and Figure 4.4 illustrate the projected changes (winter rainfall) for Sheffield. Return periods are displayed on the y-axis. The solid line signifies the central estimate (50th percentile), the dotted lines represent the possible range of return periods determined using the 10^{th} and 90^{th} percentile. The difference in return period for rainfall events with present-day return periods of 1 in 5 (red), 1 in 10 (green), 1 in 20 (blue), 1 in 30 (orange) as shown in Figure 4.3 and 1 in 50 (purple) and 1 in 100 years (grey) as shown in Figure 4.4. Current return periods are positioned at 1980 on the x-axis (marked 'Present'). The y-axis scale is different for each panel (Sanderson, 2010).

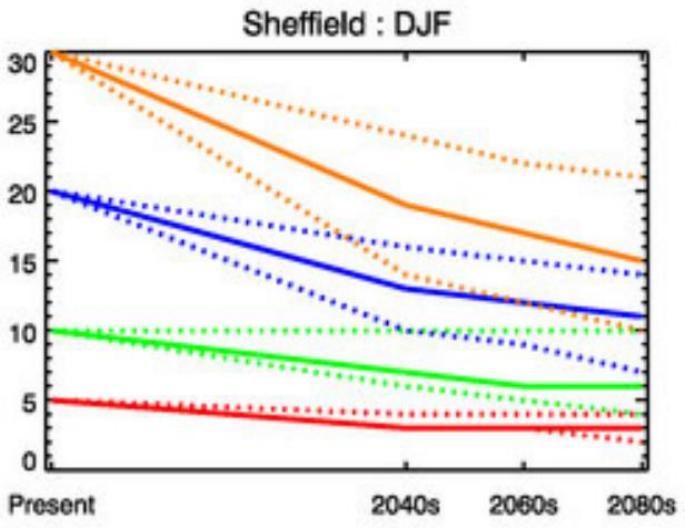


Figure 4.3 - Predicted change in return periods for Sheffield (1 in 5,10,20,30 year) (Sanderson, 2010)

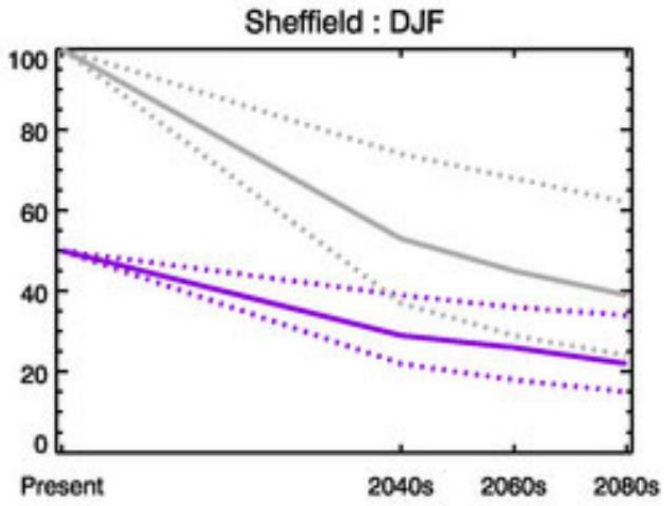


Figure 4.4 - Predicted change in return periods for Sheffield (1 in 50 and 100 year) (Sanderson, 2010)

KEY: 50th Percentile

- 1 in 5 year
- 1 in 10 year
- 1 in 20 year
- 1 in 30 year
- 1 in 50 year
- 1 in 100 year

The dotted lines represent the possible range of return periods determined using the 10th and 90th percentile.

4.4.1 Intensity, Duration, Frequency curves

As described in Section 2.3 an IDF curve signifies the relationship between the intensity (I) and duration (D) of a rainfall event with a given return period (F). The curves can be compiled for any location, using either the FSR or FEH methods (Butler and Davies, 2011). IDF curves are vital when using the modified rational method to determine the critical mean rainfall intensity for use in designing and constructing urban drainage systems. The process of creating IDF curves has limitations; it uses the assumption that recorded extreme rainfall is appropriate to characterize future extreme precipitation. As future climate change indicates an increase in extreme weather events including heavy rains of greater intensity this assumption is becoming increasingly invalid (Boucher, 2010). As a consequence highway drainage infrastructure designs using existing IDF curves may well be not be sufficiently accurately advised (X. Wu, 2012).

The existence of IDF curves created from old data is recognized and new curves are being developed, however, rectifying the situation has an associated cost (Boucher, 2010). Urban drainage computer packages, discussed previously in Section 2.7 utilize a database of existing IDF curves consequently many LAs do not seek an updated IDF curve prior to site development (Russell, 2013). Such packages automatically determine the mean critical rainfall intensity for a specific return period and duration through either the FSR or FEH methods; although new IDF curves can be adjusted to presume an increase of intense rainfall caused by climate change (Willems et al, 2012).

It was beyond the scope of this research to create a new IDF curve in relation to the case study site (Chapter 5); the site had been designed using the FEH method (Russell, 2013). Consequently, the developed risk model used in the study incorporated climate change using data produced by Sanderson (2010) this is described in Section 6.4.7.

4.5 Impact of Climate Change on Local Authorities

Local authorities acknowledge the continuing evidence that supports the view that the climate is changing, they also accept it will impact the UK's economy, society and environment (Local Government Association, 2012). In 2000 Nottingham developed guiding principles to help cities cope with climate change, in January 2015 over 300 local authorities had signed the Nottingham Declaration (Climate East Midlands, 2015).

The Climate Change Act 2008 established a new method of managing and responding to the threat of increasing carbon dioxide levels. The Flood Risk Regulations (2009) implemented the requirements of the European Floods Directive, which was aimed at providing a consistent approach to managing flood risk across Europe. This legislation tasked some Lead Local Flood Authorities (LLFAs), Natural Resources Wales and the Environment Agency to produce Flood Risk Management Plans by December 2015 in England and Wales.

The Pitt Review (2008) see (Section 3.103.10.2) reported on flood risk management in England and Wales following the extensive floods of 2007. The resulting Flood Water and Management Act (FWMA) (2010) created additional responsibilities for upper-tier and unitary authorities in relation to surface water flooding. Lead Local Flood Authorities must now implement a (LFRMS) as well as co-ordinating the activities of highway authorities and other risk management authorities, as a consequence LA's produce a Surface Water Management Plan (SWMP).

4.5.1 3 Counties Alliance Partnership (3CAP)

In July 2007 Derbyshire, Leicestershire and Nottinghamshire County Councils and business consultants United Research Services (URS) collaborated to form the 3 Counties Alliance Partnership (3CAP). 3CAP aimed at improving the delivery of highway and other professional services by combining resources to make cost and efficiency savings

(Leicestershire County Council, 2010), by 2014 two thirds of local highway authorities had formed alliances with other authorities, resulting in reduced costs. However, not all local authorities had adopted such good practice (Public Accounts Committee, 2014a).

Walters, (2009) found the total number of flooding events was not likely to drastically increase as a result of climate change, but considered that:

1. The intensity and impact of flooding events was likely to increase.
2. Locations not currently defined as 'hot-spots', namely prone to flooding during periods of heavy or prolonged rainfall, may become vulnerable.
3. Existing flooding 'hot-spots' will become more at risk during periods of heavy or prolonged rainfall.

3CAP undertook a risk assessment relating to the effects of each recognized key climate change types (hotter/ drier summers, more intense rainfall, stronger winds and more storms, warmer winters) in relation to their highway networks lack of capacity within the system, as a consequence network flooding was clearly identified as the highest risk (Walters, 2009). Identified vulnerabilities to climate change are shown in Table 4.1. Without action to adapt drainage design to climate change the frequency of flooding may not increase but the impact and number of locations affected will be (Walters, 2009). In relation to the scope of this study, Table 4.2 taken from Walters (2009) shows more intense rainfall increasingly strains the highway drainage system.

Table 4.1 - Vulnerabilities to climate change identified by 3CAP, taken from (Walters, 2009)

Drainage	Structure	Environment
• Lack of information on the asset in terms of location, condition and capacity • Lack of capacity • Differences in the maintenance regimes between the authorities and the asset owner(s) • Lack of records on damage to utilities • Property flooding • Problems with network availability during periods of flooding • Pavement damage • Embankment slips • Increased maintenance costs • Impact on the soft estate • Public health risk from sewer overflows • Road safety issues • Increased budget demands • Costs associated with clearing up after flooding • Staff and resource issues • Top soil run-off • Damage caused by tree roots • Rising water tables. • Effects of development on floodplains and hard paving	• Surface damage to structures from high temperatures • Bridge bearing and joint damage • Increased deterioration to paint on steel structures • Lack of capacity to deal with increased rainfall • Scour • Saturated backfill leading to instability • Risk of landslips • Embankment erosion • New structures will require greater capacity than currently specified • Subsidence and heave of shallow foundations • Differential settlement of foundations • Road sign and gantry damage from strong winds • Vehicles blown over on high bridges • High risk to lightweight structures for example suspension bridges. • More risk to trees and saplings from scour, flooding and prolonged high temperatures • Vegetation ingress onto structures • Lengthened growing season and increased biodiversity leading to fewer opportunities for maintenance activities	• Temporary or permanent loss of parts of the network to flooding • Issue of waste disposal after flooding and potential pollution issues • Heat damage to concrete and asphalt roads • Structural damage and shrinkage • Fire risk from dry verges • Risk of tree damage from high winds • Increased accidents on the network • Impact on the travel plans of pedestrians and cyclists • Safety, visual and mowing regimes will need to be increased to meet the lengthened growing season • Increased leaf-fall blocking drains • More vegetation on the soft estate • Some tree and plant species will die and others will thrive • Increased to clear vegetation away from road signs and street lights. • Unpredictable requirements from mowing during hot and dry summers • Potential for increased contamination of water sources during periods of flooding • Impacts on traffic flows, increased delays road works

Table 4.2 - Risk and Probability Assessment – More Intense Rainfall taken from(Walters, 2009)

Climate Change Type	Effect	Policies and Standards affected	impact (I)	Probability (P)	Score (I x P)	Local Authority Influence	Overall Risk
More intense rainfall	Lack of capacity in the drainage system and flooding of the highway network	Carriageway patching and minor repairs; carriageway surface treatment; carriageway resurfacing; high skid resistant surfacing; skidding resistant (SCRIM) policy; early life skidding resistance; flooding; emergency road closures and diversions; severe weather warnings; temporary signs; vehicle-activated interactive road signs; road safety; bridges and other structures; footbridges and subways; maintenance of monuments and historic structures in the highway; drainage; materials; highway inspections; consultation with parish and town councils; winter maintenance	3 There will be severe impacts on the highway network as a result of flooding. This will put huge pressure on authority resources	3 There is already evidence of this happening and it will worsen as climate change impacts develop	9	2 The LAs have some level of responsibility over the maintenance and operation of their drainage systems	18
	Scour to structures	Maintenance of street furniture; street lighting; bridges and other structures; footbridges and subways; maintenance of monuments and historic structures in the highway; earthworks; materials; flooding; drainage; highway inspections; materials; carriageway surface treatment; carriageway resurfacing; carriageway patching and minor repair	2 This will have effects on the maintenance needs of structures and will put pressure on the 3CAP region's financial and workforce resources	2 There is already some evidence of this and it is likely to increase in magnitude as climate change develops	4	3 The LAs are responsible for the maintenance and operation of the structures within their highway network	12
	Damage to pavement surface layers	Carriageway patching and minor repair; carriageway resurfacing, overlay and reconstruction; carriageway surface treatment; skidding resistance (SCRIM) policy; highway inspections; materials; flooding; drainage; winter maintenance	2 This will put pressure on the highway network and increase the need for maintenance work	2 There is beginning to be some evidence of the impact of heavy rainfall and flooding of pavement condition	4	3 The LAs are responsible for the maintenance and operation of their highway network	12

Climate Change Type	Effect	Policies and Standards affected	impact (I)	Probability (P)	Score (I x P)	Local Authority Influence	Overall Risk
More intense rainfall	Top soil run-off	Conservation; cultivation licences; edge cutting back (siding); grass cutting; maintenance of soft landscaped areas; tree and hedge maintenance; tree planting; verge maintenance; weed treatment; safety fencing; flooding; drainage; earthworks; mud or dung on the highway; highway inspections; consultation with parish and town councils; biodiversity; winter maintenance; carriageway surface treatment; carriageway resurfacing; materials	2 This may lead to increased financial and resource implications for the highway network authorities	2 There is already some evidence of this and it is likely to increase in magnitude as climate change develops	4	1 The LAs have little influence over the top soil run-off from the land around their highways	4
	Tree root damage	Conservation; cultivation licences; edge cutting back (siding); grass cutting; maintenance of soft landscaped areas; tree and hedge maintenance; tree planting; verge maintenance; weed treatment; safety fencing; flooding; drainage; earthworks; carriageway patching and minor repairs; carriageway resurfacing; carriageway surface treatment; highway inspections; consultation with parish and town councils; bridges and other structures; biodiversity; materials	2 This may have some effect on trees on the soft estate	1 Unknown probability	2	2 The LAs have responsibility for the maintenance and management of trees on land under their control	4
	Landslips	Conservation; cultivation licences maintenance of soft landscaped areas; verge maintenance; tree planting; tree and hedge maintenance; safety fencing; emergencies; emergency road closures and diversions; flooding; hazards on the highway; road traffic accidents; temporary signs; vehicle-activated interactive road signs; bridges and other structures; drainage; earthworks; mud or dung on the highway; highway inspections, biodiversity; highway patching and minor repair; materials	2 This will have some irregular and unpredictable impacts on the emergency department within the 3CAP authorities	2 There is some evidence of this already but the future probability is difficult to predict	4	2 The LAs have responsibility for the safety and maintenance of their land around the highway network	8

Climate Change Type	Effect	Policies and Standards affected	impact (I)	Probability (P)	Score (I x P)	Local Authority Influence	Overall Risk
More intense rainfall	Embankment erosion	Conservation; cultivation licences; edge cutting back (siding); grass cutting; maintenance of soft landscaped areas; tree and hedge maintenance; tree planting; verge maintenance; weed treatment; safety fencing; flooding; drainage; bridges and other structures; earthworks; mud or dung on the highway; highway inspections; consultation with parish and town councils; biodiversity; carriageway patching and minor repairs; carriageway surface treatment; carriageway resurfacing; materials	2 This will put pressure on the need for highway authorities and increase the need for embankment monitoring and general maintenance work.	2 There is some evidence of this already; it is likely to increase as climate change continues.	4	2 The LAs have responsibility for the safety and maintenance of their land around the highway network.	8
	Subsidence and heave on the highway	Carriageway patching and minor repairs; carriageway surface treatment; carriageway resurfacing, overlay and construction; edge cutting back (siding); tree and hedge maintenance; flooding, drainage, materials; bridges and other structures; earthworks; highway inspections; winter maintenance	2 This will lead to increased financial and resource implications for the highway network authorities.	2 There is some evidence of this already and it is likely to increase as climate change develops.	4	3 The LA's are responsible for maintenance and operation of their highway networks.	12

4.6 Summary

Chapter 3 examined the current maintenance procedures undertaken by highway authorities in relation to highway drainage infrastructure. It also explored the uncertain threats associated to highway drainage assets which may cause them to flood. The discipline of risk management was identified as a suitable framework to facilitate highway drainage management.

This chapter briefly identified some various opinions on climate change. There is some dissenting opinion on its legitimacy; however the overwhelming consensus view is that the projections indicate hotter drier summers; warmer wetter winters; sea level rises; and an increase in extreme weather events such as heavy rains and heat waves. The long-term severity of these changes depends on many factors including an international success in climate change adaptation policies, programmes, and projects to effect change from international governance down to changes in individual behaviour (Murphy et al, 2009; Bours et al, 2013).

Existing IDF curves have been created using historic data that may no longer be reliable for use when designing and constructing new urban drainage systems. This situation is recognized and remedial action has already started; new IDF curves incorporating climate change are being created.

Climate change will mean that the design of buildings, bridges and roads will have to withstand and disperse greater amounts of water more frequently. Enhancements in design regulations cost money, which must be factored into associated budgets if a sustainable infrastructure is to be created. Any increase in extreme rainfall events will impact urban drainage (Rodríguez et al, 2014; Willems, 2013; X. Wu, 2012).

Chapter 2 and Chapter 3, identified uncertainties associated with the design, management and maintenance of a road drainage system. This chapter has clearly identified that the changing climate is also an uncertainty that needs to be incorporated into the design of future drainage systems. The identification of these uncertainties addresses Objective 3.

Having identified the uncertainties, there remains a clear need to devise a methodology that incorporates each of them into a model that can help identify the parts of the drainage network at greatest flood risk. A proposed methodology is described in Chapter 5.

CHAPTER 5 METHODOLOGY

5.1 Introduction

Highway drainage infrastructure flooding may occur because the capacity of the infrastructure is insufficient to drain adequately a given volume of water in a given time period. Any lack of network capacity may be due to a number of reasons including inadequate design, insufficient maintenance, and changes in land use. All of these may be exacerbated by precipitation in excess of the drainage network designed (for example caused by climate change (Olesen and Rollings, 2012a)). Any increased potential for the drainage system to flood, given the limited resources available, emphasizes the need to have a regime that best prioritizes asset maintenance and infrastructure renewal (Lugg, 2012).

The goal of this research is therefore to develop a process which can assist the highway engineer in making such decisions. In order to manage this, the uncertainties considered to adversely influence highway drainage infrastructure flooding need to be better understood. To achieve this, a systematic approach was followed. Herein the research consisted of the following items:

1. A study of the components of road drainage systems.
2. An investigation of the uncertainties associated with a drainage system.
3. A study of the requirements for a risk based decision support for priority interventions.
4. An investigation of the necessary components of such a decision support management framework.
5. The implementation of the framework via a case study.

5.2 System requirements of components

It is evident from the findings of the literature review that a framework which incorporates a risk based approach is appropriate to assess the uncertainties associated with highway drainage infrastructure flooding. Such a system should integrate:

1. The risk management process
2. Drainage network analysis

This is shown conceptually in Figure 5.1.

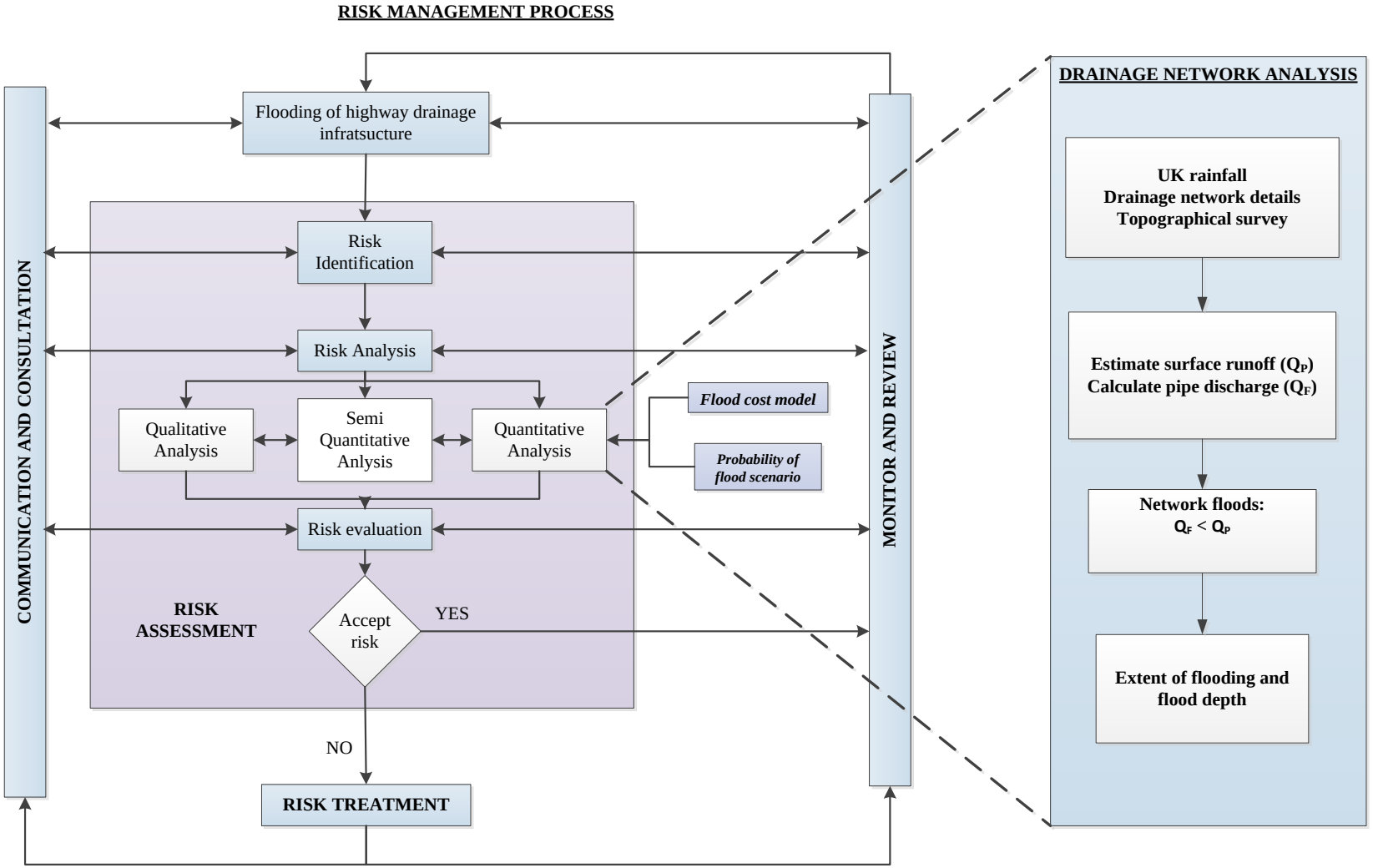


Figure 5.1 - Theoretical framework

5.3 Risk Management

Figure 5.1 shows the 4 main processes within a risk management framework which can be used to assess the uncertainties associated with highway drainage infrastructure, namely communication and consultation, risk assessment, risk treatment, monitoring and reviewing each of which are discussed further in Section 5.4 to 5.11.

5.4 Communication and consultation

This process involves sharing information on how to manage the risk. It is a dialogue between the stakeholders and an organization; for example residents and road users with contractors. This two way process should be iterative and continuous; it is important that expertize from all necessary disciplines and interested parties influence this stage of the risk management process. It may be necessary to revisit all of the components of the risk management process, see Figure 5.1. Once the process is completed decisions regarding the risk need to be made solely by the organisation, even if outside expertise has been utilized (ISO 31000, 2009).

This stage was completed in respect of risk identification and risk analysis by consulting experts at a variety of LAs and consultancies. This process was not completed in respect of risk evaluation and risk treatment, as these aspects were not included within the research; justification for non-inclusion are given in Sections 5.9 to 5.10 and also Section 10.3.

5.5 Risk assessment

Risk assessment helps to provide evidence based information and analysis that can assist the highway engineer to make better informed decisions. The process encompasses; risk identification, risk analysis and risk evaluation (Section 5.9).

The research framework utilized the risk identification and risk analysis elements of the risk assessment process as shown in Figure 5.2.

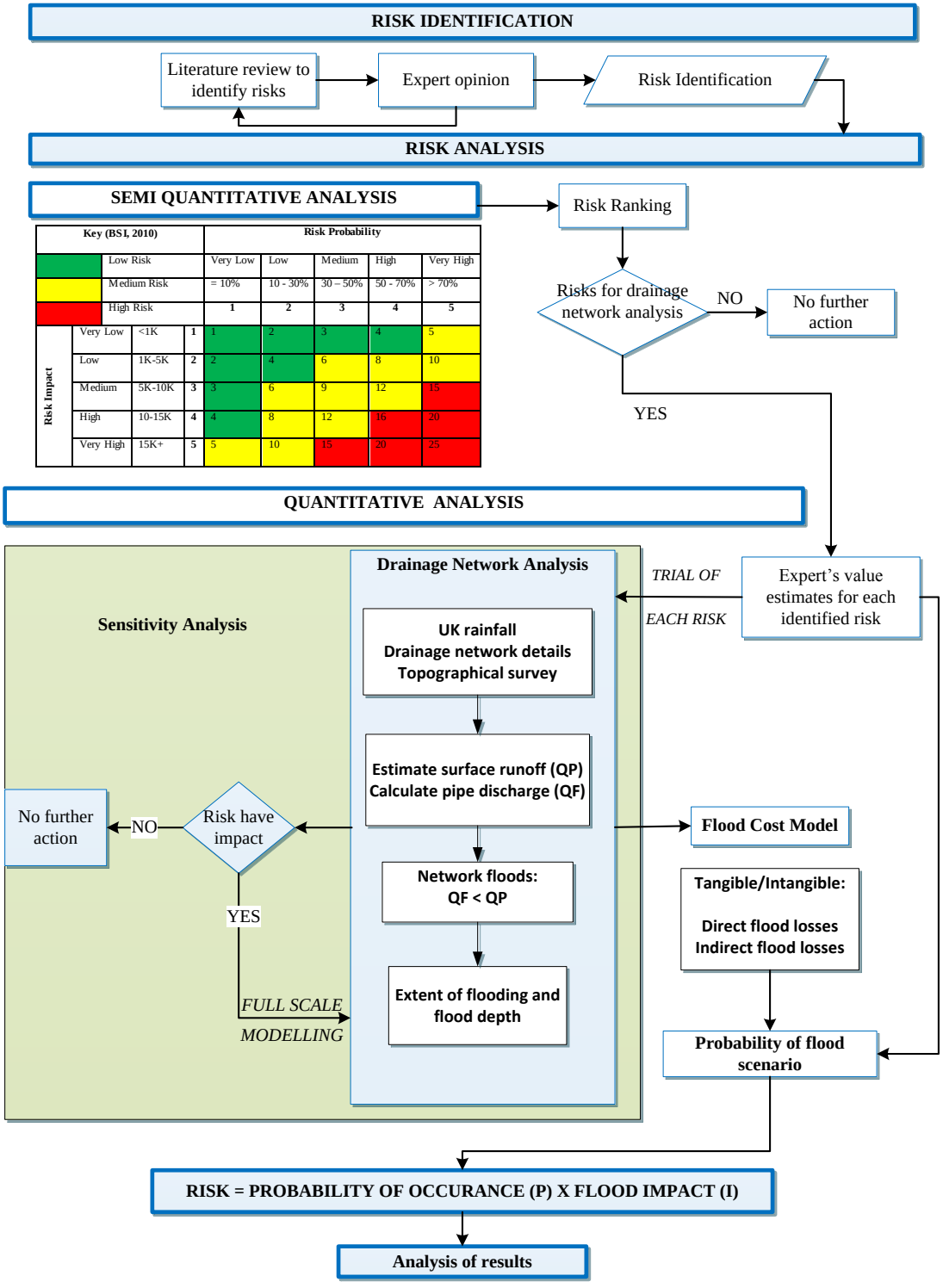


Figure 5.2 – Research framework

5.5.1 Risk Identification

This process is about discovering, recognizing, and recording risks (BSI, 2010), and as mentioned in Section 3.11.2.1 it is considered the most important stage of the risk management process. All subsequent stages relate back to these initially identified risks so it is vital that they are correctly identified (Ayyub, 2003a; Merna, 2008b).

A variety of techniques exist that help to identify risks for example; reviewing historical data, brainstorming, questionnaires, interviews with experts and HAZOP. In the context of this research it was necessary to ascertain all risks having the potential to cause highway drainage infrastructure flooding, together with the associated consequences of the flooding. To achieve this, a structured process was carried out which consisted of obtaining information from a review of the literature, augmented by expert opinion obtained from experienced highway drainage engineers/ highway asset managers, as shown in Figure 5.2.

5.5.1.1 Literature Review

The literature review identified the risk categories and associated risks and that can cause a drainage network to flood, and explored appropriate methods of quantifying these risks.

The identified risk categories were as follows:

As Built: This risk reflects that amendments to the original design are sometimes made during construction, either by intention or by accident, and these variances are not properly recorded (Russell, 2013; Bache, 2013; Green, 2013; Olesen and Rollings, 2012a). Such variances can increase flood risk and may have financial implications and ramifications for asset management and maintenance schedules (Pate, 2005).

Maintenance: Scheduled maintenance work may have been commenced prior to the discovery that existing as built documentation is inaccurate, for example an asset(s) was not

in the specified location. Such a situation would necessitate a further site investigation to locate the asset with implications as to time, resources and finance (Pate, 2005).

Even when the asset due to be maintained is correctly located, it may not be described as the one in situ. The deterioration of the asset when found will need to be assessed, particularly if no historic maintenance records are available. This similarly can adversely influence the cost effectiveness of maintenance scheduling, for example spare parts taken to site may be incorrect and have to be ordered (Russell, 2013; Bache, 2013; Green, 2013; Olesen and Rollings, 2012a).

Deterioration: Assets deteriorate over time impeding their ability to carry the flow of water for which they have been designed (Olesen and Rollings, 2012a). Brommer et al (2009) identified that understanding and quantifying deterioration rates was necessary in order to plan maintenance programmes; which in turn influence asset life.

Deterioration occurs at varying rates which are dependent on several often uncertain factors. These include the type of maintenance undertaken on them and its associated frequency, materials used in construction, the ability of the initial installation to perform the intended function, and the intensity, duration and frequency of rainfall (Hassing et al, 2004).

Climate: As discussed in Chapter 4, (Sanderson, 2010) demonstrated that climate change and the associated increase in the duration, frequency and intensity of precipitation, has implications for highway drainage systems. As climate change remains uncertain it must be considered a major risk to the functionality of drainage assets.

As noted in Section 2.3.2 drainage networks are designed using the well-established relationship; intensity, duration and frequency (IDF). IDF curves are used to determine the critical mean rainfall intensity in terms of the duration of this mean intensity. Increases in the duration, frequency and intensity of precipitation will necessitate a fundamental review of

existing IDF curves. Currently, once an IDF curve has been created it is assumed that recorded extreme rainfall is appropriate to use to characterize future extreme precipitation. As climate change indicates that in the future there will be an increase in extreme weather events including heavy rains of greater intensity; this assumption becomes increasingly invalid (Boucher, 2010). As a consequence highway drainage infrastructure designs using existing IDF curves may well not be sufficiently accurately advised (X. Wu, 2012). Consequently, climate change may well impact the rate of deterioration and, therefore, the maintenance regimes required to support a drainage network.

A number of other risks, of much lower probability were also identified. These include; an earthquake, a terrorist attack and a meteoroid strike, however, as they have a relatively low probability of occurrence they were not considered further.

5.5.1.2 Expert Opinion

Section 3.11.2.1 discusses the use of expert opinion in research surveys. A variety of opinions exist as to the number of experts required to conduct subjective research (Taylor and Bogdan, 1984; Patton, 1990; Spiggle, 1994; Maykut and Morehouse, 1994; Punch, 1998; Morse, 2000; Crouch and McKenzie, 2006; Glaser and Strauss, 2009; Creswell, 2012; Ritchie et al, 2013; Green and Thorogood, 2013).

In the UK there are 418 LAs, and 89 engineering consultancies indicating they undertook 'related work in drainage', although this term is not further defined (Transportation Consultancy Directory, 2015). As suggested by Richie and Crouch due to the limitations of time, and potential travel costs involved with visits to respondents (the option of an interview was offered), the questionnaire was circulated within a limited area. Consequently the questionnaire was circlated within an area of 80 miles of The University of Birmingham. In total 127 questionnaires were circulated, 73 to local authorities and 54 were circulated to consultancies; in total 24 replies (19 percentage of those circulated) were returned. The

purpose and structure of the questinnaire are discussed in Section 6.3. Section 10.4 discusses the sample size required to achieve a 95% confidence level in the data together with suggestions as to how an increase in the number of responses can be achieved.

As well as confirming the risk categories described previously, and in order to facilitate the risk analysis process the experts were asked to verify the identified risks associated with each risk category determined from the literature, these are shown in Table 5.1. Experts provided a range of values in respect of each risk (minimum, most likely, maximum) and their associated probability of occurrence; these values were used in quantitative risk analysis.

Table 5.1 – Risks identified through literature and consultation with experts

Asset Category	Risk Category	Risks Identified
Gully	As Built	Unknown quality of workmanship
		Unknown diameter of gully pot (mm)
		Unknown depth of gully pot (mm)
		Unknown gully pot material
		Unknown grating size (mm)
		Unknown grating material
		Unknown grating type
Pipe	As Built	Unknown diameter of pipe (mm)
		Unknown length of pipe (mm)
		Unknown pipe gradient (1:X)
		Unknown pipe roughness
		Unknown pipe capacity
		Unknown pipe material
		Unknown catchment area
Gully, Pipe and Manhole	As Built	Unknown connections
Gully, Pipe and Manhole	As built	Unknown future demand
Manhole	As Built	Unknown diameter of manhole (mm)
		Unknown depth of manhole (mm)
		Unknown type of Manhole
		Unknown material of manhole chamber
Gully, Pipe and Manhole	Maintenance	Unknown maintenance frequency
		Unknown maintenance carried out
	Deterioration	Unknown rate of deterioration
		Unknown condition
	Climate	Unknown design return period
		Unknown future rainfall intensity

This was achieved by developing a questionnaire which also formed the basis of interview. Section 6.3 describes the aims and objectives of the questionnaire and its design. The results are shown in Chapter 7.

5.5.2 Risk Analysis

This research utilized an approach which combined qualitative, semi-quantitative and quantitative risk analysis. As noted in Section 3.9.1.2, the base measure of risk, *R*, is given by equation 5.1:

$$R = P \times I \tag{5.1}$$

Where *P* is the probability of the event occurring and *I* is the impact of the event occurring.

Equation 5.1 was developed to encompass the risks given in Table 5.1. Accordingly, the overall flood risk, R, can be determined as follows:

$$R = \sum_{i=1}^{k} RCi = \sum_{i=1}^{k} \sum_{j=1}^{m} (P_j \times I_j) \tag{5.2}$$

Where *j = the number of risks in risk category RCi. Pj and Ij are the probability and impact respectively of risk j in risk category RCi*

Equation 5.2 becomes:

$$R = \sum(As\ built\ probabilities\ \times as\ built\ impacts) + \sum(maintenance\ probabilities\ \times maintenance\ impacts) + \sum(deterioration\ probabilities\ \times deterioration\ impacts) + \sum(climate\ probabilities\ \times climate\ impacts) \quad (5.3)$$

5.5.2.1 Qualitative and Semi- Quantitative Risk Analysis

Qualitative risk analysis was used to develop a set of criteria, which could be used by the experts, who were not used to risk analysis, in order to assist in the completion of the questionnaire. The participant information sheet (Appendix A4) provided information to assist in the qualitative and semi quantitative risk analysis, this included examples of the direct and indirect tangible damage impacts (Table 5.4) that were associated with each category and shown in Table 5.2.

Semi-quantitative risk analysis was used to identify the significance of each risk with a view to establishing the most influential risks. The experts assigned a score (1 to 5) for both the probability and consequence of each identified risk. The total score for each risk was then obtained by multiplying the two results together (probability and impact). This produced a range of scores from 1 to 25 as shown in Table 5.3. Risks were then ranked from highest to lowest using the resultant scores to ascertain which risks were the most influential on highway drainage infrastructure flooding. Any risk considered to be high from the semi-quantitative risk analysis process described above was further investigated through quantitative risk analysis (Vose, 2010). The values obtained for the case study are given in Section 7.3.

Table 5.2 – Qualitative and semi quantitative categories used in the risk assessment process (Adapted from (Derbyshire County Council, 2011))

Category	Score	Probability	Impact
Very High	5	Highly likely to occur. Flooding has occurred on several occasions in the past.	Severe: direct tangible damage to buildings, contents, interrupted business, agricultural losses, cleaning up after flooding, and infrastructure damage to roads, utilities and communication. Indirect tangible damage, for example: disruption to road traffic, rail services, damage to companies outside flooded area.
High	4	Likely to occur. Flooding has occurred in the past.	Considerable: damage occurs as (5) above but to a lesser degree.
Medium	3	Possible to occur. Minor flooding has occurred.	Notable: Very minor direct tangible flood damage, for example; minor cleaning up costs together with indirect tangible flood damage.
Low	2	Most likely will not occur. Very minor flooding has occurred.	Very Minor: Only indirect tangible flood damage occurs, for example: minor disruption to road traffic, rail services, damage to companies outside flooded area.
Very Low	1	Highly unlikely to occur. Flooding has not occurred.	Negligible: no direct or indirect tangible flood damage occurred.

Table 5.3 - Risk matrix used in semi quantification (BSI, 2010)

Key (BSI, 2010)				**Risk Probability**				
	Low Risk			Very Low	Low	Medium	High	Very High
	Medium Risk			≤ 10%	10 - 30%	30 – 50%	50 - 70%	> 70%
	High Risk			**1**	**2**	**3**	**4**	**5**
Risk Impact	Very Low	<1K	**1**	1	2	3	4	5
	Low	1K-5K	**2**	2	4	6	8	10
	Medium	5K-10K	**3**	3	6	9	12	15
	High	10-15K	**4**	4	8	12	16	20
	Very High	15K+	**5**	5	10	15	20	25

5.5.2.2 Quantitative risk analysis

As noted in Section 3.11.2.2 quantitative risk analysis relies exclusively on the analysis of numerical or quantifiable data, it encompasses quantifying the probability of each identified risk occurring and its associated impact. To this end two processes were utilized in the research to develop the Flood Risk Model:

(i) A process to determine the probability of a flood occurring

Ideally the probability of a flood occurring should be derived from historical data. However, such information is rarely available to local authorities and therefore, following guidance given in the Risk Management literature the opinion of experts was canvassed to determine the probability of occurrence (Merna, 2008b).

Since the range of risks could be considered to be uncertain the experts were asked to provide a probability of occurrence for each minimum, most likely and maximum value associated with all the identified risks (Appendix A3). The results, in relation to the case study, are discussed in Section 7.5.5.

(ii) A process to determine impact

This was achieved by undertaking two processes: (i) drainage network analysis and (ii) flood cost modelling. Drainage Network Analysis was carried out, using specialist drainage analysis software (see Section 5.6) to ascertain, as a function of the identified risks, the depth of flooding and the extent of flooding. Flood cost modelling allowed for the cost of flooding in respect of each climatic event to be determined as described in Section 5.7.

5.6 Drainage Network Analysis

A number of software packages exist (see Section 2.8) which can be used to determine the depth and extent of flooding of a given drainage network under given rainfall scenarios. In this research MicroDrainage™ was utilized for this purpose at it is the most widely used by local authorities and drainage engineers in the UK (Bache, 2013; Daniels, 2013; Doorman, 2013; Green, 2013; Wells, 2013).

MicroDrainage™ was used to analyse the drainage network using the range of values for each identified risk (provided by expert opinions), to identify the parts of the network which will flood. Flood flow analysis using the MicroDrainage™ software was undertaken to ascertain the extent of flooding and its depth for each climate scenario modelled.

5.6.1 UK Rainfall

As discussed in Section 4.3 UKCP09 provides rainfall datasets at 5km and 25km gridded resolutions which could be utilized within the proposed framework (Figure 5.2) and applied to any site in the UK, by ascertaining the relevant return periods. In 2010 OFWAT commissioned the Met Office to provide guidance on future daily rainfall return periods for England and Wales, in respect of 40 towns and cities in England and Wales (see Section 4.4).

The data sets provided by UKCP09 are relevant to the methodology used as they can be used to predict increases in rainfall. Evidently it is important to include future likely increases in rainfall within the developed system, as highway drainage systems have been designed on the basis of current rainfall patterns, rather than future possible ones (X. Wu, 2012; Butler and Davies, 2011; Boucher, 2010). Furthermore Walters (2009) utilized expert opinion to identify 'lack of capacity in the drainage system and flooding of the highway network' as the highest risk to highway drainage infrastructure.

5.6.2 Network Details

In order for a drainage network to be analysed it is necessary to obtain or develop a map containing topographical, network and surface runoff characteristics as described below.

Topographical details

- Establish the location and levels of existing or proposed details such as:
    - Contours
    - Physical features
    - Road layout
    - Category of building
    - Sewer and other services
    - Outfall point

Network Details

- Develop a layout of the drainage network, examples include:
    - Installation of inlet types and their location (e.g. position of gully)
    - Pipe location
    - Pipe sizes
    - Pipe length
    - Manhole locations
    - Manhole sizes
    - Cover levels
    - Inlet levels
    - Outfall details

Development on the study area began in 2005; part of the reason for its choice was the existence and ready availability of relevant electronic data. However, all site features were not contained within the same document and were subsequently added, see Appendix A1 and A2. Further details as to how the data was collected are discussed further in Chapter 6.

Estimating surface runoff

For the purposes of this work the MRM recommended by the Wallingford Procedure (Butler and Davies, 2011) was used. It is the most commonly used method by UK LAs and is the most appropriate method to use to estimate surface runoff (MicroDrainage, 2012f; Olesen and Rollings, 2012a; Butler and Davies, 2011). It is accurate for catchment sizes up to 150 ha. Using the MRM the Peak rate runoff (QP) in a given area is related to average rainfall intensity and is expressed as:

$$Q_P = 3.61 C_V i A_i \tag{5.4}$$

Where: Q_P = Peak Flow Rate (l/s), Cv = Volumetric runoff coefficient, I = average rainfall intensity (mm/h) and *A* = Catchment area (ha).

The rainfall intensity can be obtained either by developing IDF curves or by using the FSR or FEH methods as described in Section 27. The volumetric runoff coefficient and catchment area also need to be defined (see Section 2.4.1.1)

Pipe discharge

As discussed in Section 2.6 the flow rate (Q_F) (m^3/s) of a pipe is calculated using equation 5.5, where A is the cross sectional area of the flow and V_F is the full velocity (m/s)

$$Q_F = V_F A \tag{5.5}$$

The mean velocity of a pipe can be calculated using Manning's equation or the Colebrook White equation. Further information regarding hydraulic principles can be found in Hamill (2006).

Exceeding network capacity

The network capacity is exceeded if $Q_F < Q_P$, therefore, the extent of the flooding and depth of flood can be analysed and quantified.

Flood flow analysis

A well-established means of simulating surface flooding utilizes a 1D or a 2D model or a combined model. A 1D model adequately represents surface flooding within a road. However, if the flow goes over the top of the kerb then 2D models provide a more accurate flow path (Spry and Zhang, 2006; Mark et al, 2004).

Both 1D and 2D models use a Geographic Information System (GIS) interface in order to identify the various surface heights throughout the catchment surface. The GIS typically comprises of a Digital Terrain Model (DTM) and a Digital Elevation Model (DEM). A DTM is a topographical survey of the existing ground surface, whereas a DEM uses the information from DTM but also includes additional information regarding elevation data of buildings and other protruding features (Butler and Davies, 2011).

To date, combining 1D and 2D models are considered to be the most accurate representation available regarding surface flooding (Bamford et al, 2008). However, such models require a considerable amount of data and time in order to be produced (Blanksby et al, 2007; Allitt et al, 2009). Section 2.7 briefly introduced the concepts of 1D and 2 D models, however, further information can be found in (Butler and Davies, 2011). MicroDrainage has the facility to calculate the overland flow path using a 1D-2D model.

5.7 Flood cost modelling

The majority of flood damage is a function of the nature and extent of the flooding; this includes duration, contamination of flood water, flood depth and flood velocity. These factors affect flood damages and losses, whilst the location of the flood affects economic networks and social activities that cause indirect losses (Zevenbergen et al, 2010). Flood damages are invariably categorised as direct or indirect, tangible and intangible damages, Table 5.4 shows examples of the flood damage categories.

Direct damage is defined herein as that which may be considered to consist of all varieties of harm which relate to the immediate contact with flood water to humans, property and the environment. These are usually measured as damage to stock. Indirect damage has been defined as that which causes disruption of physical and economical linkages of the economy, and the additional costs of emergency, together with other necessary actions required to prevent flood damage and other losses. Tangible damage refers to damages that are quantifiable in monetary terms (and as shown in Table 5.4 can include both direct damage and indirect damage). Intangible damages are r more difficult to assess in monetary terms (Messner et al, 2007; Zevenbergen et al, 2010).

Table 5.4 – Example of flood damage categories (Zevenbergen et al, 2010)

Type of Damage	**Tangible**	**Intangible**
Direct	Buildings and contents	Fatalities and injuries
	Interruption to business within flooded area	Memorabilia losses
	Agricultural losses including animals	Mental and physical health
	Cost of cleaning up after flooding	Cultural and historical losses
	Infrastructure damage – roads, utilities and communication	Environmental losses
Indirect	Disruption - road traffic	Post flood clean up
	Disruption – rail services	Trauma, stress and anxiety
	Damage to companies outside flooded area	Social disruption
	Evacuation	Decrease in faith of public authority

Many methods and models have been developed to quantify tangible direct and indirect costs; however, there is little agreement amongst academics and experts as to the best method to use for a number of reasons including Huntingdon and MacDougall (2002):

- Difficulty in establishing the relevant boundaries for any analysis.
- Variations are also found in the spatial and temporal scale of analysis.
- The spatial scales vary from national, regional, urban and local levels.
- Temporal scales vary from years, weeks, hours.

This research solely concentrated on quantifying direct and indirect tangible flood losses that result from highway drainage infrastructure flooding. It necessitated costs being allocated to the various identified features at identified site locations, and included building types, land use and emergency maintenance costs.

During the past forty years, The Flood Hazard Research Centre (FHRC) at Middlesex University has produced a variety of publications specifically on flood risk and water management of natural hazards. The current version is the Multi-Coloured Handbook (2013) and its accompanying data (2014). They together provide the most up to date monetary figures regarding the cost of residential, non-residential and other flood losses, for example (road disruption, emergency services, electricity and gas, school disruption, hospitals, rail disruption).

For each cost element, the Multi Coloured Handbook provides a low, indicative and high value; these were used to calculate the minimum, most likely and maximum financial impact cost values for input into the risk model.

Consequently, the total flood impact was determined as a function of the unknown risks (Table 5.1Section 3.11.2.1 discusses the use of expert opinion in research surveys. A variety of opinions exist as to the number of experts required to conduct subjective research (Taylor

and Bogdan, 1984; Patton, 1990; Spiggle, 1994; Maykut and Morehouse, 1994; Punch, 1998; Morse, 2000; Crouch and McKenzie, 2006; Glaser and Strauss, 2009; Creswell, 2012; Ritchie et al, 2013; Green and Thorogood, 2013).

In the UK there are 418 LAs, and 89 engineering consultancies indicating they undertook 'related work in drainage', although this term is not further defined (Transportation Consultancy Directory, 2015). As suggested by Richie and Crouch due to the limitations of time, and potential travel costs involved with visits to respondents (the option of an interview was offered), the questionnaire was circulated within a limited area. Consequently the questionnaire was circlated within an area of 80 miles of The University of Birmingham. In total 127 questionnaires were circulated, 73 to local authorities and 54 were circulated to consultancies; in total 24 replies (19 percentage of those circulated) were returned. The purpose and structure of the questinnaire are discussed in Section 6.3. Section 10.4 discusses the sample size required to achieve a 95% confidence level in the data together with suggestions as to how an increase in the number of responses can be achieved.

As well as confirming the risk categories described previously, and in order to facilitate the risk analysis process the experts were asked to verify the identified risks associated with each risk category determined from the literature, these are shown in Table 5.1. Experts provided a range of values in respect of each risk (minimum, most likely, maximum) and their associated probability of occurrence; these values were used in quantitative risk analysis.

Table 5.1) which may affect the ability of any drainage network to perform adequately and the cost of any resulting flood (the extent and depth of which were calculated using the drainage modelling software described above). The resulting Flood Risk Model was affected through a Monte Carlo simulation process as described below.

5.8 Flood Risk Model

The Monte Carlo Simulation process was used to evaluate the Flood Risk Model (Equation 5.3), it was chosen because it:

- Allows probability distributions to be allocated to all uncertain components of the mathematical model (Equation 5.3) of the problem, and then, through random sampling of these distributions, determines the distribution of all potential outcomes that could occur under the uncertainties (Vlasta Molak, 1997).
- Provides a means of evaluating the effect of the risks associated with highway drainage infrastructure.
- Offers the opportunity to utilise a variety of distributions, see Section 3.11.2.2. The output from the Monte Carlo simulation can be used to identify the parts of the network most at risk from flooding.

The use of the Monte Carlo simulation required frequency distributions to be chosen to represent the likelihood of occurrence of each flood risk (ascertained by experts) and the range of possible flood impacts of the risks (determined from the Network Analysis and Flood Cost modelling components). For the former the binomial function was adopted whilst the latter was represented using a triangular distribution.

A binomial function was used to represent the probability of occurrence since it provides a probability distribution when only two possible outcomes can occur (Freund, 1972) flood or no flood). Experts indicated the probability of each minimum, maximum and most likely value occurring as discussed in Section 5.5.2.2.

A triangular distribution which increases linearly from a minimum to a maximum was chosen for use in this research to represent the impact of a flooding event since it is the most

commonly used form of distribution used for modelling expert opinion defined by a minimum, most likely and maximum values (Merna, 2008b; Vose, 2010).

This research used the @RISK® software to implement the Monte Carlo simulation. @RISK® calculated the model to a pre-defined set of iterations (number of times model is run). For the purpose of this research, 5,000 iterations were used in order to generate a risk frequency distribution, as the literature review indicated this number was adequate (Vose, 2010).

5.9 Risk evaluation

Evaluating risks helps inform the decision maker as to what action to take (Vose, 2010). Further information can be found in BSI (2010) and ISO 31000 (2009). The process involves comparing the risk criteria initially established to the modelled measures of risk. The evaluation determines the significance of the level and type of risk (BSI, 2010). However, no standard method exists as to how risk evaluation should be conducted; it is up to the decision maker (BSI, 2010). A detailed treatment of this element of the risk assessment process was considered beyond the scope of this research.

5.10 Risk treatment

In a risk management process identified risks may need to be mitigated. Treatment options to reduce a risk include: removing the source of the risk, avoiding the risk, transferring the risk and modifying the consequences and probabilities occurrence. It is also possible to simply retain the risk or to increase it with a view to being aware of it earlier (BSI, 2010). Further information can be found in BSI (2010) and ISO 31000 (2009) (Vose,2010).

This element of the risk management process was not included within this research as the focus of the research was to develop a process of facilitate the identification and quantification of flood risk.

5.11 Monitor and review

Risks frequently change over time, for example climate change. On some occasions if the risk changes it may well necessitate changing or invalidating the risk assessment. Ideally, a continuous monitoring and assessment process needs to be put in place to constantly review any changes to the identified risks. Further information can be found in BSI (2010) and ISO 31000 (2009).

5.12 Case Study

5.12.1 Introduction

A case study to demonstrate the Risk Analysis framework described above was chosen from a number of sites identified during a work placement with DCC. The case study was chosen because there was a comprehensive electronic data set relating to the site which was compatible with MicroDrainage. Although it is recognised it had some limitations in terms of the research outputs as discussed in Section 10.5.4. The case study area depicted in Figure 5.3 utilized data from DCC. The study area is described further in Section 6.1.1. The results of the case study are shown in Chapters 7 - 9.

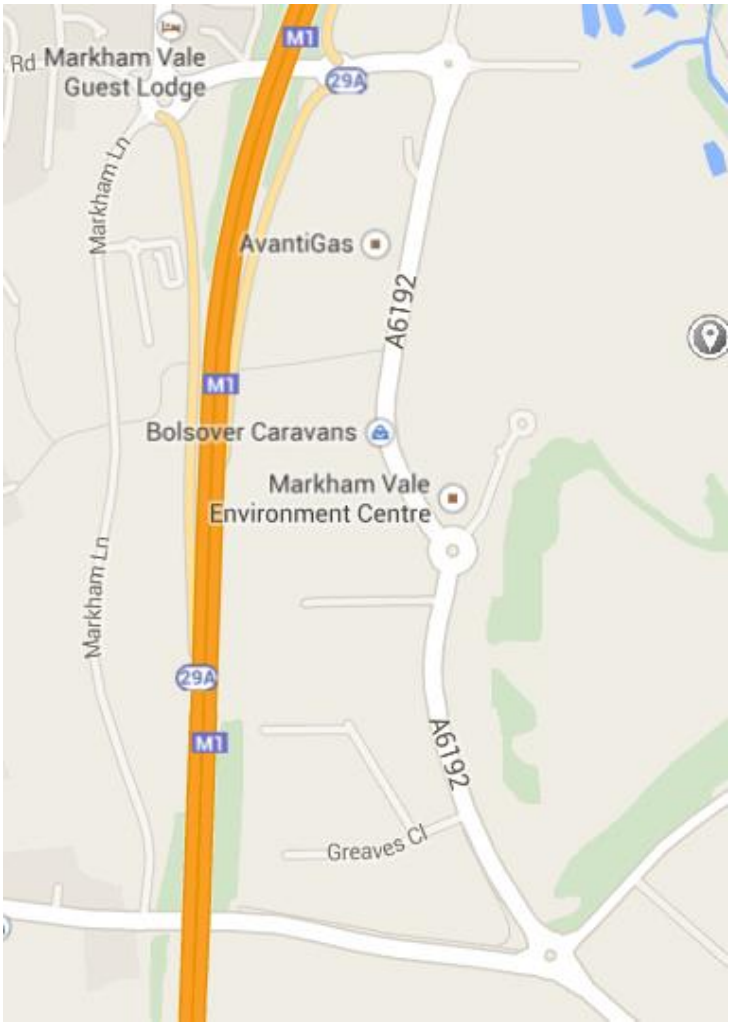


Figure 5.3 - Case study area (Google Earth, 2015)

An overview of how the research framework described in Sections 5.3 and 5.6 was applied to the case study is shown in Figure 5.4.

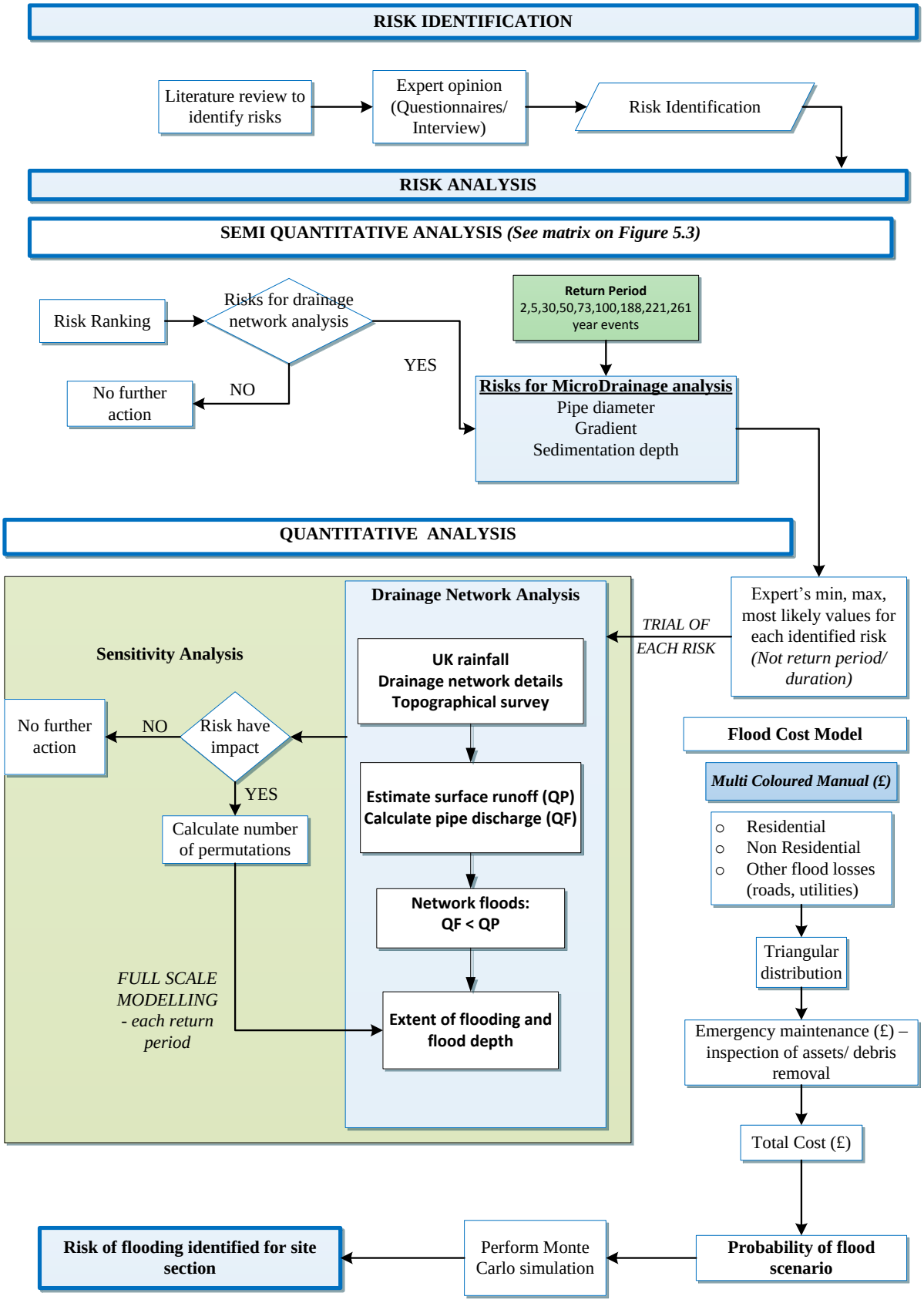


Figure 5.4- Research framework: Case Study

5.12.2 Risk Identification

As noted in Section 5.5.1 risk identification involved a literature review augmented by expert opinion. As far as the Case Study was concerned the experts were presented with the risks shown in Table 5.1, from this they determined the risks they considered to influence highway drainage infrastructure flooding. They also provided a range of values for each identified risk associated with the case study area. The associated values are given in Section 7.5.

5.12.3 Risk Analysis

5.12.3.1 Qualitative and Semi Quantitative Analysis

As noted in Section 5.5.2.1, experts assigned a score (1-5) to the consequences and probability of each risk in relation to the case study. Using Equation 5.1 the score for each risk was calculated and ranked using the matrix shown in Table 5.3. The resultant number of risks is shown in Section 7.3. Any risks scoring greater than or equal to 15 (considered high risk) that were compatible with MicroDrainage^{TM}, were further investigated by conducting a sensitivity analysis, the results are shown in Section 7.4. Any risk incompatible with drainage network analysis was not included; the implications of this are discussed in Section 10.4.3.

Risks for network analysis

Any risk considered high, that was compatible with drainage network analysis software, was further investigated through quantitative risk analysis as this research concentrated solely the most significant risks. Any risk incompatible with drainage network analysis was not included and no further action was taken in respect of them.

5.12.3.2 Quantitative Analysis

Sensitivity analysis

To further confirm that the high level risks identified through semi quantitative analysis would positively impact highway drainage infrastructure flooding a sensitivity analysis was undertaken. This was done by adjusting the original value of each identified risk by the following increments; 10%, 20%, 30%, 40% and 50% while keeping the remaining risks at their original value, this tested how sensitive each risk was to the network examined. Risks found not to impact flooding as a result of this process were excluded from further analysis. It is possible that the risks identified in Section 5.5.2.1 can interact with each other in ways that are not predictable from examining each one individually (Vose, 2010). An exhaustive model which considered all possible interactions of *n* identified risks each of three different values (minimum, maximum and most likely) resulted in 3^nscenarios.

The climate risk category and its associated risks were not suitable for inclusion because it would have been impossible to ascertain the effect of different return periods and storm durations (extent of flooding) on the examined network. Consequently, to ascertain the effect of precipitation on the drainage network, a return period and its duration was used as a test condition utilizing the other identified risks, the results are shown in Chapters 8 and 9.

As discussed in Section 5.5.1.1, Spink et al (2014) identified that the deterioration of an infrastructure asset is strongly influenced by the standard of maintenance it has received. Pipe replacement was not included as a risk as it was considered beyond the scope of this research. In order to include the maintenance/deterioration risks into the drainage analysis software these risks needed to combine to form one risk; this was necessary as the commercial software available does not have the facility to include them individually. The most appropriate parameter within software to represent maintenance/deterioration is

sedimentation depth as this parameter replicates a restriction of flow within the network analysis (MicroDrainage, 2012h).

The results of the sensitivity analysis as described in Section 7.4 identified four main risks suitable for quantitative analysis. Therefore, as these risks can interact with each other in ways that are not predictable from examining each one individually, 34 scenarios existed. Microsoft Excel was used to randomly select 24 scenarios from the 27 identified, as this was considered a large enough sample size (Hurt, 2013), they are shown in Table 5.5.

Table 5.5 - Random scenarios modelled

Scenario	Diameter of Pipe	Gradient	Sedimentation Depth
1	Minimum	Minimum	Minimum
2	Most Likely	Most Likely	Most Likely
3	Maximum	Maximum	Maximum
4	Most Likely	Maximum	Maximum
5	Minimum	Most Likely	Maximum
6	Minimum	Maximum	Minimum
7	Minimum	Most Likely	Most Likely
8	Most Likely	Maximum	Maximum
9	Most Likely	Minimum	Most Likely
10	Maximum	Minimum	Maximum
11	Most Likely	Minimum	Maximum
12	Most Likely	Maximum	Minimum
13	Minimum	Minimum	Minimum
14	Maximum	Maximum	Most Likely
15	Maximum	Maximum	Most Likely
16	Minimum	Maximum	Maximum
17	Minimum	Minimum	Minimum
18	Minimum	Most Likely	Minimum
19	Maximum	Minimum	Minimum
20	Most Likely	Minimum	Minimum
21	Minimum	Most Likely	Maximum
22	Most Likely	Most Likely	Maximum
23	Minimum	Maximum	Minimum
24	Most Likely	Most Likely	Most Likely

5.12.3.3 Drainage network analysis

MicroDrainage™ was used to incorporate the values provided by experts relating to each identified risk, to enable flood flow analysis to be performed. Flood flow analysis (1D - 2D model) was performed using MicroDrainage™ to reveal the extent of flooding and its flood depth in relation to the climate scenarios modelled; the results are shown in Chapter 8.

UK Rainfall

The design standard return periods augmented by expert opinion were modelled namely; 2, 30 and 100 year events. Sanderson (2010) examined how current rainfall return periods are expected to change in the future (2040, 2060 and 2080); see Section 4.4. The results from this comprehensive study, relating to Sheffield, were used in this research, see Section 6.4.7.

5.12.3.4 Flood cost model

Appendix A1 and A2 show the site features identified by a site visit and Google Earth™. A unique ID number was allocated to each of the following; roads, car parks, buildings, substations, fields and wasteland. Buildings were further delineated as residential and non-residential in accordance with Multi Coloured Handbook, and their areas calculated as shown in Table 6.8 and 6.9.

For the case study the following sections of the Multi Coloured Handbook (2014) were used:

- Residential
- Non- Residential
- Road disruption

The maintenance cost (£) together with the estimated flood impact calculated using the MCM provided the total flood impact cost. A triangular distribution was then assigned to the total

flood impact of each return period and duration. These distribution values formed part of the input into Monte Carlo.

5.12.3.5 Probability of flood scenario

Experts provided a probability of occurrence for each minimum, most likely and maximum value associated with each identified risk. Using Table 5.5, the probability of each scenario occurring was calculated by multiplying the probability associated with each risk value. A binomial distribution was assigned as the probability of each value either occurred or it did not occur (Vose, 2010). The results are shown in Section 9.3.

5.12.3.6 Monte Carlo Simulation

@RISK® was used to generate random values by allocating the appropriate impact and probability distributions for each return period and storm duration. The results are shown in Section 9.4.

5.13 Summary

This Chapter described the research methodology undertaken to develop a theoretical risk analysis framework for drainage risk modelling. The framework integrated the risk management process and drainage network analysis. The components of the risk management process utilized were; risk identification, risk analysis and communication and consultation. Risk identification incorporated a literature review augmented by expert opinion, and risk analysis involved; qualitative, semi-quantitative and quantitative analysis.

The following chapter is concerned with how data was collected and processed from a case study site near Sheffield, UK in order to demonstrate the proposed framework.

CHAPTER 6 DATA COLLECTION

6.1 Introduction

Chapter 5 described the research methodology undertaken to develop a theoretical risk analysis framework which integrated the risk management process and drainage network analysis (Figures 5.2 and 5.4).

This chapter describes the collection and processing of the data utilized in the case study to demonstrate the framework set out in Chapter 5. Section 6.1 introduces the geographical location of the case study. Section 6.2 describes the layout of the highway drainage infrastructure in relation to the case study area. Section 6.3 describes the purpose of the questionnaire, together with its structure. Section 6.4 describes the data inputs required for drainage network analysis using MicroDrainage^{TM}. Section 6.5 describes how the Multi Coloured Handbook (2014) was used to help quantify the flood impact costs.

6.1.1 The Study Area

Following consultation with DCC a number of potential study sites were considered, resulting in the selection of Markham Vale, a 200 acre business and distribution park containing a diverse range of offices, warehouses and industrial units. The fact that a comprehensive electronic data set of geographical features and the drainage network relating to the site were available assisted the selection. The conversion of paper records to electronic form would have imposed a prohibitive time constraint. Other factors influencing this choice were the willingness of DCC to participate in the study and the accessibility of the site. The ease of accessibility to the site enabled frequent visits which resulted in a comprehensive understanding of the study area.

Markham Vale is a former colliery site adjacent to Junction 29A of the M1 in Derbyshire, the River Doe Lea passes through the east of the development. Recent commercial development on the site had necessitated an improved road infrastructure, including an upgraded surface water drainage system to augment the existing drainage network and comply with UK Environment Agency requirements (Russell, 2010). Figure 6.1 shows the site divided into two sections to aid analysis, Table 6.1 shows the roads located in the area that were examined.



Figure 6.1 - Case Study Area

Table 6.1 - Study Road Lengths

Road Number	Road Name	Road Length (km)
A632	Chesterfield Road	0.483
A1692	Markham Lane	1.93
Undesignated	Markham Lane	0.483

6.2 Site Layout Data

This research solely concentrated on surface drainage systems, consequently all 'as built' features needed to be incorporated into one drawing to enable the drainage network analysis within MicroDrainage™. The following electronic drawings (AutoCAD) were incorporated into the comprehensive as built drawing:

- Existing surface water drainage layout
- Highway drainage layout
- Terrain layout

The existing surface water layout drawings showed the main carrier pipes and manholes together with pipe diameters, cover levels, inlet levels and manhole types. An example is shown in Figure 6.2.

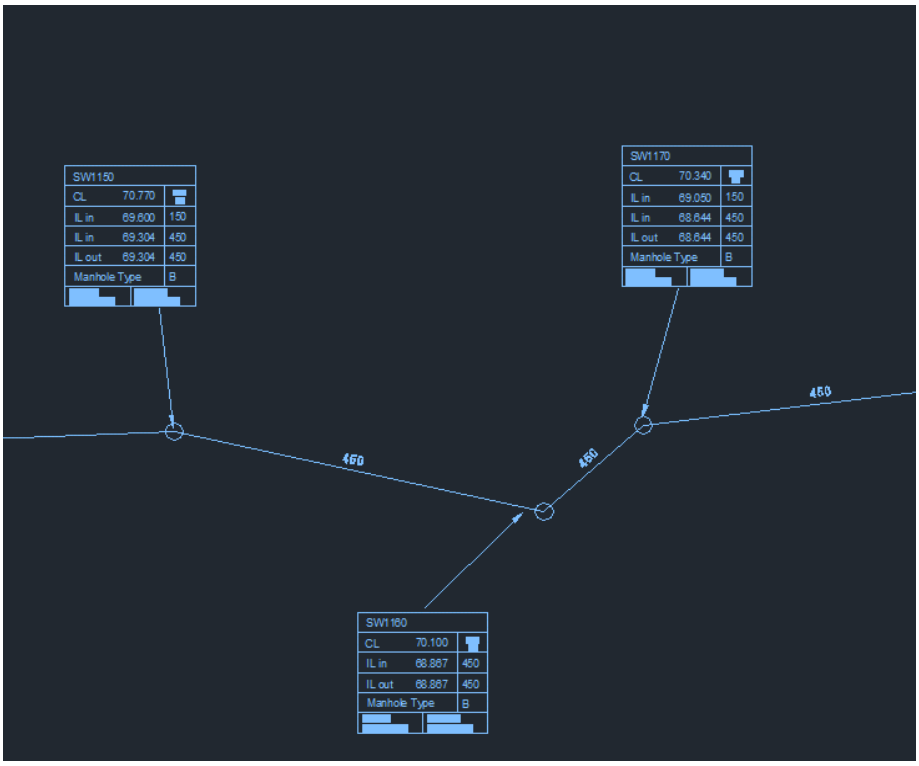


Figure 6.2 - Existing surface water layout

The existing highway drainage layout included the position of gullies and associated connectors, an extract is shown in Figure 6.3.

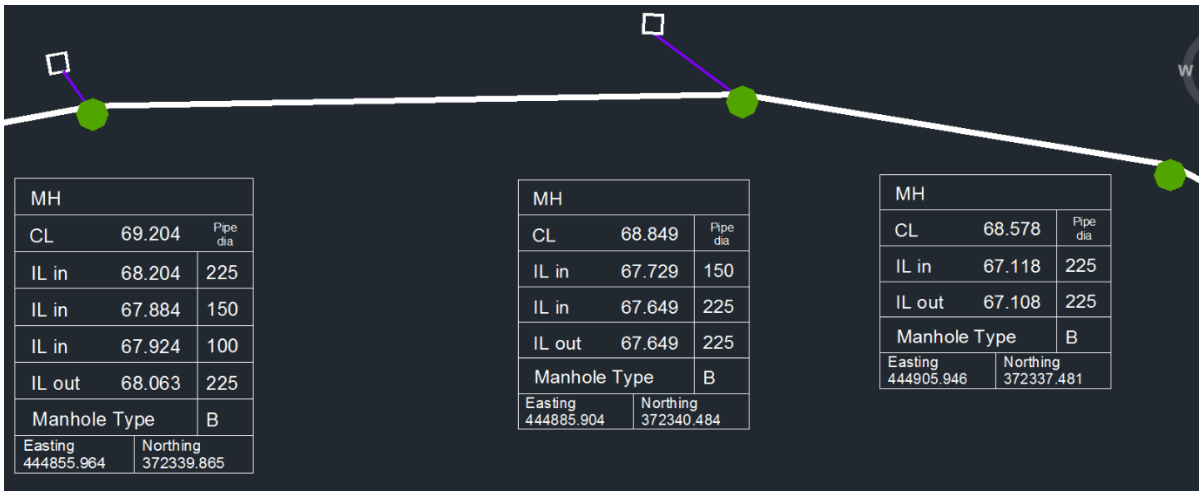


Figure 6.3 – The existing highway drainage layout

An Ordinance Survey map was obtained and attached as an external reference (XRef**)** to the as built drawing. The completed comprehensive site drawing (Appendix A1 and A2) formed the basis of the questionnaire design and input for the drainage modelling software. A DTM relating to the site was incorporated into the site lay out drawing to enable flood flow analysis to be performed.

6.3 Development of questionnaire

6.3.1 Purpose of questionnaire

This was developed to elicit the appropriate information from the group of experts so that risk identification and quantification could take place; see Section 5.5.1.2.

Questionnaire objectives:

a) Verify the risks, previously identified from the literature review, likely to impact on highway drainage infrastructure flooding.
b) In relation to the risks identified and for use in the Risk Model (Equation 5.3), obtain respondents opinion as to the;
    - Most likely value of each identified risk.
    - Minimum value of the identified risk.
    - Maximum of the identified risk.
c) Obtain an estimate of the probability of occurrence for each identified risk identified in (b).

The questionnaire was designed to be self-contained or used as the basis for interview. In order to achieve this, a participant information sheet describing the aim and objectives of the research was attached to the questionnaire together with a consent form for signature. Drawings of the site layout were also made available. A copy of the questionnaire, and the participant information sheet are shown in Appendix A3 and A4 respectively.

6.3.2 Participants

Prior to the distribution of the questionnaire it was approved by the ethics team at the University of Birmingham in August 2013. Distribution was confined to the highways departments of local authorities in the UK and well established engineering consultancies

known to be involved with highway drainage. Table 6.2 shows a summary of the participants by organization, positions held, and years of experience in highway drainage.

6.3.3 Structure of questionnaire

The questionnaire was divided into seven main sections (Appendix A3).

Section 1: Reminded participants of the background behind the research, and provided site background.

Section 2: Risk Identification (Section 6.3.3.2): Participants were asked to verify the risks associated with the flooding of highway drainage infrastructure.

Section 3: Risk semi-quantification (Section 6.3.3.3): For each identified risk, participants were asked to assign a value for probability of occurrence (P) and Impact (I) using the range 1-5; 1= Very low, 2 = Low, 3 = Medium, 4 = High and 5 = Very high.

Section 4: Risk Quantification – as built risks (Section 6.3.3.4): Relates to issues concerning the 'as built' drainage infrastructure.

Section 5: Risk Quantification – maintenance risks (Section 6.3.3.5): Relates to the maintenance of highway drainage infrastructure.

Section 6: Risk Quantification – deterioration associated risks (Section 6.3.3.6): Relates to the deterioration of highway drainage infrastructure.

Section 7: Risk Quantification – probability of occurrence (Section 6.3.3.7): Participants were asked to assign a probability of occurrence to each risk value specified.

Table 6.2 - Questionnaire/Interview Participants

ID	Company	Position	Years of experience
1	Mouchel	Senior Engineer	10
2	Mouchel	Assistant Engineer	6
3	Derbyshire County Council	Senior Project Engineer	13
4	Derbyshire County Council	Senior Technician	5
5	Derbyshire County Council	Senior Project Engineer	10
6	Derbyshire County Council	Senior Project Engineer	18
7	Derbyshire County Council	Senior Project Engineer	11
8	Derbyshire County Council	Highways Systems Manager	9
9	Retired	Retired	28
10	Dudley Metropolitan Borough Council	Section Engineer (Civils & Flood Risk)	18
11	Hydro Consultancy	Senior Engineer	10
12	Arup	Senior Engineer	10
13	WSP	Associate	13
14	WSP	Principal Engineer	11
15	Atkins	Assistant Engineer	7
16	Atkins	Assistant Engineer	5
17	Consultant	Principal Engineer	25
18	Highways Associates	Consultant	27
19	Warwickshire County Council	Flood Risk and Water Management Manager	9
20	Gloucestershire County Council	Drainage Engineer	9
21	Nottingham City Council	Senior Drainage Engineer	25
22	Nottingham City Council	Senior Drainage Engineer	20
23	Lincolnshire County Council	Sustainable Drainage and Major Development Technical Manager	24
24	Consultant	Consultant	6

6.3.3.1 Section 1: Background of research

The research background and the aim and objectives of the questionnaire were provided. Site background including; an area description, road classification, surface type, age of the drainage infrastructure, assumed volumetric run-off and assumed time of entry were provided.

Participants were asked for personal details including: name, company, position held, engineering discipline and years of experience. In accordance with The University of Birmingham's Ethical Procedure, participants were asked to sign a consent form prior to participation. Personal information has been kept confidentially in paper and/or electronic records in accordance with the Data Protection Act 1998.

6.3.3.2 Section 2: Risk Identification

The purpose of this section was to both verify the risks identified from the literature review and identify their relative importance. The findings are shown in Section 7.2.

Question 1: addressed risks associated with highway drainage infrastructure, participants were asked to verify the risks associated with the flooding of highway drainage infrastructure.

6.3.3.3 Section 3: Risk semi-quantification

The purpose of this section was to identify risks suitable for further investigation through quantitative analysis. Using Equation 5.1 the risk score for each risk was calculated and ranked using the matrix shown in Table 5.3. The results are shown in Section 7.3.

Question 2: Participants were asked to assign a value for probability of occurrence (P) and Impact (I) using the range 1-5; 1= Very low, 2 = Low, 3 = Medium, 4 = High and 5 = Very high for each risk.

6.3.3.4 Section 4: Risk Quantification – as built risks

Questions were asked relating to the 'as built' uncertainties on the site namely; the quality of workmanship, size of assets, pipe gradients, catchment areas and the most likely material used for asset construction, as a range of values were needed for inclusion within the MicroDrainage™ aspect of the Flood Risk Model.

Question 3: Opinions as to the general quality of workmanship of highway drainage infrastructure assets using the following rating scale index: Very Poor, Poor, Good, Very Good and Excellent. The rating scale used contained two positive and two negatives options and do not lead respondents in either direction (Brace, 2013).

Question 4 (i): Participants were provided with the known as built (most likely) dimensions for pipes and gullies. Opinions were sought as to the minimum and maximum value of each dimension.

Question 4 (ii): Participants were provided with the minimum internal diameter of a manhole for a variety of pipe ranges in accordance with Sewers for Adoption 7th Edition (2012). Opinions were then sought on the most likely and maximum internal diameter for each pipe range.

Question 4 (iii): Participants were provided with the minimum, most likely and maximum depth for Type A and Type B manhole types in accordance with Sewers for Adoption 7th Edition (2012).

Question 5: Opinions were sought as to the possible percentage change in relation to the original gradient.

Question 6 (i): For each of the 3 asset types (gullies, pipes, manholes), participants were asked to indicate the type of material used in asset construction, using the following choices

(least likely, most likely and likely). The choice of materials provided were cast iron, clay, concrete, plastic, porous plastic and brick.

Question 6 (ii): When existing pipe conditions are unknown, pipe roughness (k_s) was assumed to be 0.6mm for storm sewers, irrespective of pipe material and age (Butler and Davies, 2011). Participants were asked to consider the most appropriate minimum and maximum pipe roughness value.

Question 6 (iii): The DMRB offers 5 different grating types; P, Q, R, S, T for use in drainage design. The direction and number of slots, together with the size of grating effects hydraulic capacity. Respondents were asked for their opinion as to the minimum, maximum and most likely type of grating to have been installed.

6.3.3.5 Section 5: Risk Quantification – maintenance risks

This section was aimed at establishing a range of values for use within drainage network analysis, the results are in Section 7.5. Questions relating to maintenance uncertainties namely; the frequency and type of maintenance carried out on each asset were asked.

Question 7 (i): Participants were asked if they agreed with the various maintenance options available to assets.

Question 7 (ii): Participants were asked to indicate the minimum, most likely and maximum maintenance option each asset would receive.

Question 7 (iii): Participants were asked to comment on the overall adequacy of highway drainage infrastructure maintenance.

Question 8 (i): Participants were informed the study area was nine years old at the time of research. They were asked to indicate the number of times each asset (gully, pipes, manholes) would have received each maintenance option.

Question 8 (ii): Participants were asked to provide an estimate as to the cost (£) of carrying out each maintenance option; in respect of each asset on one occasion.

6.3.3.6 Section 6: Risk Quantification – deterioration risks

Question 9: Participants were asked to provide an estimate as to the likely percentage of functionality loss due to the asset being clogged with debris; taking into account the maintenance frequency (removing debris from asset) identified in Q8.

6.3.3.7 Section 7: Risk Quantification – probability of occurrence

Question 10: Participants assigned a probability of occurrence to each risk value (minimum, most likely and maximum) specified. The data obtained from the questionnaire was used to perform drainage network analysis; to ascertain the extent of flooding and flood depth.

6.4 Flood Modelling: MicroDrainage Inputs

6.4.1 Introduction

As previously discussed in Section 2.8 several different types of drainage modelling software packages are available which allow flooding to be calculated as a function of road drainage characteristics and rainfall. MicroDrainage™ software was chosen (see Section 5.9) as many practising engineers considered it a proven tool to use (Russell, 2013; Bache, 2013; Boyack, 2013; Daniels, 2013; Green, 2013; Wells, 2013; Doorman, 2013; Millership, 2013). It allows surface water and waste water systems to be designed and modelled. Figure 6.4 provides a brief overview of the MicroDrainage™ software modules used for this research project.

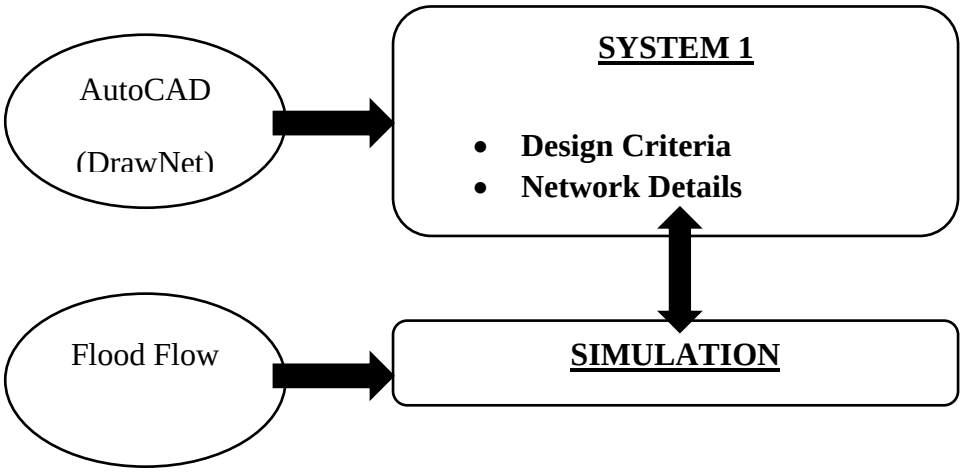


Figure 6.4 - Modules of MicroDrainage used in this research

6.4.2 FEH Values

The FEH method is suitable for use on areas greater than 50 hectares, the study area was greater than 50 hectares, consequently it was assumed that the FEH and been utilized to design the drainage network, see Section 2.3.

For each modelled scenario (Table 5.5) the FEH rainfall Depth-Duration-Frequency (DDF) model parameters were obtained by the FEH CD-ROM 3 using the grid reference x: 444947, y: 371838, see Table 6.3.

Table 6.3 - FEH values relating to the case study area

Parameter	Value
C	-0.027
D1	0.358
D2	0.395
D3	0.275
E	0.299
F	2.415

6.4.3 Design and simulation criteria

The design and simulation criteria used in this research are shown in Tables 6.5 and 6.6.

Table 6.4 - Summary of MicroDrainage design criteria inputs

Software component	Parameter	Value
System 1: Design Criteria	FEH Rainfall	See 6.4.4
	Return Period (years)	2, 5, 30, 50, 73, 100, 188, 221 and 261
	Time of Entry (minutes)	5
	Max Rainfall (mm/hr)	250
	Max Time of Concentration (minutes)	30
	Foul sewage per hectare (l/s)	0
	PIMP (%)	100
	Volumetric runoff coefficient	0.75
	Additional flow/climate change (%)	0
	Minimum backdrop height (m)	0.200
	Maximum backdrop height (m)	1.500
	Minimum depth for optimization (m)	1.200
	Minimum velocity for auto design only (m/s)	1.000
	Minimum slope for optimisation (1:X)	500

Table 6.5 - Summary of MicroDrainage™ simulation inputs

Software component	Parameter	Value
Simulation	FEH Rainfall	See 6.4.4
	Return Period (years)	2, 5, 30, 50, 73, 100, 188, 221 and 261 see
	Storm Duration (minutes)	15, 180
	Profile	Winter
	Volumetric runoff coefficient	0.840
	Areal reduction factor	1.000
	Hot start (minutes)	0.000
	Hot start level (mm)	0.000
	Manhole head-loss coefficient (global)	0.000
	Foul sewage per hectare (l/s)	0.000
	Additional flow - % of total flow	0.000
	MADD factor storage *10m^3/ha	0.000
	Inlet coefficient (global)	0.000
	Flow per person per day (l/per/day)	0.000
	Run time (minutes)	0.000
	Output interval (minutes)	0.000

6.4.4 As Built Network

The network was constructed in accordance with the UK MicroDrainage User Manual (2012). The 'as built' network was constructed using the data shown in Section 6.2 together with the range of values provided by the experts as shown in Section 7.5.

6.4.4.1 Catchment Area

As discussed in Section 2.4 the size of the catchment area was needed to estimate surface runoff, Equation 5.4, it was measured in hectares. The catchment area used in the initial design is unknown, it was determined using a method utilized by engineers at DCC (Russell 2012). The method is illustrated in Figure 6.5, it consisted of measuring the mid-point of a gully to the mid-point of the nearest gully on the same side of the centre line of the road. The topography of the area also needed consideration; for example, runoff occurring due to the gradient of land is then removed from the carriageway by the gully under discussion. The relevant area was also included in the measurement. This process was repeated across the site and involved 636 pipes.

With reference to Figure 6.5, the catchment areas assigned to the appropriate pipe (P) were as follows:

$P_4 = \sum A_1$

$P_5 = \sum A_2$

$P_6 = \sum A_3$

$P_7 = \sum A_4$

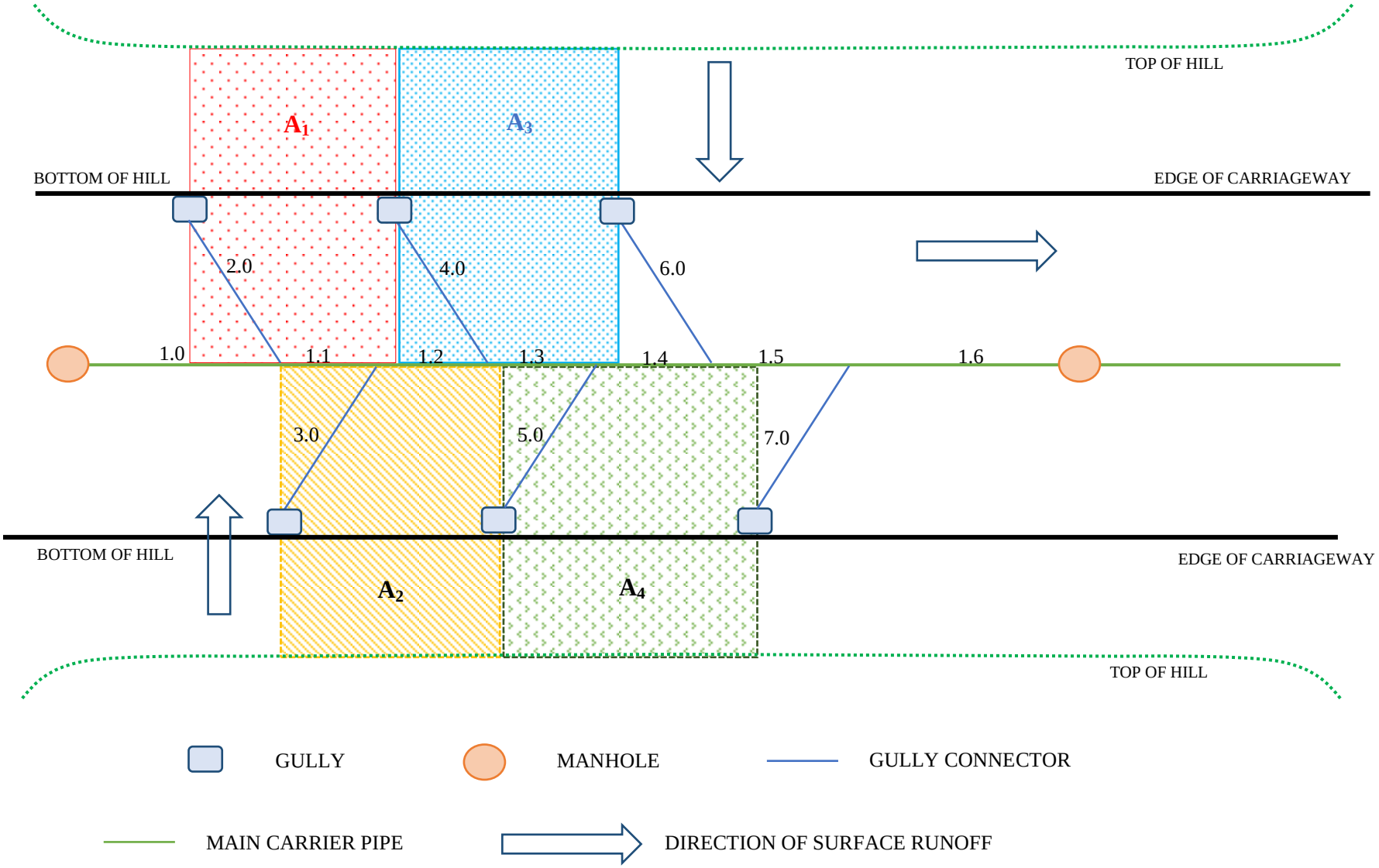


Figure 6.5 – Method used to determine the catchment area of each pipe

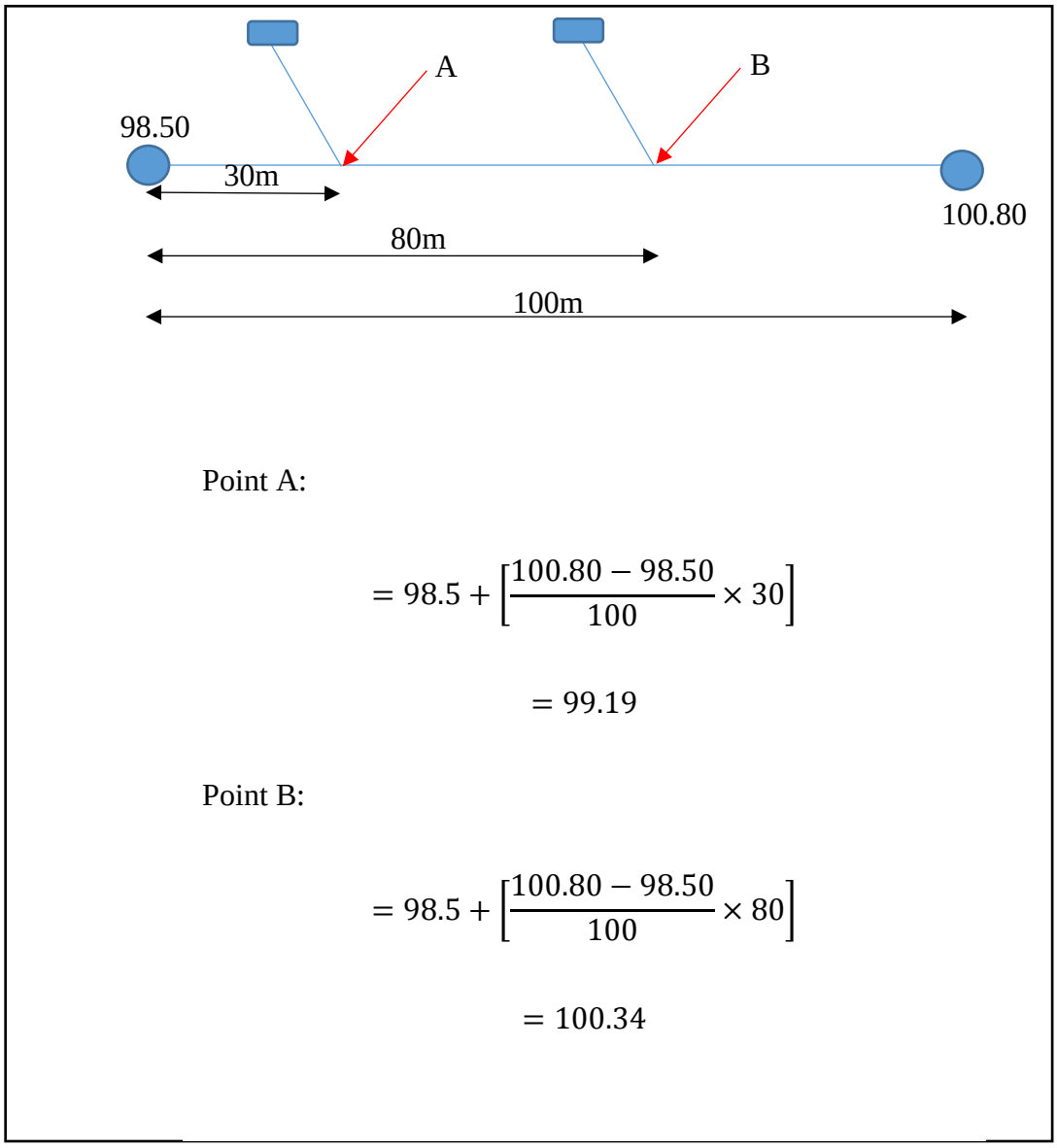
6.4.5 Unknown Levels

The site layout discussed in Section 6.2 provided known cover levels for gullies and manholes. Normally, engineers model the main carrier pipes and manholes within a network with extra storage taken into consideration by using a Manhole ADDitional Factor (MADD) (simulation criteria within MicroDrainage™). The MADD factor was originally a software which added storage to a model, it is used by Wallingford to ensure peripheral storage through small branch lines, gully connections and other sewerage systems not explicitly defined in the network (MicroDrainage, 2012h). As this research sought to include all gully connections as well as all gullies, the MADD factor was set at 0. Cover levels for the point at which the gully connectors joined the main carrier pipe were calculated using Equation (6-1).

$$Cover\ Level = \pm \frac{Height\ Difference}{Distance} \times New\ Distance \quad (6\text{-}1)$$

The resultant value was then either added to or subtracted from the original cover level value as necessary. It as necessary. It was added if the original cover level was lower and subtracted if it was higher. An example is higher. An example is shown in

Figure 6.6. All known levels were entered into the software; MicroDrainage™ then calculated the pipe gradients.



Point A:

$$= 98.5 + \left[\frac{100.80 - 98.50}{100} \times 30\right]$$

$$= 99.19$$

Point B:

$$= 98.5 + \left[\frac{100.80 - 98.50}{100} \times 80\right]$$

$$= 100.34$$

Figure 6.6 – An example of how an unknown cover level was calculated

6.4.6 Minimum/Maximum network

For the purposes of risk analysis, in order to model the minimum and maximum values of the identified risks (Table 5.5) the network was adjusted using the results obtained from the questionnaire, they are discussed in Chapter 7.

6.4.7 Climate Data

6.4.7.1 Sampled climate data

The design standard return periods augmented by expert opinion were modelled namely; 2, 30 and 100 year events. Sanderson (2010) examined how current rainfall return periods are expected to change in the future (2040, 2060 and 2080) as discussed in Section 4.4. The results from this comprehensive study, relating to Sheffield, were used in this research the return periods are shown in Table 6.6. The data provided related to an area only 21 miles from the case study site. Had this data not been available then datasets provided by UKCP09 could have been used to determine the predicted return periods for each climate event (2040, 2060 and 2080). UKCP09 provides rainfall datasets in 5km and 25km gridded resolutions which can be utilized to provide data relating to any site in the UK.

Table 6.6 - Predicted future rainfall return periods for Sheffield (Sanderson, 2010)

Present day Return Period	**2040**			**2060**			**2080**		
	10	50	90	10	50	90	10	50	90
5	4	3	3	4	3	3	4	3	2
10	10	7	6	10	6	5	10	6	4
20	16	13	10	15	12	9	14	11	7
30	24	19	14	22	17	12	21	15	10
50	39	29	22	36	26	18	34	22	15
100	74	53	37	68	45	29	62	39	24

Using the data in Table 6.6 the future return periods for 2, 30 and 100 year events were extrapolated for each year using the 50th percentile. The return periods modelled are shown in Table 6.7.

Table 6.7 - Return periods modelled

Current Return Period	**Future Return Period**		
	2040	**2060**	**2080**
2	5	5	5
30	50	50	73
100	188	221	261

6.5 Flood Cost Model

6.5.1 Multi Coloured Handbook

Penning-Rowsell et al (2013) produce a variety of publications (including the MCM) specifically on flood risk and water management of natural hazards as part of the Flood Hazard Research Centre (FHRC). Depth/damage data and techniques are provided to assess the cost of residential, non-residential and other flood losses; for example in relation to disruption caused to road and rail services, hospitals, schools, emergency services, electricity and gas supplies.

In the context of the study area, this research used the following sections of the MCM:

- Residential
- Non- Residential
- Road disruption (delayed hour method)

Appendix A1 and A2 show all site features namely: roads, car parks, buildings, substations, fields and wasteland, each were given an identification (ID) number. Using Google Earth™ all buildings were further delineated as residential and non-residential in accordance with the procedure described within the MCM.

6.5.1.1 Residential

The length and width of each residential property was measured using details from the AutoCAD drawings.

6.5.1.2 Non-residential

The length and width of each building, car park and substation were measured using details from the AutoCAD drawings. Their associated areas were calculated for inclusion in the flood cost model, described in Section 9.2. Table 6.8 and Table 6.9 show how the features for Section 1 and Section 2 were delineated.

Table 6.8 – The location, description and area of each feature ID within Section 1

ID	Location	Description	Area (m^2)
1	Part A	Electricity Sub	2908
2	Part B	Car Park	1390
3	Part B	Warehouses	1461
4	Part B	Warehouses	402
5	Part B	Warehouses	1461
6	Part B	Warehouses	402
7	Part B	Warehouses	402
8	Part B	Car Park	402
9	Part B	Car Park	402
10	Part B	Warehouses	2697
11	Part B	Warehouses	1517
12	Part B	Warehouses	595
13	Part C	Car Park	150
14	Part C	Warehouses	295
15	Part C	Warehouses	1306
16	Part C	Warehouses	402
17	Part C	Car Park	402
18	Part C	Warehouses	494
19	Part C	Warehouses	1346
20	Part C	Warehouses	4041
21	Part C	Warehouses	1209
22	Part C	Offices	434
23	Part C	Offices	81
24	Part C	Offices	88
25	Part C	Offices	545
26	Part C	Offices	261
27	Part C	Offices	212
28	Part C	Industry	9645
29	Part C	Offices	121
30	Part C	Offices	240
31	Part C	Offices	333
32	Part C	Offices	1687
33	Part C	Car Park	2674
A632	Part A	Road	Road
A6192	Part B	Road	Road
AG1	Part B	Agricultural Field	Field
W1	Part B	Wasteland	Wasteland

Table 6.9 - The location, description and area of each feature ID within Section 2

ID	Location	Description	Area (m^2)
1	Part A	Electricity Sub Station	663
2	Part A	Retail	871
3	Part A	Offices	667
4	Part A	Offices	3986
5	Part A	Offices	104
6	Part A	Offices	151
7	Part A	Offices	101
8	Part A	Offices	101
9	Part A	Offices	687
10	Part A	Offices	129
11	Part A	Industry	668
12	Part A	Car Park	1213
13	Part B	Electricity Sub Station	127
A1692	Part B	Road	Road
Markham Lane	Part B	Road	Road
W1	Part A	Wasteland	Wasteland

6.5.1.3 Road Disruption Cost

The need for traffic data in relation to the study area

No Average Annual Daily Traffic (AADT) data was available in respect of the study area, therefore to quantify possible road disruption due to flooding it was necessary to ascertain the number/ types of vehicles using the roads; this data is a required parameter within the MCM. Appendix A1 and A2 show the highway drainage infrastructure for each road within the site. A traffic survey was undertaken over a 5 day period from September 1st to 5th 2014, between 8am to 5pm, Monday to Friday. The hours were chosen to coincide with the vast majority of business opening hours. September would probably represent a typical month for trade as none of the businesses appeared to be seasonally influenced. The site has a small number of residential properties. The data collected were carefully recorded and they were considered a good representation of traffic volume by classification, see Appendix A5. Weekend vehicular traffic was expected to be significantly less due to limited Saturday opening hours of 8am–12noon. The limitations of this survey are discussed in Section 10.6.1.2

The Department for Transport (DfT) uses the vehicle classifications shown in Figure 6.7. The definitions of each classification are stated in DMRB HD 24/06 (2006), they are:

Cars – 4 wheel vehicles including taxis, estate cars, 'people carriers' and other passenger vehicles (for example, minibuses and camper vans) with a gross vehicle weight of less than 3.5 tonnes, normally ones which can accommodate not more than 15 seats.

Motorcycles – 2 wheel vehicles powered by an engine, including scooters and mopeds.

Light Goods Vehicles (LGV) - All goods vehicles up to 3.5 tonnes gross vehicle weight, for example delivery vans and milk floats.

Other Goods Vehicles (OGV) – Includes OGV 1 and OGV 2. OGV 1 and contains all rigid vehicles over 3.5 tonnes gross vehicle weight with two or three axles and OGV 2 are all rigid vehicles with four or more axles and all articulated vehicles.

Public Service Vehicles (PSV) - Includes all public service vehicles and works buses with a gross vehicle weight of 3.5 tonnes or more, usually vehicles with more than 16 seats.

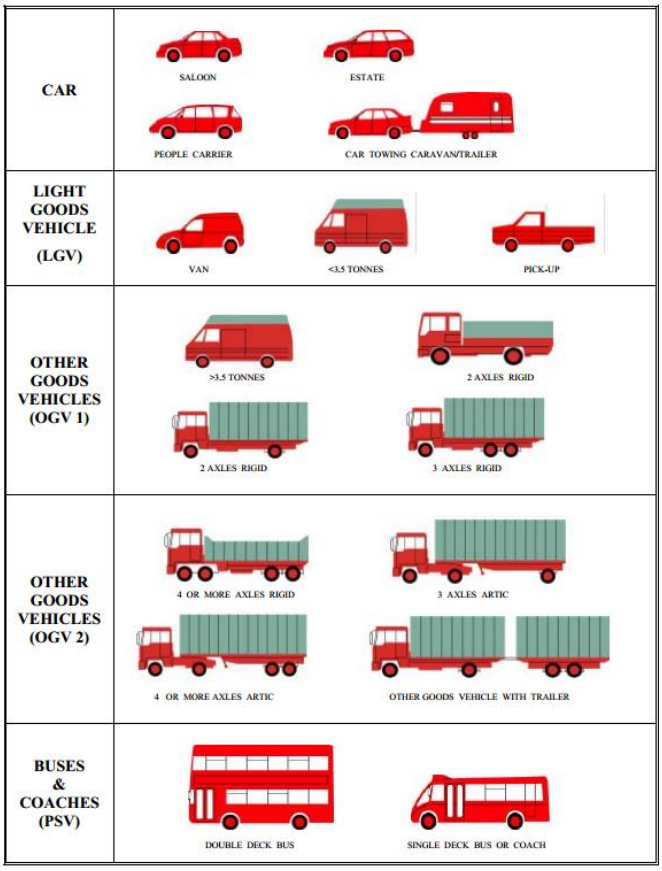


Figure 6.7 - Vehicle Classifications (DMRB HD 24/06, 2006)

Penning-Rowsell et al (2013) identifies 4 methodologies to help ascertain potential financial losses caused by a road network flooding; Delayed Hour Method, Diversion-Value Method, Speed-Limit Method and Origin-Destination Method, each method is described fully in Penning-Rowsell et al (2013). The delayed hour method was used as it is the most commonly used method by local authorities for costing floods on small developments (Russell, 2013; Boyack, 2013; Doorman, 2013).

6.6 Summary

This chapter described the case study area (Markham Vale), a former collier site adjacent to J29A of the M1 in Derbyshire, together with justification for its selection. Site layout data in respect of the 'as built' highway drainage infrastructure features were obtained from DCC.

The questionnaire was divided into seven sections (Appendix A3) and completed by highway drainage/asset managers (the experts). It had three objectives; to verify the risks identified from the literature review likely to impact on drainage infrastructure flooding. Secondly, to obtain expert opinion as to a range of values for each identified risk and thirdly to get an estimate of their probability of occurrence. The questionnaire informed the experts as to the study location and provided all as built information as recorded by DCC.

The data inputs required for network analysis within MicroDrainage™ were discussed. The unknown variables were identified as catchment area size and the cover levels relating to the points at which gully connectors joined the main carrier pipes. The methodology used to determine the size of catchment was widely used by engineers at DCC (Figure 6.5). The cover levels of each pipe junction (gully connection joining main carrier pipe) were needed as MicroDrainage™ required this information to perform drainage network analysis.

The areas (m^2) relating to each feature ID contained within the case study were measured. A traffic survey was undertaken to ascertain the number and classification of vehicles using the site. This information was required so that total direct tangible flood damage costs for each section and part of site could be calculated using the relevant sections of the MCM.

Chapter 7 presents the results of risk identification and semi quantitative analysis. The chapter also describes the risks taken further for quantitative analysis. A sensitivity analysis associated with the results of the semi quantitative analysis was undertaken to explore the major risk factors involved.

CHAPTER 7 CASE STUDY: IDENTIFIED RISKS FOR DRAINAGE NETWORK ANALYSIS

7.1 Introduction

The proceeding chapter described the techniques used to gather the data required for the case study to demonstrate the research framework presented in Chapter 5. This chapter presents the results of the questionnaire and identifies the risks used for further quantitative analysis. Section 7.2 presents the results of risk identification, Section 7.3 shows the results of semi quantitative risk analysis which were further investigated through a sensitivity analysis. The results of the sensitivity analysis are provided in Section 7.4 with the values of each identified risk, provided by the experts, for use in MicroDrainage^{TM} shown in Section 7.5.

7.2 Risk Identification

As noted in Section 5.5.1, the risk identification section of the research framework involved two elements; a literature review and consultation with experts. The literature review identified four main risk categories that may impact on highway drainage infrastructure flooding namely; as built, maintenance, deterioration and climate. These categories helped inform the development of a questionnaire completed by the experts. The purpose and structure of the questionnaire are described in Section 6.3. Table 7.1 shows the risks identified in the literature review, together with the risks added by the experts (highlighted). The percentage of experts agreeing with each identified risk is also shown.

Table 7.1 – Results of risk identification and associated percentage of expert agreement

Asset	Risk Category	Identified Risk	% Agreeing
Gully	As Built	Quality of workmanship	92
		Diameter of gully pot (mm)	48
		Depth of gully pot (mm)	48
		Gull pot material	28
		Grating size (mm)	84
		Grating material	16
		Grating type	72
Pipe	As Built	Diameter of pipe (mm)	96
		Length of pipe (mm)	36
		Pipe gradient (1:X)	96
		Pipe roughness	68
		Pipe capacity	80
		Pipe material	44
		Catchment area	88
Gully, Pipe and Manhole	As Built	Unknown connections	16
Gully, Pipe and Manhole	As built	Future developments	8
Manhole	As Built	Diameter of manhole (mm)	72
		Depth of manhole (mm)	68
		Type of Manhole	48
		Material of manhole chamber	28
Gully, Pipe and Manhole	Maintenance	Unknown maintenance frequency	96
		Unknown maintenance carried out	96
	Deterioration	Unknown rate of deterioration	84
		Unknown condition	96
	Climate	Unknown design return period	92
		Unknown future rainfall intensity	88

Table 7.2 - Identified risks ranked in order of agreement by experts

Identified Uncertainty	% Agreeing
Diameter of pipe (mm)	96
Pipe gradient (1:X)	96
Unknown maintenance frequency	96
Unknown maintenance carried out	96
Unknown condition	96
Quality of workmanship	92
Unknown design return period	92
Catchment area	88
Unknown future rainfall intensity	88
Grating size (mm)	84
Unknown rate of deterioration	84
Pipe capacity	80
Grating type	72
Diameter of manhole (mm)	72
Pipe roughness	68
Depth of manhole (mm)	68
Diameter of gully pot (mm)	48
Depth of gully pot (mm)	48
Type of Manhole	48
Pipe material	44
Length of pipe (mm)	36
Gull pot material	28
Material of manhole chamber	28
Grating material	16
Unknown Connections	16

Table 7.2 illustrates the percentage of experts having the same opinion:

1. 96% agreed with Spink et al (2014); Walters (2009); Olesen and Rollings (2012t) that pipe diameter, pipe gradient, maintenance frequency, maintenance carried out and condition of asset were the most influential aspect of highway drainage infrastructure flooding.

2. 92% considered quality of workmanship as having a major influence on the construction of highway drainage infrastructure. This risk impacts the construction of all highway infrastructure not just the drainage aspect (Okigbo, 2012).
3. 92% considered the design return period strongly influenced the risk of flooding, this finding was supported by 88% indicating future rainfall intensity would similarly strongly influence flooding; these findings are supported by X. Wu (2012); Willems et al (2012); Willems (2013); Chang et al (2013).
4. 48% indicated that gully pot diameter and depth was a potential risk, but having half the importance of the risk identified in 1 above. This was probably because following consultation with experts, the size of a gully pot was seen as standard (450mm x 750mm) as opposed to a pipe which can have varying diameters.
5. The types of material relating to pipe, manhole chambers and gully pots was recognized as a potential risk, however, it was not considered to have such an important influence.
6. 16% indicated unknown connections within a network had the least influence on flooding. This was slightly surprising as an unknown connection will not have an associated maintenance schedule that could fail and/or directly influence the failure of other assets.

7.3 Semi Quantification Analysis

In line with BSI (2010) each expert allocated a probability and impact score to the risks they considered would impact the flooding of highway drainage infrastructure. The total score for each risk was obtained by multiplying the two results together (probability and impact) and using the matrix shown in Table 5.3 to define the risk as high, medium or low. Risks were

ranked from highest to lowest using the resultant scores. The highest scores are highlighted in red, the medium scores in yellow and the low scores in green, see Table 7.3.

A well-recognised approach to ascertain the degree of dispersion within a data set is to calculate the standard deviation, a score near 0 indicates the value is very close to the mean value, a high standard deviation represents the data is spread over a range. The standard deviation associated with each average risk score is shown in Table 7.3.

Table 7.3 - Results of semi quantification obtained through expert opinion

Asset	Risk Category	Identified Risk	Average Risk Score	Standard Deviation
Gully	As Built	Quality of workmanship	23	3
		Diameter of gully pot (mm)	6	2
		Depth of gully pot (mm)	7	1
		Gull pot material	1	0
		Grating size (mm)	8	2
		Grating material	1	1
		Grating type	4	2
Pipe	As Built	Diameter of pipe (mm)	21	2
		Length of pipe (mm)	13	7
		Pipe gradient (1:X)	17	2
		Pipe roughness	6	3
		Pipe material	2	0
		Catchment area	12	5
Gully, Pipe and Manhole	As Built	Unknown connections	8	2
Gully, Pipe and Manhole	As built	Future developments	2	0
Manhole	As Built	Diameter of manhole (mm)	8	3
		Depth of manhole (mm)	8	1
		Type of Manhole	9	0
		Material of manhole chamber	2	1
Gully, Pipe and Manhole	Maintenance	Unknown maintenance frequency	21	2
		Unknown maintenance carried out	23	3
	Deterioration	Unknown rate of deterioration	22	2
		Unknown condition	22	2
	Climate	Unknown design return period	13	3
		Unknown future rainfall intensity	14	2

Table 7.3 shows the two highest standard deviations (highlighted in yellow), a standard deviation of 5 and above was considered high for the purpose of this research. There is no authority as to what is considered a high standard deviation, each must be considered separately, but a standard deviation of 5 or above is usually considered high (Freund, 1972). These slightly higher figures correspond to the level of disagreement between the experts, for example; if one expert assigned a score of 1 and another expert assigned a score of 10 to the same risk than the average score is 5.5. However, the standard deviation in relation to that risk would be 6.4; showing the experts disagreed with each other, however, if two experts had assigned the same score, the average would be the same, and consequently the standard deviation would be 0. 36% of identified risks had an average score of 15 or above: the experts considered these risks to have the most significant effect on highway drainage infrastructure. Similarly, 40% of identified risks had an average score between 5 and 12 and were considered medium risks. The remaining 24% had an average score between 1 and 4 and considered low risk. The risks designated as being significant (high risk) which could be analysed using MicroDrainage™ were then reviewed by conducting a sensitivity analysis, reducing the number. Table 7.4 shows the risks identified having a high score. The results of the sensitivity analysis are discussed in Section 7.4.

Table 7.4 - Risks identified for sensitivity analysis

Asset	Risk Category	Identified Risk	Average Risk Score
Gully	As Built	Quality of workmanship	23
Gully, Pipe and Manhole	Maintenance	Unknown maintenance carried out	23
Gully, Pipe and Manhole	Deterioration	Unknown rate of deterioration	22
Gully, Pipe and Manhole	Deterioration	Unknown condition	22
Gully, Pipe and Manhole	Maintenance	Unknown maintenance frequency	21
Pipe	As Built	Diameter of pipe (mm)	21
Gully, Pipe and Manhole	Climate	Unknown future rainfall intensity	19
Gully, Pipe and Manhole	Climate	Unknown design return period	17
Pipe	As Built	Pipe gradient (1:X)	17

Network analysis using MicroDrainage™ necessitated maintenance/deterioration to be expressed as sedimentation depth, consequently, as deterioration is a function of maintenance; the maintenance/deterioration parameters were combined to form one risk.

7.3.1 Risks excluded from sensitivity analysis

Ideally 'quality of workmanship' would be included within the sensitivity analysis and taken further for quantitative analysis. However, as this risk could not be modelled within MicroDrainage™ it was excluded. As mentioned in Section 5.12.3.2 a sensitivity analysis was undertaken incorporating all risks capable of being modelled within MicroDrainage™ to ascertain which of them had the greatest impact on the network flooding.

7.4 Sensitivity Analysis Results

For the purpose of demonstration the network was modelled using a 30 year return period and 15 minutes storm duration. The return period and the storm durations were chosen following consultation with experts, and in accordance with DMRB HA37/97 (1997). Figure 2.13 shows that for a lower return period and lower duration the rainfall intensity is considerably lower than that of a higher return period with the same lower duration.

The sensitivity analysis involved adjusting the original value of each identified risk by increments of: 10%, 20%, 30%, 40% and 50% while keeping the remaining risks at their original value, this was done to test how sensitive each risk was to the network under consideration. The results of the sensitivity analysis are shown in Figure 7.1.

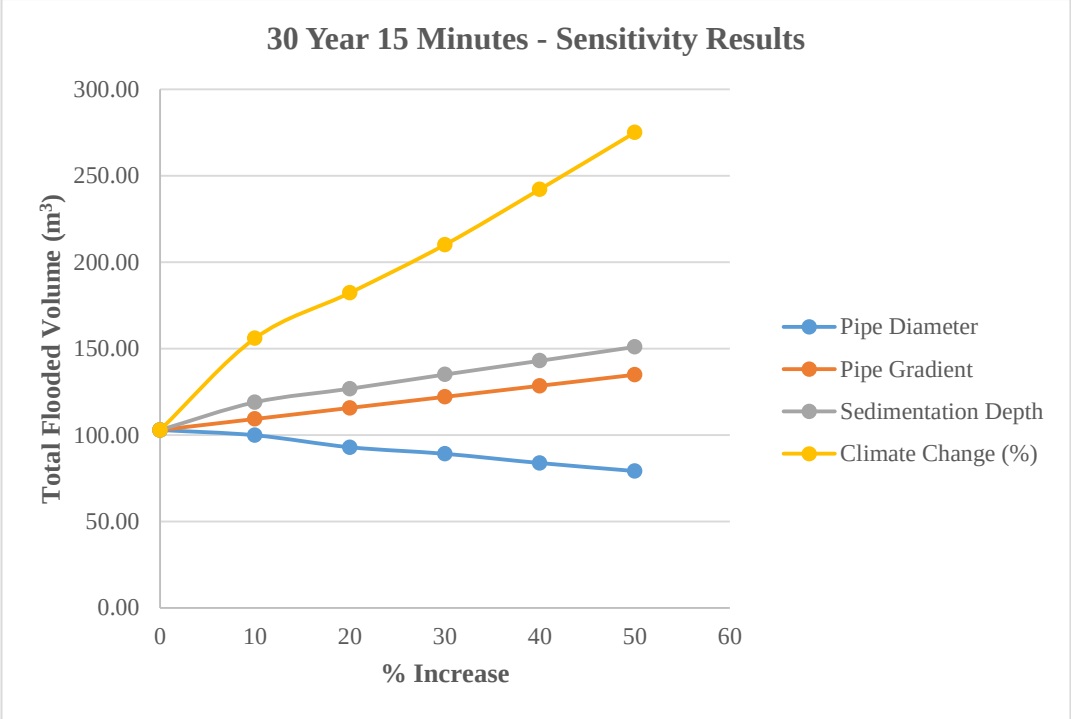


Figure 7.1 - Results of the sensitivity analysis

Figure 7.1 demonstrates the following:

Pipe diameter – the volume of flood decreased when the pipe diameter increased; this was expected as the capacity within the network increased.

Pipe gradient – the total volume of flood increased when the pipe gradient increased, this was expected as the velocity within the network reduced as a result.

Sedimentation depth – the volume of flood increased when the sedimentation depth increased, this was expected as the area of the pipe was reduced within the network; consequently, network capacity reduced accordingly.

Climate Change – as additional flow increased within the network so did the total volume of flood. Any increase in flow (when all other parameters remain constant) would result in a greater strain on the network, and hence a flood if no network capacity remained.

The results of the sensitivity analysis (Figure 7.1), indicated climate change was the most influential risk affecting highway drainage infrastructure flooding. The risks were ranked in order of importance as follows: climate change, sedimentation depth, pipe gradient and pipe diameter**.**

7.5 Experts opinion on values

The risks identified in Section 7.4 for quantitative analysis needed to be modelled within MicroDrainage ™, this necessitated a single value being associated with each minimum, most likely and maximum values related to each risk. Therefore, the modal value for each identified risk was incorporated into the MicroDrainage ™ analysis. The research was not concerned with modelling the response of each expert separately.

7.5.1 Pipe Diameter

Section 3.4.1 shows that UK LAs recognize that asset inventory regarding highway drainage infrastructure is inadequate although the situation is improving (Lugg, 2012) but is likely to never be fully complete and accurate (Spink et al, 2014). As mentioned in Section 6.3.3.4 the as built 'most likely' pipe diameters were provided to the experts (Question 4i – Appendix A3) who were also asked for their opinion as to minimum and maximum value of each most likely pipe diameter to facilitate risk modelling. 96% of participants considered pipe diameter to strongly impact highway drainage infrastructure flooding. All participants agreed that no pipe diameter within a highway drainage system would exceed 450mm, and that any pipe of a larger diameter would be classified as surface water drainage. Table 7.5 shows the modal minimum and modal maximum diameters obtained from expert opinions.

Table 7.5 – Range of pipe diameters used in network analysis

Identified Risk	Most Likely (mm)	Minimum (mm)	Maximum (mm)
Pipe Diameter (mm)	150	100	225
	225	150	300
	300	225	375
	375	300	450
	450	375	525
	600	525	750
	750	750	900
	900	750	1050
	1050	900	1200
	1200	1050	1200

7.5.2 Pipe Gradient

As mentioned in Section 6.4.4 the as built 'most likely' gradients were known and formed the basis of the most likely simulation within MicroDrainage™. 96% of experts identified pipe gradient as a risk strongly influencing highway drainage infrastructure flooding. Participants were asked to give an opinion as to the possible percentage change in respect of pipe gradient, the results are shown in Table 7.6.

Table 7.6 - Expert opinion as to how the gradient may have changed (percentage)

Participant ID	± % Change
1	10
2	10
3	10
4	5
5	5
6	10
7	10
8	10
9	5
10	5
11	5
12	10
13	10
14	Not a risk
15	10
16	5
17	10
18	10
19	10
20	5

Participant ID	± % Change
21	10
22	10
23	10
24	5
Mode	**10**

The modal percentage was used to calculate the minimum and maximum values in respect of pipe gradient for drainage network analysis.

7.5.3 Maintenance/ Deterioration of assets

Section 7.2 showed 96% of respondents identified maintenance as a major factor impacting highway drainage infrastructure flooding. Although the experts were told the site was approximately 9 years old they were unaware of previous maintenance. The experts verified the types of maintenance options a gully, manhole and pipe would usually have received since installation (Question 7i). Question 8i asked for an opinion as to the number of times each gully, manhole and pipe was likely to have received each of the identified maintenance options since site completion, the results are shown in Table 7.7. The responses indicated removal of debris was the most necessary type of maintenance required. Nobody considered it would have been necessary to have replaced any of the assets.

Table 7.7 - Expert opinion as to asset maintenance

Maintenance Option	Asset Type		
	Gully	Manhole	Pipe
Do nothing	0	0	0
Inspect asset (Do Nothing)	3	4	5
Inspect asset (Remove debris from the asset)	12	1	2
Inspect asset (Repair the asset)	4	0	2
Inspect asset (Replace the whole asset)	0	0	0

As noted in Section 3.6 the deterioration of an infrastructure asset is strongly influenced by the standard of maintenance received (Spink et al, 2014). As a consequence of the results shown in Table 7.7; the experts then estimated the percentage change in functionality of the asset due to it being clogged with debris (Question 9), the results are shown in Table 7.8. Experts assumed the minimum scenario was that the pipes had been designed to be self-cleansing and consequently clear of debris, they also assumed that removal of debris from pipes would only have occurred twice since installation.

Table 7.8 - Efficiency loss for each asset (%)

		Efficiency Loss (%)		
Risk	**Size**	**Minimum**	**Maximum**	**Most Likely**
Pipe Diameter	100 – 300	0	100	40
	375-600	0	100	10
	750-1200	0	100	5
Gully Depth	750	0	100	50
Manhole Depth	Type A	0	20	10
	Type B	0	20	10

Using the results shown in Table 7.8, the sedimentation depth for each pipe size was calculated, see Table 7.9. Although theoretically a pipe could have been fully blocked with debris, MicroDrainage™ does not allow sedimentation depth to be equal to or larger than the pipe diameter, therefore, the maximum sedimentation depth allowed was 1mm less than the pipe diameter, for example a 100mm pipe diameter was modelled as a 99mm pipe diameter. This would have had minimal effect on the analysis as the flow was nearly completely restricted.

Table 7.9 - Calculated sedimentation depth for use in MicroDrainage™

	Sedimentation Depth (mm)		
Pipe Diameter (mm)	**Min**	**Max**	**Most likely**
100	100	99	40
150	150	149	60
225	225	224	90
300	300	299	120
375	375	374	38
450	450	449	45
600	600	599	60
750	750	749	38
900	900	899	45
1050	1050	1049	53
1200	1200	1199	60

7.5.4 Climate Change (Return Period and Storm Duration)

Tables 4.2 and 4.3 (extracted from Walters (2009) show the vulnerability of a drainage network to more intense rainfall as a result of climate change. The IDF relationship indicates that for a given return period and duration, the mean rainfall intensity can be determined (Chang et al, 2013). Rainfall intensity can then be used to estimate surface runoff (Equation 5.4) (Lumbroso et al, 2011).

Section 6.4.7 detailed how the return period specified in the original design was considered uncertain as no supporting documentation was available in relation to the network examined. During discussion, each expert considered the examined network would have been designed to a 2, 30 or 100 year event. Therefore, in the absence of historic data, each of the recognized return periods were modelled to ascertain the effect each return period would have on network functionality.

Sanderson (2010) examined how rainfall return periods are expected to change in the future in relation to 2040, 2060 and 2080. Section 6.4.7 explained that the climate data used within

this research was extracted from Sanderson (2010). The future return periods in respect of Sheffield were used as they related to the study area, as Sheffield is only approximately 21 miles away from the study area.

This research modelled two different storm durations, namely; 15 minutes and 180 minutes, these durations were chosen as experts indicated that in their experience these durations had the most impact on flooding (Russell, 2013; Bache, 2013; Boyack, 2013; Green, 2013; Wells, 2013; Doorman, 2013).

7.5.5 Probability of values occurring

Question 10 of the questionnaire asked experts to provide a probability of occurrence for each minimum, most likely and maximum value associated with each identified risk (pipe diameter, gradient, sedimentation depth), the result are in Table 7.10.

Table 7.10 - Probability of values occurring as identified by the experts

	% chance of occurrence		
Identified Risk	*Minimum value*	*Most Likely value*	*Maximum value*
Pipe Diameter	5	90	5
Pipe Gradient	5	90	5
Sedimentation Depth	90	5	5

Table 5.5 identified each modelled scenario by number, the probability associated with each scenario was then calculated by:

1. Substituting the probability associated with each risk value (minimum, most likely and maximum), using Table 7.10.
2. Multiplying the probability of each risk (diameter, gradient and sedimentation depth).

An example for Scenario 1 is shown below;

Using Table 5.5, scenario 1 consists of:

Diameter of pipe (minimum), gradient (minimum), sedimentation depth (minimum)

Therefore, using Table 7.10, scenario 1 becomes:

Diameter of pipe (0.05), gradient (0.05), sedimentation depth (0.9)

The total probability of occurrence is:

Diameter of pipe (0.05) × gradient (0.05) × sedimentation depth (0.9) = 0.00225

The results in relation to all the scenarios are shown in Table 7.11.

Table 7.11 – Overall probability of occurrence associated with each scenario

Scenario	**Probability**			**Total Probability of occurrence**
	Diameter of pipe	Gradient	Sedimentation depth	
1	0.05	0.05	0.9	0.00225
2	0.9	0.9	0.05	0.0405
3	0.05	0.05	0.05	0.000125
4	0.9	0.05	0.05	0.00225
5	0.05	0.9	0.9	0.0405
6	0.05	0.05	0.05	0.000125
7	0.05	0.9	0.05	0.00225
8	0.9	0.05	0.9	0.0405
9	0.9	0.05	0.9	0.0405
10	0.05	0.05	0.05	0.000125
11	0.9	0.05	0.05	0.00225
12	0.9	0.05	0.05	0.00225
13	0.05	0.05	0.05	0.000125
14	0.05	0.05	0.9	0.00225
15	0.05	0.05	0.05	0.000125
16	0.05	0.05	0.9	0.00225
17	0.05	0.05	0.05	0.000125
18	0.05	0.9	0.05	0.0045
19	0.05	0.05	0.05	0.000125
20	0.9	0.05	0.05	0.00225
21	0.05	0.9	0.9	0.0405
22	0.9	0.9	0.05	0.0405
23	0.05	0.05	0.05	0.000125

Scenario	Probability			Total Probability of occurrence
	Diameter of pipe	Gradient	Sedimentation depth	
24	0.9	0.9	0.9	0.729

Scenario 24 in Table 7.11 showed the highest probability of occurrence (0.729). This scenario represented the as built situation, the pipe diameter and the gradient both had the most likely value. Similarly, sedimentation depth was minimal; consequently high probabilities were associated with each risk value.

7.6 Summary

This chapter presented the results of the questionnaire regarding risk identification and semi quantitative analysis together with the values provided by the experts that were associated with each risk.

Table 7.2 showed the risks identified by the experts ranked in order of importance. 96% agreed pipe diameter, pipe gradient, unknown maintenance frequency, unknown maintenance carried out, and unknown condition of the assets had the most impact on causing highway drainage infrastructure to flood. 92% considered the design return period strongly influenced flooding, interestingly 92% considered quality of workmanship influenced highway drainage infrastructure flooding. However, this parameter could not be included within the Flood Risk Model as MicroDrainage™ has no facility for its incorporation. The results of the semi quantitative analysis (Table 7.4) identified 9 high risks namely risks with a score greater than 15. However, drainage network analysis using MicroDrainage™ necessitated maintenance/deterioration to be expressed as sedimentation depth, consequently, as deterioration is a function of maintenance; the maintenance/deterioration parameters were combined to form one risk. A sensitivity analysis was undertaken to ascertain if the risks identified through semi quantitative analysis would positively impact highway drainage

infrastructure flooding. The findings indicated climate change was the most influential risk effecting highway drainage infrastructure flooding. The risks were ranked in order of importance as follows; climate change, sedimentation depth, pipe gradient and pipe diameter. Section 7.5 discussed the range of values relating to each identified risk provided by experts. These values were then used to undertake drainage network analysis using MicroDrainage™ and the results are presented in Chapter 8..

CHAPTER 8 CASE STUDY: DRAINAGE NETWORK ANALYSIS RESULTS

8.1 Introduction

This chapter utilizes the data collected as described in Chapter 6 together with the results contained in Chapter 7. As discussed in Section 6.1.1 the study area was divided into two sections; Section 1 and Section 2. Section 1 was divided into parts; A, B and C and Section 2 into A and B. The modules of MicroDrainage ™ used within this research are illustrated in Figure 6.4. Section 7.4 identified four risks that impact highway drainage infrastructure flooding; pipe diameter, pipe gradient, sedimentation depth and climate change (return period and storm duration). This chapter presents the results of modelling these risks through MicroDrainage™. Section 8.2 describes how the network was constructed for each of the 24 scenarios modelled. Section 8.3 provides the flood flow analysis results for Section 1 of the study area and Section 8.4 provides the results for Section 2.

8.2 Network Details

Figure 2.14 illustrated a typical layout of a drainage network. This approach was adopted when constructing the drainage network within MicroDrainage™. The longest pipe upstream of the outfall was labelled 1.000, the point at which the first branch enters 1.000 was labelled 2.000, and the point at which the first branch enters 2.000 was labelled 3.000; this process was repeated throughout the network. The as built network for each site section was constructed using the existing network layout details as described in Section 6.2 together with the assumed MicroDrainage™ (Section 6.4). Section 1 contained 105 gully pots, 172 pipes and 44 manholes. Section 2 contained 113 gully pots, 265 pipes and 88 manholes.

In order to calculate the surface runoff (Q_p) and discharge (Q_F) of each pipe several parameters were required. Using the example network details identified in Figure 2.14

networks for both site sections were designed within MicroDrainage™ utilizing the details shown in Table 8.1.

Table 8.1 – An example of the necessary input parameters required to specify the network details within MicroDrainage

Pipe no	Pipe Length	Fall (m)	Slope (1:X)	Area (ha)	Time of Entry (Minutes)	Base Flow (l/s)	Pipe Roughness	Upstream Invert Level (m)	Upstream Cover Level (m)	Pipe Diameter (mm)	Sediment Depth (mm)
1.000											
1.001											
2.000											
3.000											
2.001											
1.002											

Due to software limitations (see Section 10.5.4) and to accommodate modelling for each scenario (Table 5.5), the following was undertaken:

- Section 1: for each pipe (172) the diameter, gradient and sedimentation depth were adjusted to comply with the values provided by the experts (Section 7.5). This entailed 516 adjustments (172×3).
- Section 2: similarly each pipe (265) entailed 795 adjustments (265×3)
- In total 12,384 (516×24) adjustments for Section 1 and 19,080 (795×24) adjustments for Section 2 were necessary to model the 24 scenarios.

Appendix B1 shows the volume of flood for each simulation and site section relating to each storm duration and return period. A summary of each return period, storm duration and section of site showing the number of pipes flooded, at flood risk, surcharged and those that did not flood are shown in Appendix B2. The scenario having the greatest volume of flood over all return periods is shown to vary for both durations within Section 1. Simulations 16 and 6 had the greatest flooded volume for both durations for Section 2.

8.3 Simulation Results

The IDF relationship (Section 2.3.2) shows the greater the return period for a given duration, the higher the rainfall intensity value used within Equation 5.4. Analysis was undertaken as described in the UK MicroDrainage™ User Manual (2012). Each simulation file was analysed for each climatic event:

- (2, 30, 100 year events)
- 2040 (5, 30, 188 year events)
- 2060 (5, 50, 221 year events)
- 2080 (5, 73, 261 year events)

Storm durations of 15 and 180 minutes were used for analysis (Bache, 2013; Boyack, 2013; Green, 2013; Doorman, 2013; Wells, 2013). The network analysis results for Section 1 and Section 2 showed for higher return periods with durations of 15, or 180 minutes there was an increased number of the flooded pipes, pipes at flood risk or which surcharged. Figures 8.1 and 8.2 show the percentage of flooded pipes in Section 1 and Section 2 for all return periods and both storm durations (15 and 180 minutes).

Figure 8.1 illustrates Section 1 Part C had more pipes flood than in Parts A and B; this was less than 25% of the network within Part C for a 15 minute duration. Part B experienced the least flooding under both durations. The network details, for example; pipe gradient, pipe diameter and catchment area are different in Parts A, B and C. The topography of an area also effects the flow of water, as Part C is relatively flat and situated at the bottom of a hill, runoff not able to enter the network in Parts A and B naturally accumulates within Part C. Reflecting the principles of an IDF relationship (Section 2.3.2), the rainfall intensity is higher for the 15 minute duration, consequently Q_P increases and more pipes flood compared to the 180 minute duration.

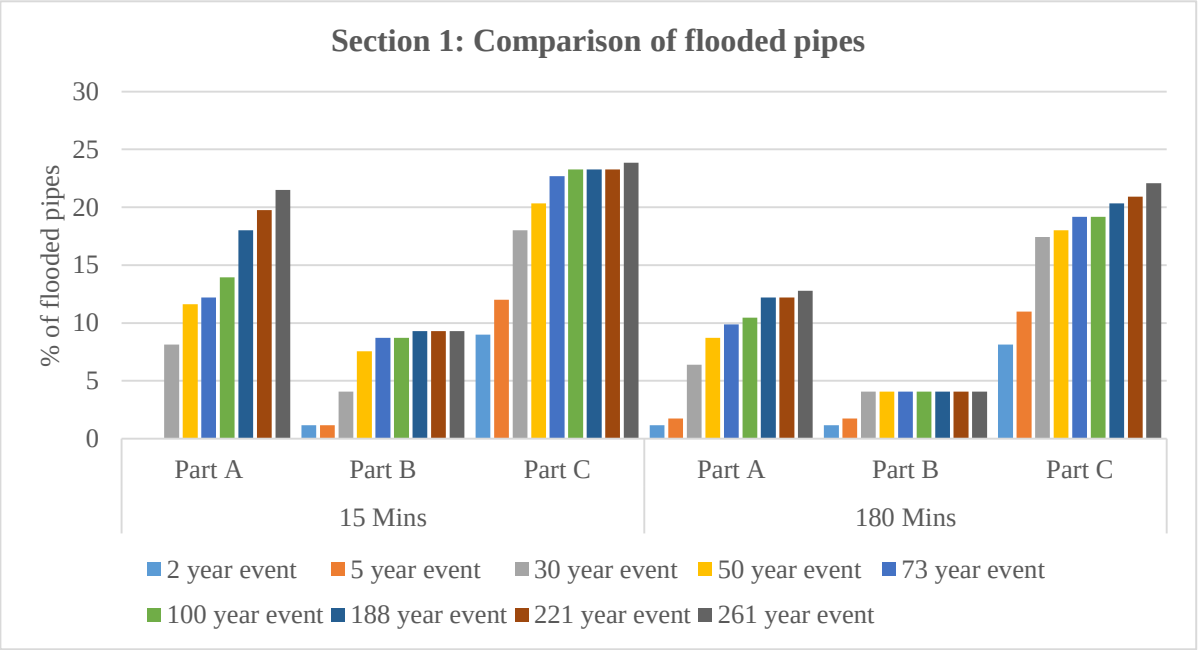


Figure 8.1 – A comparison showing the percentage of flooded pipes in Section 1 Parts A, B and C for 15 minute and 180 minute storm durations

Section 2, Part A had more flooded pipes, less than 35% of the network for a 15 minute duration. Part B experienced the least flooding under both durations. Parts A and B have different network details and a different topography these factors taken together with IDF principles (Section 2.3.2) explains why there is a difference in the number of flooded pipes within each part, see Figure 8.2.

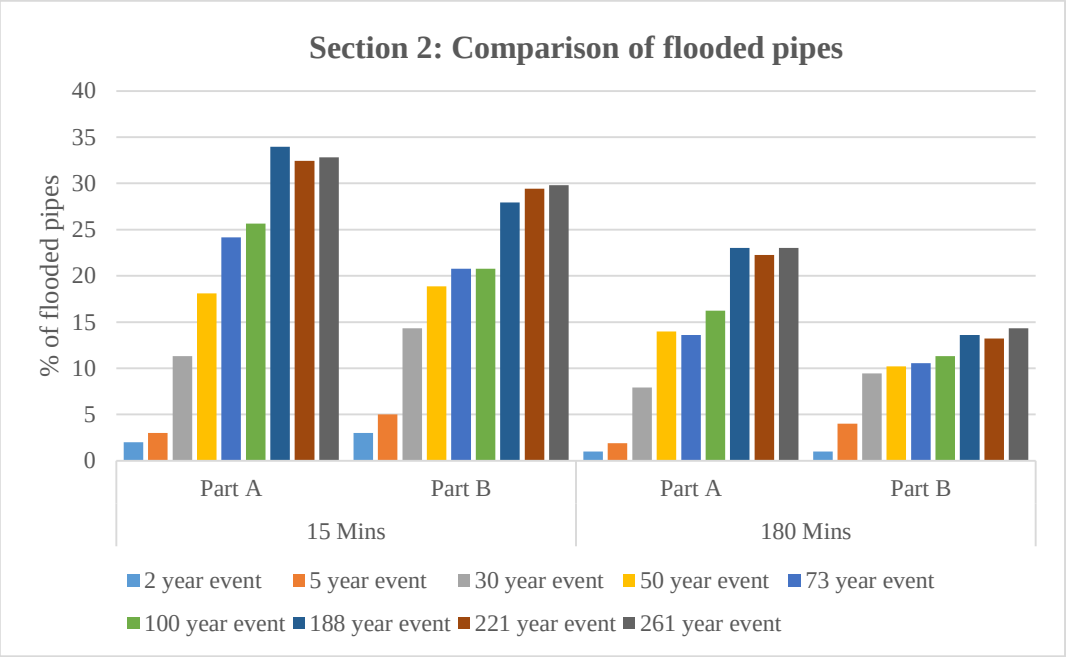


Figure 8.2 – A comparison showing the percentage of flooded pipes in Section 2 Parts A and B for 15 minute and 180 minute storm durations

Appendix B3 shows an example (Scenario 16) of the MicroDrainage™ simulation results; in total 450 simulations were performed. The example relates to Section 1, 261 year event, 15 minute duration, this was the event that produced the most flooded volume. The MicroDrainage™ simulation results for each scenario under all return periods and both storm durations were exported individually to Microsoft Excel, then sorted by flooded volume. This enabled all flooded pipes to be isolated enabling sections of flooded site to be identified. Flood Flow Analysis was then undertaken on all flooded scenarios.

8.4 Flood Flow Analysis

The flood flow analysis module was used in conjunction with the simulation module, it is a 2D analysis engine that creates overland flood flow paths. The output of the module shows the direction of flood, the depth of flood and associated velocity. The default settings were used following consultation with experienced users of MicroDrainage™ (Russell, 2013; Bache, 2013; Boyack, 2013; Doorman, 2013). The graphical result of flood flow analysis uses default colours shown in Table 8.2.

Table 8.2 - Default flood flow display settings (MicroDrainage, 2012f)

Depth < (mm)	**Colour**
10	Not drawn
100	
300	
600	

Each flooded simulation file was further examined to determine the extent and depth of flooding for each modelled scenario, climatic event and storm duration.

8.4.1 Section 1

Figures 8.5 to 8.11 show examples of the flood flow analysis relating to Scenario 16 for a 15 minute duration for each of the climatic events modelled. Scenario 16 consisted:

- Pipe diameter – Minimum
- Gradient - Maximum
- Sedimentation depth – maximum

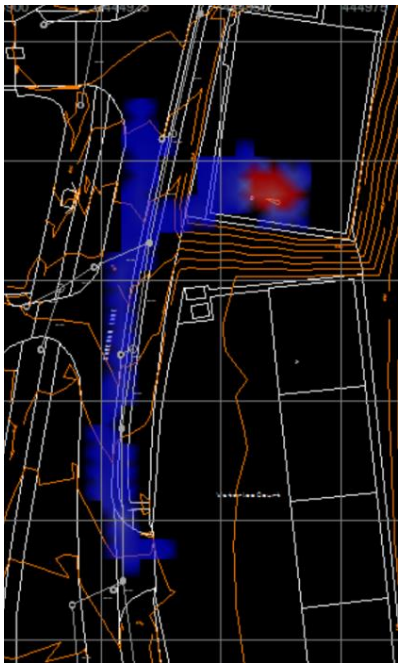


Figure 8.3 - Section 1 5 year 15 minutes

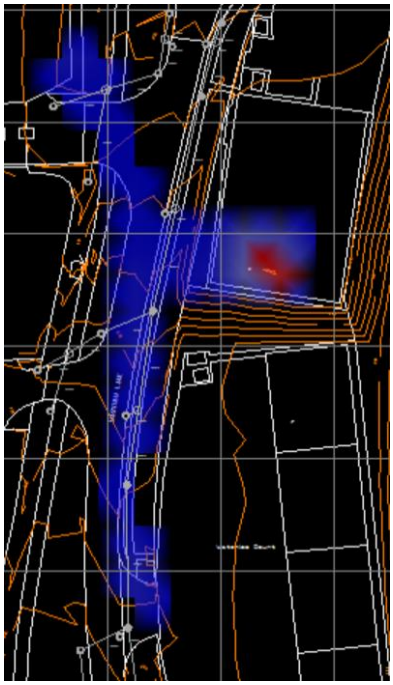


Figure 8.4 - Section 1 5 year 15 minutes

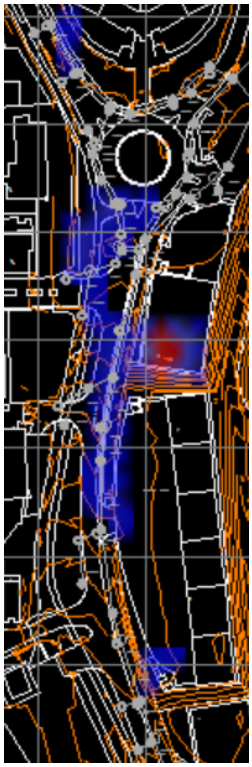


Figure 8.5 - Section 1 30 year 15 minutes

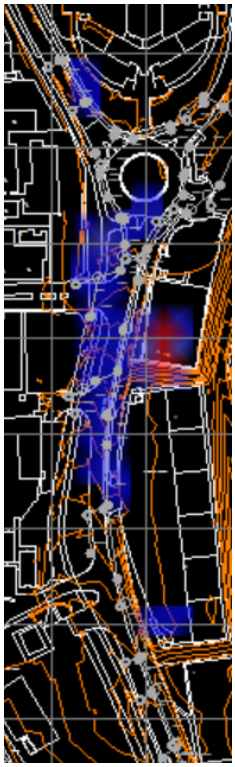


Figure 8.6 - Section 1 50 year 15 minutes

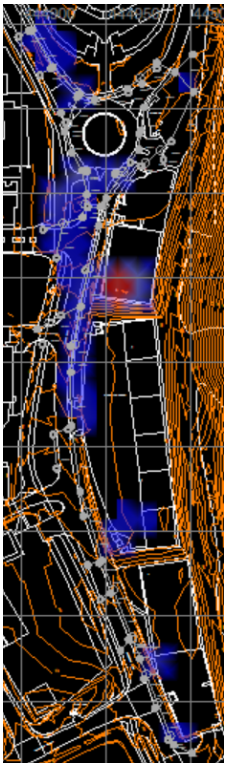


Figure 8.7 - Section 1 73 year 15 minutes

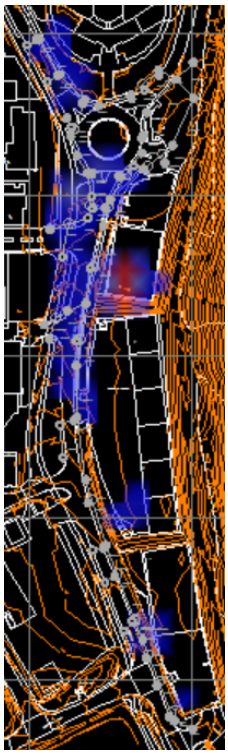


Figure 8.8 - Section 1 100 year 15 minutes

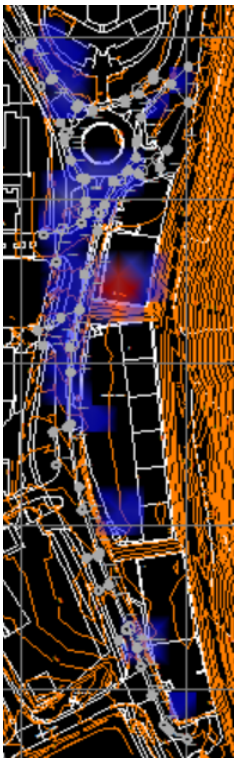


Figure 8.9 - Section 1 188 year 15 minutes

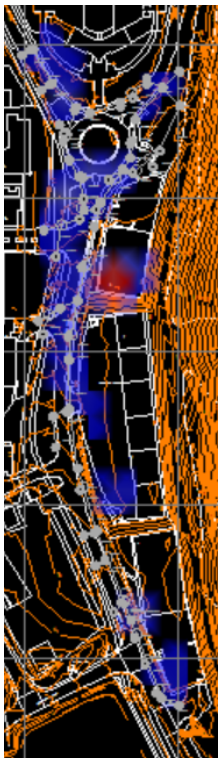


Figure 8.10 - Section 1 221 year 15 minutes

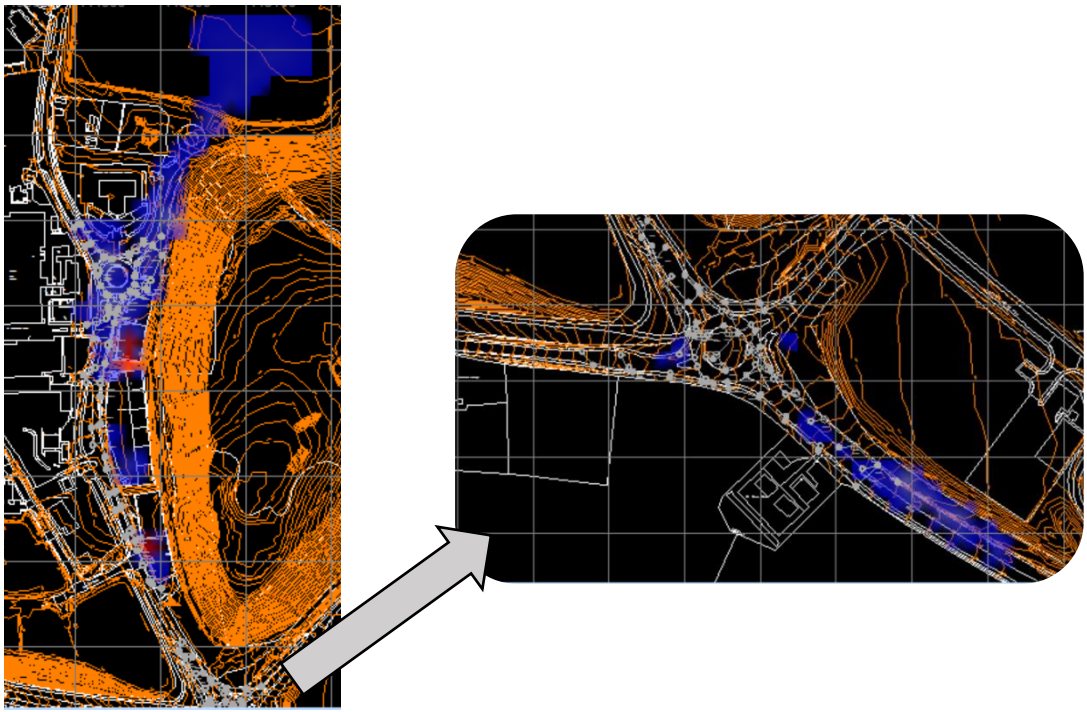


Figure 8.11 - Section 1, 261 year 15 minutes

8.4.1.1 Comparison of 15minute and 180 minute durations

Table 8.3 provides a summary of the times each ID flooded over the 24 modelled scenarios for both durations and each return period. Appendices B4 to B7 show the IDs and depth of flood under each return period for 15 minutes and Appendices B8 to B11 show 180 minutes respectively, for each scenario modelled. Appendices B4 to B11 show that for the majority of IDs the flood depth does not change across return periods. The flood depth for IDs 16, 17 and 21 increased to 250mm for all return periods greater than a 5 year event.

8.4.1.2 Non-residential properties

Table 8.3 shows the IDs affected by flooding, namely: 1, 2, 3, 4, 5, 8, 13, 16, 17 and 21 for both durations. Table 6.8 identified the IDs as an electricity sub-station, car parks and warehouses. However, ID 33 (a car park) only flooded during the 180 minutes storm duration.

8.4.1.3 Road disruption

The A6192 flooded for all return periods and both durations at a depth of 100mm. The A632 only flooded for all return periods greater than 5 years for a storm duration of 15 minutes; however, for a 180 minute duration it flooded under all return periods.

8.4.1.4 Other flooded features

The agricultural area flooded in 4 out of 24 modelled scenarios. Scenario 4 produced the greatest flooded area see Figure 8.12. The field only flooded if the return period was greater than 50 years. The depth of flood for the field did not change during all the simulations and remained at less than 100mm.

Table 8.3 - Summary of the number of times each ID flooded over 24 scenarios under each climatic event (Section 1: 15 Minutes)

Section 1			Return Period																					
			2080						2060						2040						Current Standard			
Feature ID	Location (Appendix A1)	Description	261		73		5		221		50		5		188		30		5		100		30	
			Storm Duration (Minutes)																					
			15	180	15	180	15	180	15	180	15	180	15	180	15	180	15	180	15	180	15	180	15	180
0		No Flood	0	1	0	1	0	5	0	1	0	1	0	5	0	1	0	1	0	5	0	1	0	1
1	Part A	Electricity Sub Station	3	1	0	0	0	0	3	1	0	0	0	0	2	0	0	0	0	0	2	0	0	0
2	Part B	Car Park	7	6	2	1	0	0	7	6	0	0	0	0	4	5	0	0	0	0	4	4	0	0
3	Part B	Warehouses	8	7	3	2	0	0	8	7	1	0	0	0	5	6	0	0	0	0	4	5	0	0
4	Part B	Warehouses	7	8	3	2	0	0	7	8	0	0	0	0	7	5	0	0	0	0	6	6	0	0
5	Part B	Warehouses	3	8	0	3	0	0	3	8	0	1	0	0	3	5	0	0	0	0	1	5	0	0
6	Part B	Warehouses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Part B	Warehouses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Part B	Car Park	23	13	19	10	0	0	23	12	11	4	0	0	23	12	6	1	0	0	23	12	6	1
9	Part B	Car Park	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	Part B	Warehouses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	Part B	Warehouses	1	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
12	Part B	Warehouses	1	0	1	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0
13	Part C	Car Park	22	12	19	12	0	0	22	12	14	8	0	0	22	12	8	2	0	0	22	12	8	2
14	Part C	Warehouses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	Part C	Warehouses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	Part C	Warehouses	23	21	23	19	0	9	23	21	23	19	0	9	23	19	23	15	0	9	23	19	23	15
17	Part C	Car Park	19	14	17	14	0	2	19	14	14	14	0	2	19	14	6	13	0	2	19	14	6	13
18	Part C	Warehouses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	Part C	Warehouses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	Part C	Industry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	Part C	Warehouses	22	3	21	3	0	0	22	3	20	2	0	0	22	3	10	0	0	0	22	3	10	0
22	Part C	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	Part C	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Part C	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Part C	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Part C	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	Part C	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	Part C	Industry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	Part C	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	Part C	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	Part C	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	Part C	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	Part C	Car Park	0	1	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
A632	Part A	Road	20	10	16	8	0	1	20	10	16	8	0	1	19	8	8	7	0	1	19	8	8	7
A6192	Part B	Road	24	23	24	23	24	19	24	23	24	23	24	19	24	23	24	23	24	19	24	23	24	23
AG1	Part B	Agricultural Field	4	1	1	0	0	0	4	1	0	0	0	0	4	0	0	0	0	0	4	0	0	0
W1	Part B	Wasteland	0	8	0	8	0	0	0	8	0	8	0	0	0	8	0	3	0	0	0	8	0	3

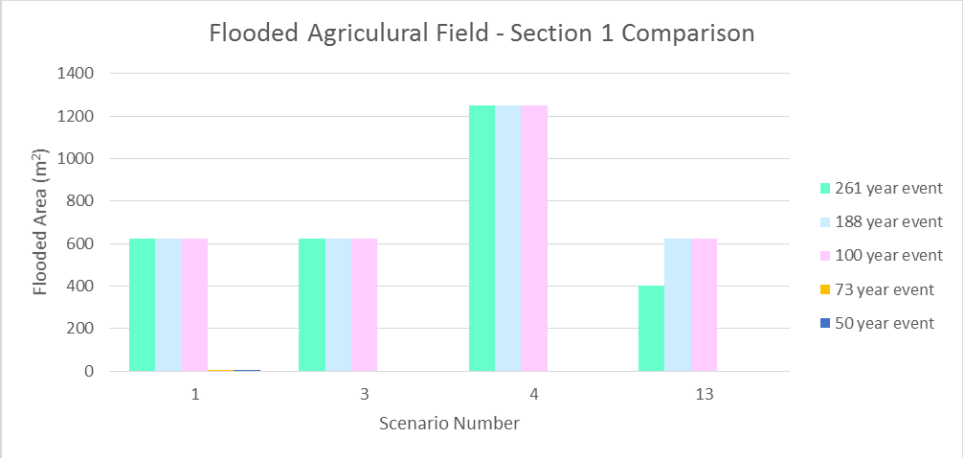


Figure 8.12 - Section 1 scenario comparison - agricultural field

Table 8.3 shows that for each return period under a 15 minute duration none of the wasteland flooded. However, during a 180 minute duration flooding occurred as shown in Figure 8.13. As the return period increased so did the total amount of flooded area, reflecting the principles of an IDF relationship (Section 2.3.2).

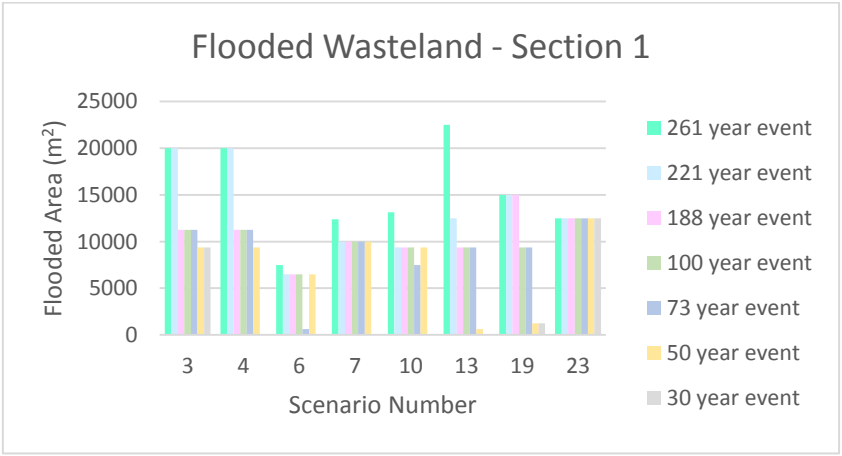


Figure 8.13 - Wasteland flooded area Section 1 180Mins

The results of flood flow analysis for each modelled scenario for all return periods and both storm durations were manually recorded within Microsoft Excel to calculate the total monetary impact of the flood as discussed in Section 10.5.4.

8.4.2 Section 2

8.4.2.1 Comparison of 15minute and 180 minute durations

Table 8.4 summarizes the specific parts of Section 2 that flooded, identified by the allocated ID reference. Appendices B12 to B15 show the flood depth under each return period for 15 minutes and Appendices B16 to B19 show 180 minutes for each ID and scenario modelled. The flood depth affecting all IDs did not change across return periods and durations, it remained less than 100mm. Figure 8.14 gives an example of flood flow analysis in respect of Scenario 6 for a 15 minute duration for each of the climatic events modelled.

8.4.2.2 Non-residential properties

Table 8.4 shows only ID 13 flooded (the electricity sub-station).

8.4.2.3 Road disruption

The A6192 and Markham Lane (A632 to A1692) flooded for all return periods and both durations at a depth of less than 100mm.

Table 8.4 - Feature ID Comparison Section 2

Section 2			Return Period (year)																					
			2080						2060						2040						Current Standard					
Feature ID	Location (Appendix A2)	Description	261		73		5		221		50		5		188		30		5		100		30		2	
			Storm Duration (Minutes)																							
			15	180	15	180	15	180	15	180	15	180	15	180	15	180	15	180	15	180	15	180	15	180	15	180
0		No Flood	3	9	10	12	17	15	3	9	10	12	17	15	4	9	10	13	17	15	5	12	10	13	23	15
1	Part A	Electricity Sub Station	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Part A	Retail	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Part A	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Part A	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Part A	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Part A	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Part A	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Part A	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Part A	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	Part A	Offices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	Part A	Industry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Part A	Car Park	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Part A	Electricity Sub Station	4	4	0	0	0	0	3	3	0	0	0	0	2	2	0	0	0	0	2	1	0	0	0	0
A1692	Part A and B	A1692	20	15	14	12	7	9	19	15	14	12	7	9	19	15	13	11	7	9	19	12	13	11	1	9
Markham Lane (A632 to A1692)	Part B	Markham Lane (A632 to A1692)	19	12	14	12	0	9	18	12	12	12	0	9	17	12	7	11	0	9	16	12	7	11	0	8
W1	Part A and B	Wasteland	22	27	7	21	0	6	19	27	7	21	0	6	14	27	0	13	0	6	13	21	0	13	0	3

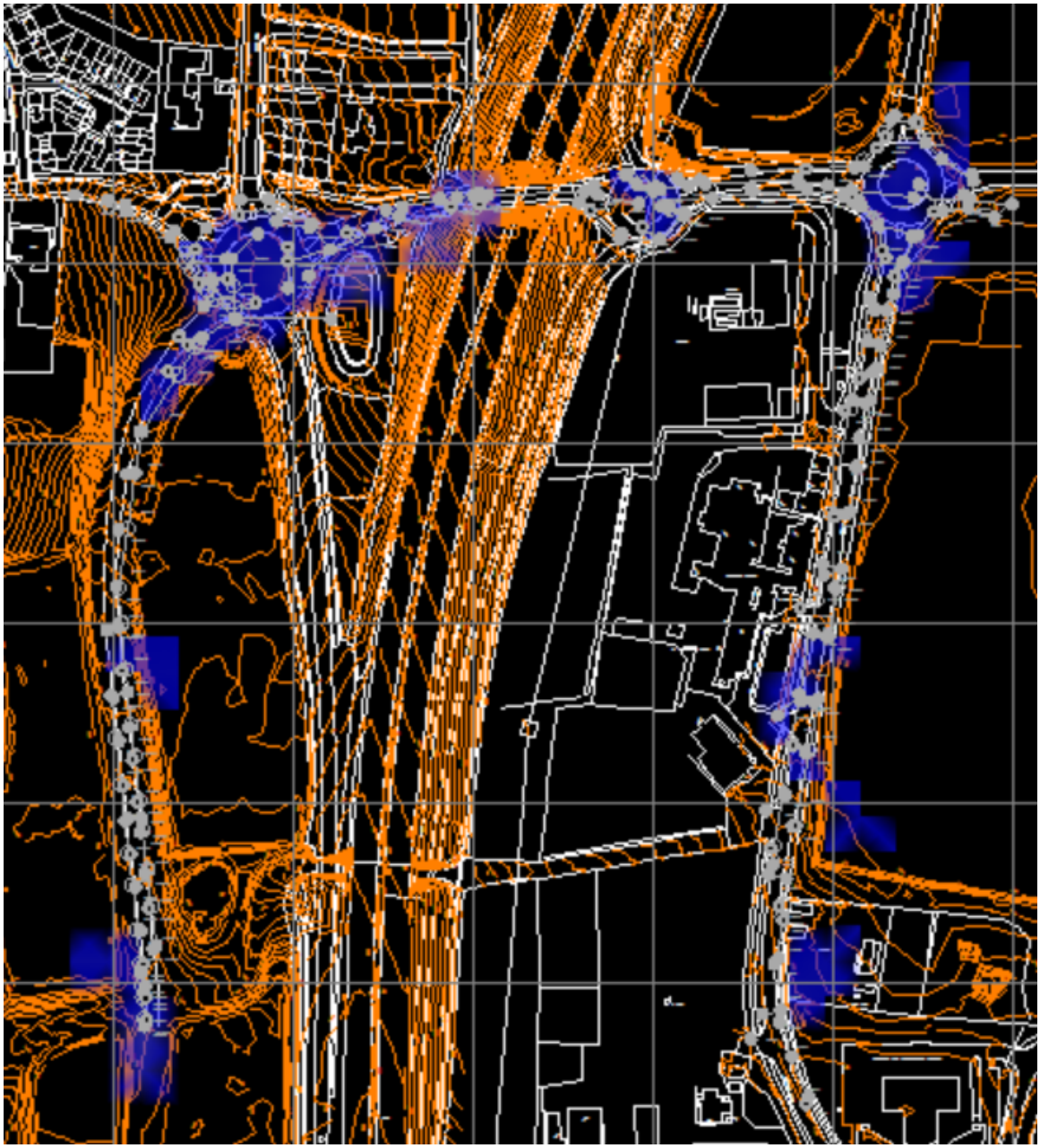


Figure 8.14 - Flood Flow analysis relating to Section 2 (Scenario 6, 15 minute duration)

8.4.2.4 Other flooded features

Wasteland areas flooded in 4 of the 24 modelled scenarios. Scenarios 2, 7, 10 and 13 produced the greatest flooded area (188, 221, 261return periods) see Table 8.4. The depth of flood did not change during all the simulations and remained at less than 100mm. Figure 8.16 shows that only 10/24 modelled scenarios flooded under a 180 minute duration, however, when flooding occurred the total flooded area was greater when compared to the 15 minute duration shown in Figure 8.15.

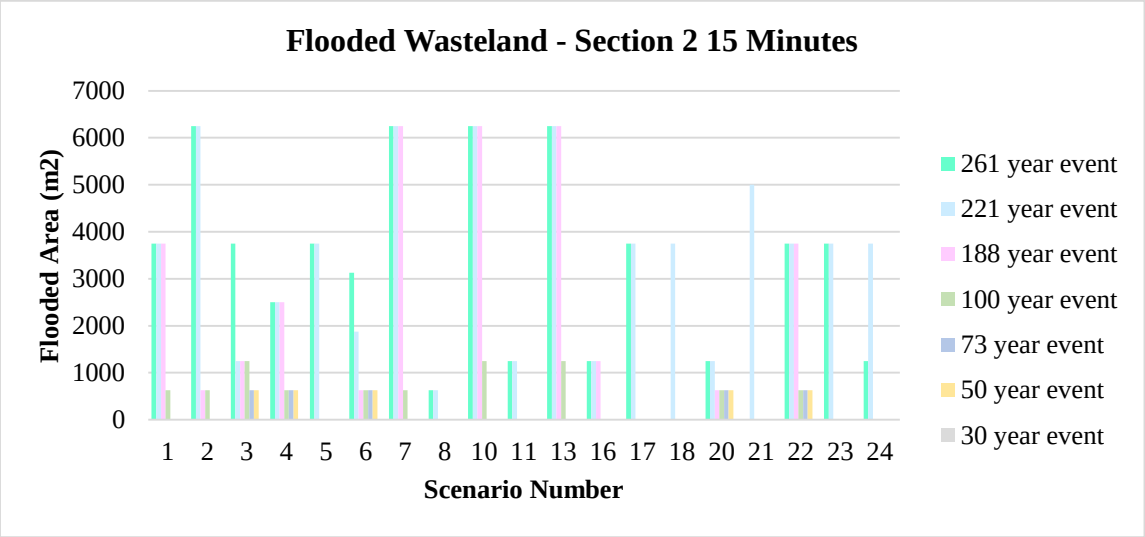


Figure 8.15 - Flooded wasteland Section 2 15 Minutes

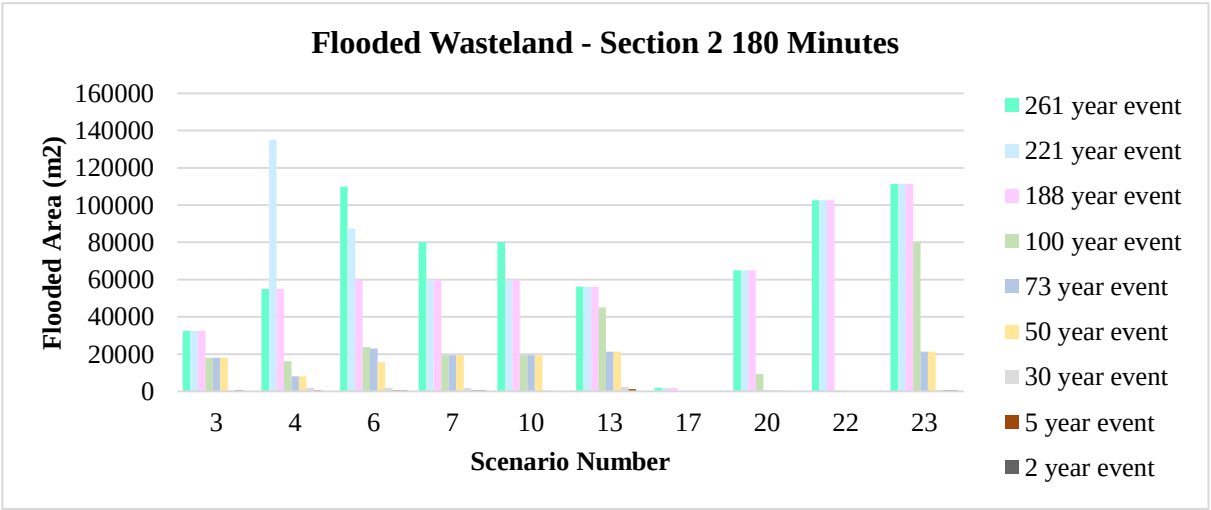


Figure 8.16 - Flooded Wasteland Section 2 180 Minutes

8.5 Summary

This chapter presented the results of drainage network analysis. Appendix B4 to B19 provide a summary of all return periods and storm durations for both sections of site for each of the 24 scenarios.

Tables 8.3 and 8.4 show that more IDs flood in Section 1 than in Section 2. All flooded IDs were at a depth of less than 100mm, except ID 16 (Warehouse) which flooded to a depth of less than 300mm. The roads running through the site flooded under a variety of return periods and storm durations, however, the flood depth remained unchanged at less than100mm with an average of less than or equal to 36mm.

The results presented within this chapter were then utilized to quantify the total flood impact within the Flood Risk Model (Figure 5.2). @RISK® was then used to identify the parts of the highway drainage infrastructure at greatest flood risk, to fulfil the aim of this research. This is described in the following chapter

CHAPTER 9 CASE STUDY: RISK QUANTIFICATION (MONTE CARLO SIMULATION)

9.1 Introduction

Chapter 8 presented the results of drainage network analysis that were then used to quantify the total flood impact within the Flood Risk Model (Figure 5.2). This chapter presents the results of the Monte Carlo simulation performed using @RISK® as part of the processes to quantify the risk of each section of the case study area flooding. Section 9.2 presents the cost model used to generate the range of costs associated with the range of impacts. The probability distribution for each return period examined are considered in Section 9.3. Finally, the results of the Monte Carlo simulation are discussed in Section 9.4.

9.2 Cost Model

Table 6.8 and Table 6.9 shows the unique reference number for each identified feature (ID) shown in Appendix A1 and A2. The impact distribution included in the Monte Carlo simulation consisted of non-residential properties, road disruption and the cost of emergency maintenance; each are discussed further in 9.2.1 to 9.2.3. The flood impact of each scenario (Table 5.5) is expressed by Equation 9.1.

$$Flood\ Impact\ (£) = \sum NRP + \sum Road\ disruption\ + \sum Emergency\ Road\ Maintenance \quad (9.1)$$

Where NRP = Non - residential properties

Figure 9.1 illustrates the methodology used to calculate the flood impact (£).

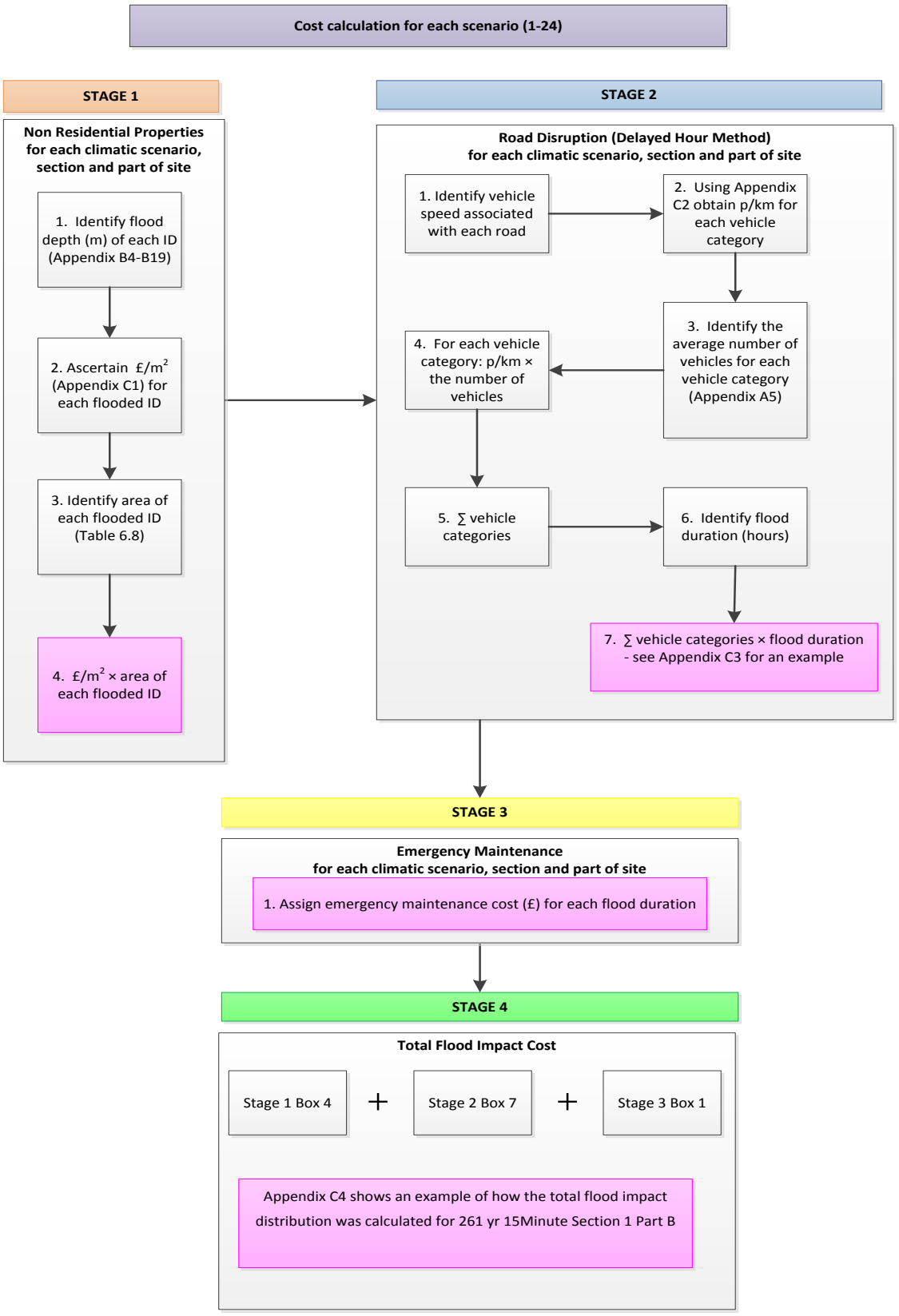


Figure 9.1 - Methodology used to calculate the flood impact for each climatic event, section and part of site

9.2.1 Flood Impact

The results presented in Chapter 8 and Appendices B4 to B19 show the extent of predicted flooding for each climate scenario; current design standard (2, 30,100 year events), 2040 (5, 30,188 year events), 2060 (5, 50, 221 year events) and 2080 (5, 73, 261 year events) and the durations simulated using MicroDrainage^{TM}. The results showed only non-residential properties, the roads through the site, one agricultural field and some wasteland flooded. Section 1experienced a greater number of flooded IDs compared to Section 2. The majority of flooded IDs had a flood depth of 0.05m. Only IDs 16, 17 and 21 flooded at a depth greater than 0.25m. The MCM provides estimated costs relating to a range of flood depths; 0m to 3m, in 0.25m intervals (Appendix C1). This data is updated annually in January in line with the Consumer Price Index, however as the rate of inflation was 1.00315 percent for 2014/2015 period 'the figures were hardly worth updating'(Owen, 2015). Therefore, to quantify the flood impact on each identified feature, the following assumptions were made in accordance with the MCM:

1. A non-residential property was assumed to have flooded entirely even if only part of that property had actually been flooded.
2. The flood impact for each non-residential property was calculated assuming a flood depth of less than or equal to 0.25m: this assumption was made as the flood costs provided by the MCM for a flood depth of 0m are associated only with areas below the ground. 'Goods and equipment stored in sub-ground areas, such as basements and cellars, are particularly susceptible to flood damage, either from flood waters rising from below due to seepage or, more commonly, from water pouring down from above once threshold levels have been exceeded (e.g. in older public houses and high street premises). Even after flood waters have subsided, damage due to

damp penetration and condensation on the walls is possible. More modern buildings do not often have sub-ground areas. In the case of petrol stations, fuel supplies in underground tanks are at risk of contamination by flood waters if the pumps are flooded by deep water. The fuel tanks themselves are usually double-lined and should survive immersion' (Penning-Rowsell et al, 2013). Consequently, calculating the flood impact for non-residential properties using the value listed under 0m was considered to under estimate the actual flood impact. As a result the values listed under a depth of 0.25m were used as they were considered to better reflect the cost of flooding.

3. Although the agricultural field and several pieces of wasteland flooded, the costs, if any, associated to this type of land were not included within the cost model as the flood depth was less than 0.05m.
4. The roads going through the study area were; A632, A1692 and A632 (Markham Lane); each road flooded to a varying extent under different scenarios, and under different return periods and durations. The assumption was made that the roads were still safe to road users as flooding was less than 0.05m (on average less than or equal 0.036m), however, road users would need to make adaptations to their driving style; including slowing down (Jordan, 2014).
5. The delayed hour method was used to provide a crude estimate regarding road disruption, Appendix C2 shows the prices in relation to each vehicle category (pence/km).

Each scenario (Table 5.5) resulted in various identified features being flooded (Appendices B4 to B19). Table 9-1 shows the flood impact in monetary value for each of the flooded identified features within Section 1 and Section 2.

Table 9-1 – The monetary value of each NRP located in the study area calculated using MCM (Penning-Rowsell et al, 2013)

Section	Feature ID	Location *	Description	Area (m^2)	Flood Depth (m)	£/m^2 **	(£)
1	1	Part A	Electricity Sub Station	2908	0.25	849	2,468,892.00
	2	Part B	Car Park	1390	0.25	8	11,120.00
	3	Part B	Warehouses	1461	0.25	373	544,953.00
	4	Part B	Warehouses	401	0.25	373	149,573.00
	5	Part B	Warehouses	1461	0.25	373	544,953.00
	8	Part B	Car Park	401	0.25	8	3,208.00
	11	Part B	Warehouses	1516	0.25	373	565,468.00
	12	Part B	Warehouses	595	0.25	373	221,935.00
	13	Part C	Car Park	149	0.25	8	1,192.00
	16	Part C	Warehouses	401	0.25	373	149,573.00
	17	Part C	Car Park	401	0.25	8	3,208.00
	21	Part C	Warehouses	1209	0.25	373	450,957.00
2	13	Part B	Electricity Sub Station	127	0.25	849	107,823.00

* Site layout shown in Appendices A1 and A 2.

** Appendix C1 provides a direct extract as to flood cost damages (£ per square metre) from (Penning-Rowsell et al, 2013).

Appendix C1 shows values relating to short flood durations (no cellar), namely; less than 12hours; these details were the most appropriate as no building had a cellar. The MicroDrainage™ results (Chapter 8) indicated flood water at an average depth of less than or equal to 0.036m would remain on the carriageway for 1hr during a 15 minute storm duration, and 6 hours during a 180 minute storm duration. Stage 2 of the process depicted in Figure 9.1 was utilized to calculate road disruption costs for A632, A6192 and Markham Lane (A632 to A1692). Appendix C2 provides a direct extract as to price (pence/km) in relation to each vehicle category used to calculate road disruption (Penning-Rowsell et al, 2013). An example for the A6192 15 minute storm duration is shown in Appendix C3, the process was repeated for all roads and both durations (15 and 180 minutes). The road

disruption costs associated with each road contained in Section 1 and 2 are shown in Table 9.2.

Table 9-2 - Road disruption cost distribution

Section	Storm Duration	Road Name	Flooded Road Impact (£)
Section 1	15 Minutes	A632 (Part A)	39.53
		A1692 (Part B)	43.59
		A1692 (Part C)	43.59
	180 Minutes	A632 (Part A)	237.16
		A1692 (Part B)	261.53
		A1692 (Part C)	261.53
Section 2	15 Minutes	A1692 (Part A)	43.59
		Markham Lane (A632 to A1692) (Part B)	31.42
		A1692 (Part B)	43.59
	180 Minutes	A1692 (Part A)	261.53
		Markham Lane (A632 to A1692) (Part B)	188.50
		A1692 (Part B)	261.53

9.2.2 Total flood impact

The total flood impact was calculated for each part of the site, Section 1 (A, B, C) and Section 2 (A, B) using Equation 9.1. Each modelled scenario (Table 5.5) caused various identified features to flood (Appendix B4-B7); the non-residential flood impact and road disruption impact varied depending on the scenario, return period and duration. A total flood impact distribution for each return period and storm duration was obtained for all flooded scenarios (Tables 9.3 to 9.6). Appendix C4 provides an example of how the total flood impact distribution was calculated for 261yr 15Minute Section 1 Part B.

Table 9-3 - Section 1 15 minute duration flood impact ranges

Section 1 - 15 Minutes		**Part A**			**Part B**			**Part C**		
		Impact Cost (£)			***Impact Cost (£)***			***Impact Cost (£)***		
Climate Scenario	***Return Period***	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*
2080	261 year event	51.53	370,385.33	2,468,943.53	55.59	332,577.30	1,253,862.59	150,820.59	560,405.97	604,985.59
	73 year event	51.53	51.53	51.53	55.59	123,146.13	790,666.59	149,628.59	541,150.09	604,985.59
	5 year event	0.00	0.00	0.00	55.59	322.92	3,263.59	55.59	55.59	55.59
2060	221 year event	51.53	370,385.33	2,468,943.53	55.59	332,577.30	1,253,862.59	150,820.59	560,405.97	604,985.59
	50 year event	51.53	51.53	51.53	55.59	33,479.59	548,216.59	149,628.59	521,760.55	604,985.59
	5 year event	0.00	0.00	0.00	55.59	322.92	3,263.59	55.59	55.59	55.59
2040	188 year event	51.53	259,934.90	2,468,943.53	55.59	263,068.17	1,253,862.59	150,820.59	560,405.97	604,985.59
	30 year event	51.53	51.53	51.53	55.59	857.59	3,263.59	149,628.59	332,494.47	604,985.59
	5 year event	0.00	0.00	0.00	55.59	322.92	3,263.59	55.59	55.59	55.59
Design Standard	100 year event	51.53	259,934.90	2,468,943.53	55.59	188,715.02	790,666.59	150,820.59	560,405.97	604,985.59
	30 year event	51.53	51.53	51.53	55.59	857.59	3,263.59	149,628.59	332,494.47	604,985.59
	2 year event	0.00	0.00	0.00	55.59	55.59	55.59	55.59	55.59	55.59

Table 9-4 - Section 1 180 minute duration flood impact ranges

Section 1 - 180 Minutes		**Part A**			**Part B**			**Part C**		
		Impact Cost (£)			***Impact Cost (£)***			***Impact Cost (£)***		
Climate Scenario	***Return Period***	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*
2080	261 year event	261.16	247,162.36	2,469,273.16	285.53	447,364.78	1,254,092.53	3,493.53	199,177.36	605,215.53
	73 year event	261.16	261.16	261.16	285.53	133,638.18	694,811.53	285.53	186,171.01	605,215.53
	5 year event	261.16	261.16	261.16	285.53	285.53	285.53	285.53	623.21	3,493.53
2060	221 year event	261.16	247,162.36	2,469,273.16	285.53	447,231.11	1,254,092.53	3,493.53	199,177.36	605,215.53
	50 year event	261.16	261.16	261.16	285.53	24,537.05	545,238.53	285.53	165,426.79	605,215.53
	5 year event	261.16	261.16	261.16	285.53	285.53	285.53	285.53	623.21	3,493.53
2040	188 year event	261.16	261.16	261.16	285.53	304,025.40	1,254,092.53	285.53	186,171.01	605,215.53
	30 year event	261.16	261.16	261.16	285.53	425.01	3,493.53	285.53	99,750.01	153,066.53
	5 year event	261.16	261.16	261.16	285.53	285.53	285.53	285.53	623.21	3,493.53
Design Standard	100 year event	261.16	261.16	261.16	285.53	279,836.94	1,254,092.53	285.53	186,171.01	605,215.53
	30 year event	261.16	261.16	261.16	285.53	425.01	3,493.53	285.53	99,750.01	153,066.53
	2 year event	261.16	261.16	261.16	285.53	285.53	285.53	285.53	285.53	285.53

Table 9-5 - Section 2 flood impact ranges for 15 minute duration

Section 2 - 15 Minutes		**Part A**			**Part B**		
		Impact Cost (£)			***Impact Cost (£)***		
Climate Scenario	***Return Period***	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*
2080	261 year event	55.59	55.59	55.59	55.59	20,621.73	107,910.01
	73 year event	55.59	55.59	55.59	87.01	87.01	87.01
	5 year event	55.59	55.59	55.59	55.59	55.59	55.59
2060	221 year event	55.59	55.59	55.59	55.59	15,484.31	107,910.01
	50 year event	55.59	55.59	55.59	55.59	82.52	87.01
	5 year event	55.59	55.59	55.59	55.59	55.59	55.59
2040	188 year event	55.59	55.59	55.59	55.59	10,863.03	107,910.01
	30 year event	55.59	55.59	55.59	55.59	69.06	87.01
	5 year event	55.59	55.59	55.59	55.59	55.59	55.59
Design Standard	100 year event	55.59	55.59	55.59	55.59	6,071.94	107,910.01
	30 year event	55.59	55.59	55.59	55.59	69.06	87.01
	2 year event	55.59	55.59	55.59	55.59	55.59	55.59

Table 9-6 - Section 2 flood impact ranges for 180 minute duration

Section 2 - 180 Minutes		**Part A**			**Part B**		
		Impact Cost (£)			***Impact Cost (£)***		
Climate Scenario	***Return Period***	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*
2080	261 year event	285.53	285.53	285.53	285.53	29,189.13	108,297.03
	73 year event	285.53	285.53	285.53	474.03	474.03	474.03
	5 year event	285.53	285.53	285.53	474.03	474.03	474.03
2060	221 year event	285.53	285.53	285.53	285.53	22,000.93	108,297.03
	50 year event	285.53	285.53	285.53	474.03	474.03	474.03
	5 year event	285.53	285.53	285.53	474.03	474.03	474.03
2040	188 year event	285.53	285.53	285.53	285.53	14,812.73	108,297.03
	30 year event	285.53	285.53	285.53	474.03	474.03	474.03
	5 year event	285.53	285.53	285.53	474.03	474.03	474.03
Design Standard	100 year event	285.53	285.53	285.53	474.03	9,459.28	108,297.03
	30 year event	285.53	285.53	285.53	474.03	474.03	474.03
	2 year event	285.53	285.53	285.53	285.53	453.09	474.03

9.2.3 Maintenance Impact

For each return period and storm duration pipes were sorted by flooded volume (m^3), this allowed for each flooded asset to be identified, see Tables 9.7 and 9.8. Experts provided opinions as to the cost of a variety of maintenance options; inspecting assets, removing debris and replacing assets, these were then used within Equation 9.1 to provide the emergency road maintenance cost aspect. The MicroDrainage™ results (Chapter 8) indicated the duration of flood varied from 1 hour for a 15 minute storm duration to 6 hours for a 180 minute duration, consequently varying degrees of emergency maintenance were associated with each storm duration.

9.2.3.1 15 Minute Durations

For the 15 minute storm duration (1 hour flood duration), it was assumed:

1. The flood would be reported to the relevant LA.
2. Each LA would comply with its statutory requirements and ensure the road was safe for road users.
3. A highway inspector would visit a flooded road and assess the costs associated with the maintenance required. The modal hourly inspection rate of £12 was used (provided by the experts).

9.2.3.2 180 minute storm duration

For the 180 minute duration (6 hour flood duration), it was assumed:

1. The flood would be reported to the relevant LA.
2. Each LA would comply with its statutory requirements to ensure the road was safe for road users.
3. A highway inspector examined the flooded assets if it was safe to do so whilst ensuring all health and safety protocols were followed. The modal hourly inspection rate of £12 was used (provided by the experts)
4. The highway inspector would request a gully sucker team to attend to remove debris from gully gratings and empty the gully pots as well as inspect and remove debris from each section of manhole. For the purpose of this research, one team of two people was deemed to attend at an hourly cost of £24 (2*£12).

Table 9-7 - Number of flooded gullies and manholes in Section 1

	Section 1 - 15 minute storm duration						**Section 1 - 180 minute storm duration**					
	Part A		**Part B**		**Part C**		**Part A**		**Part B**		**Part C**	
Return Period	*Gullies*	*Manholes*	*Gullies*	*Manholes*	*Gullies*	*Manholes*	*Gullies*	*Manholes*	*Gullies*	*Manholes*	*Gullies*	*Manholes*
2	0	0	2	0	10	3	0	2	1	1	6	7
5	0	0	2	0	13	6	1	2	1	2	10	9
30	5	9	3	4	20	10	4	7	3	4	16	13
50	10	10	9	4	23	12	4	11	3	4	17	13
73	11	10	11	4	25	14	5	12	3	4	18	14
100	13	11	11	4	26	14	6	12	3	4	18	14
188	16	15	12	4	26	14	6	15	3	4	19	15
221	18	16	12	4	26	14	6	15	3	4	20	15
261	18	19	12	4	27	14	6	16	3	4	22	15

Table 9-8 - Number of flooded gullies and manholes in Section 2

	Section 2 - 15 minute storm duration				**Section 2 - 180 minute storm duration**			
	Part A		**Part B**		**Part A**		**Part B**	
Return Period	*Gullies*	*Manholes*	*Gullies*	*Manholes*	*Gullies*	*Manholes*	*Gullies*	*Manholes*
2	3	0	1	2	0	1	1	7
5	5	1	3	8	1	4	2	12
30	17	13	21	17	4	17	4	21
50	26	23	30	20	10	26	4	21
73	37	27	34	21	8	28	7	21
100	40	28	34	21	12	31	9	21
188	51	30	44	23	23	33	13	22
221	52	31	52	23	24	35	13	22
261	53	31	55	23	26	35	16	22

9.3 Probability of occurrence

For Section 1 (A, B, C) and Section 2 (A, B) it can be seen that:

- Using Table 7.11 and Appendices B4 to B19, the probability of a flood occurring under each return period and duration changed depending on the modelled scenario (Table 5.6).
- The minimum, most likely and maximum probabilities were calculated for each return period and storm duration in respect of each part of both Sections. A triangular distribution of the probabilities in respect of each part of site, return period, and storm duration was assigned so that a single number could be randomly generated using a Monte Carlo simulation (Section 9.4). A binomial function was then assigned to the single value generated in order to model the probability of occurrence. The probability of occurrence for both site sections under each return period, relating to 15 and 180 minutes are shown in Table 9.9 and Table 9.11 respectively.

Table 9-9 - Probability of occurrence distributions for Section 1 15 minute

Section 1 - 15 Minutes		**Part A**			**Part B**			**Part C**		
		Probability			***Probability***			***Probability***		
Climate Scenario	***Return Period***	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*
2080	261 year event	0.00	0.04	0.73	0.00	0.04	0.73	0.00	0.04	0.73
	73 year event	0.00	0.05	0.73	0.00	0.04	0.73	0.00	0.04	0.73
	5 year event				0.00	0.04	0.73	0.00	0.04	0.73
2060	221 year event	0.00	0.04	0.73	0.00	0.04	0.73	0.00	0.04	0.73
	50 year event	0.00	0.05	0.73	0.00	0.04	0.73	0.00	0.04	0.73
	5 year event				0.00	0.04	0.73	0.00	0.04	0.73
2040	188 year event	0.00	0.05	0.73	0.00	0.04	0.73	0.00	0.04	0.73
	30 year event	0.00	0.01	0.04	0.00	0.04	0.73	0.00	0.04	0.73
	5 year event				0.00	0.04	0.73	0.00	0.04	0.73
Design Standard	100 year event	0.00	0.05	0.73	0.00	0.04	0.73	0.00	0.04	0.73
	30 year event	0.00	0.01	0.04	0.00	0.04	0.73	0.00	0.04	0.73
	2 year event				0.00	0.05	0.73	0.00	0.05	0.73

Table 9-10 - Probability of occurrence distributions for Section 1 180 minute

Section 1 - 180 Minutes		**Part A**			**Part B**			**Part C**		
		Probability			***Probability***			***Probability***		
Climate Scenario	***Return Period***	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*
2080	261 year event	0.00	0.00	0.00	0.00	0.04	0.73	0.00	0.04	0.73
	73 year event	0.00	0.00	0.00	0.00	0.04	0.73	0.00	0.04	0.73
	5 year event	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.01	0.04
2060	221 year event	0.00	0.00	0.00	0.00	0.04	0.73	0.00	0.04	0.73
	50 year event	0.00	0.00	0.00	0.00	0.04	0.73	0.00	0.04	0.73
	5 year event	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.01	0.04
2040	188 year event	0.00	0.00	0.00	0.00	0.04	0.73	0.00	0.04	0.73
	30 year event	0.00	0.00	0.00	0.00	0.04	0.73	0.00	0.04	0.73
	5 year event	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.01	0.04
Design Standard	100 year event	0.00	0.00	0.00	0.00	0.04	0.73	0.00	0.04	0.73
	30 year event	0.00	0.00	0.00	0.00	0.04	0.73	0.00	0.04	0.73
	2 year event	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.04

Table 9-11 - Probability of occurrence distributions for Section 2

Section 2		**15 Minute**						**180 Minute**					
		Part A			**Part B**			**Part A**			**Part B**		
		Probability			***Probability***			***Probability***			***Probability***		
Climate Scenario	***Return Period***	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*
2080	261 year event	0.00	0.05	0.73	0.00	0.05	0.73	0.00	0.01	0.04	0.00	0.01	0.04
	73 year event	0.00	0.01	0.04	0.00	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.04
	5 year event	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.01	0.04
2060	221 year event	0.00	0.01	0.04	0.00	0.05	0.73	0.00	0.01	0.04	0.00	0.01	0.04
	50 year event	0.00	0.01	0.04	0.00	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.04
	5 year event	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.01	0.04
2040	188 year event	0.00	0.01	0.04	0.00	0.05	0.73	0.00	0.01	0.04	0.00	0.01	0.04
	30 year event	0.00	0.01	0.04	0.00	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.04
	5 year event	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.01	0.04
Design Standard	100 year event	0.00	0.01	0.04	0.00	0.05	0.73	0.00	0.00	0.04	0.00	0.00	0.04
	30 year event	0.00	0.01	0.04	0.00	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.04
	2 year event	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.01	0.04

9.4 Monte Carlo Simulation

This research used the commercially available @RISK® software to perform quantitative risk analysis by building models of possible results by substituting a range of values of each uncertain parameter (impact and probability distributions) for each return period and storm duration. @RISK® calculates the model to a pre-defined set of iterations (number of times model is run). For the purpose of this research, 5000 iterations were used in order to generate a frequency distribution for each return period. Tables 9.3 to 9.11 show the impact and probability distributions for both Section 1 (A, B, C) and Section 2 (A, B) which formed the inputs of the Monte Carlo simulation within @RISK®.

9.4.1 Risk Quantification

As noted in Section 1.1 the aim of this research is to explore the use of a risk based approach to better inform the decision making process used by highway drainage engineers when seeking to identify the parts of the highway drainage infrastructure at greatest flood risk. @RISK® allows for an overall risk cost distribution to be created in respect of each return period and site section. An example for a 261year, 15 minute event for the study area (see Figure 9.2) shows there is a 90% chance of the risk costing between £0 and £1.787 million. Although this type of distribution can be used in cost modelling to assess the overall risk cost, it was not suitable to fulfil the aim of this study. However, further discussion as to the possible use of this type of distribution is contained in Section 10.8.

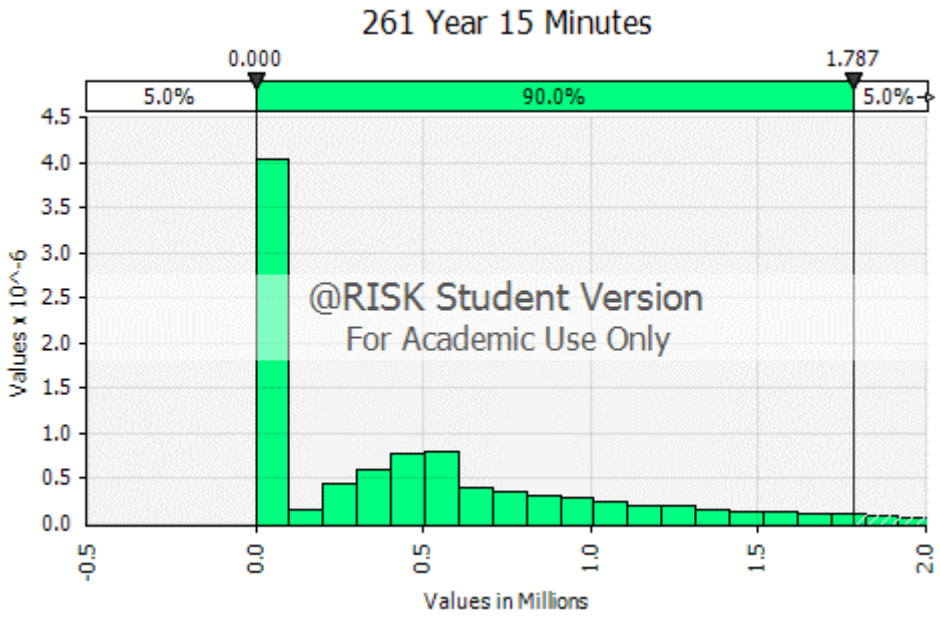


Figure 9-2 - Risk contribution in respect of a 261 year event for the study area

A sensitivity analysis was undertaken to ascertain which of the input variables {Section 1 (A, B, C) and Section 2 (A, B)} were at greatest risk for a given return period and duration. This was achieved using @RISK® to understand the relative importance of the input variables, the results were displayed using tornado charts. This output was chosen as it identifies the variables within the model having the greatest influence on the overall risk cost for each section and part of site. The results are shown and discussed in Section 9.4.1.1 to 9.4.1.2.

9.4.1.1 Sensitivity Analysis 15 minute and 180 minute durations

Each input variable is represented by a horizontal bar, which indicates the range of risk cost associated with that variable. The input variables having the greatest influence on the overall risk costs are represented by the longest bars (Vose, 2010). Figures 9.3 to 9.10 show tornado charts displaying the input variables Section 1 (A, B, C) and Section 2 (A, B) together with their associated overall risk cost distributions, which are ranked in order of greatest influence

on the overall risk cost. The most influential variable on overall risk cost generally has an associated low probability of occurrence and higher total cost of flood, when compared to the second most influential variable. For the purpose of discussion, the 30 year 15 minute and 100 year 15 minute results (see Figure 9.3) are:

- In relation to the 30 year 15 minute event the probability of occurrence regarding Section 1 (Part C) has the greatest impact on the overall risk costs. The second most influential variable was total cost of flood. This is explained by the probability of occurrence being low, and the total cost of flood being higher than any other section of site.
- In relation to the 100 year15 minute event the probability of occurrence for Section 1 (Part A) has the greatest impact on the overall risk costs. The second most influential variable was the probability of occurrence relating to Section 1 (Part C). This is explained by the total cost of flood being higher for Section 1 (Part A) compared to Section 1 (Part C), however, the probability of occurrence remained low for both.

Figures 9.3 – 9.10 demonstrate that for a given return period the most influential and second most influential variable can change for the two storm durations. This is explained by the MicroDrainage results (Appendix B4-B19) identifying different ID features flood under each modelled scenario, effecting total flood cost and probability of occurrence.

The sensitivity analysis results have been presented in a table as recommended by Ayyub (2003b). Table 9.12 provides a summary of the most influential and second most influential variables having influence on the overall risks costs, it utilized data shown in Figures 9.3 to 9.10.

Present Climate (Current Design 15 Minute Event)

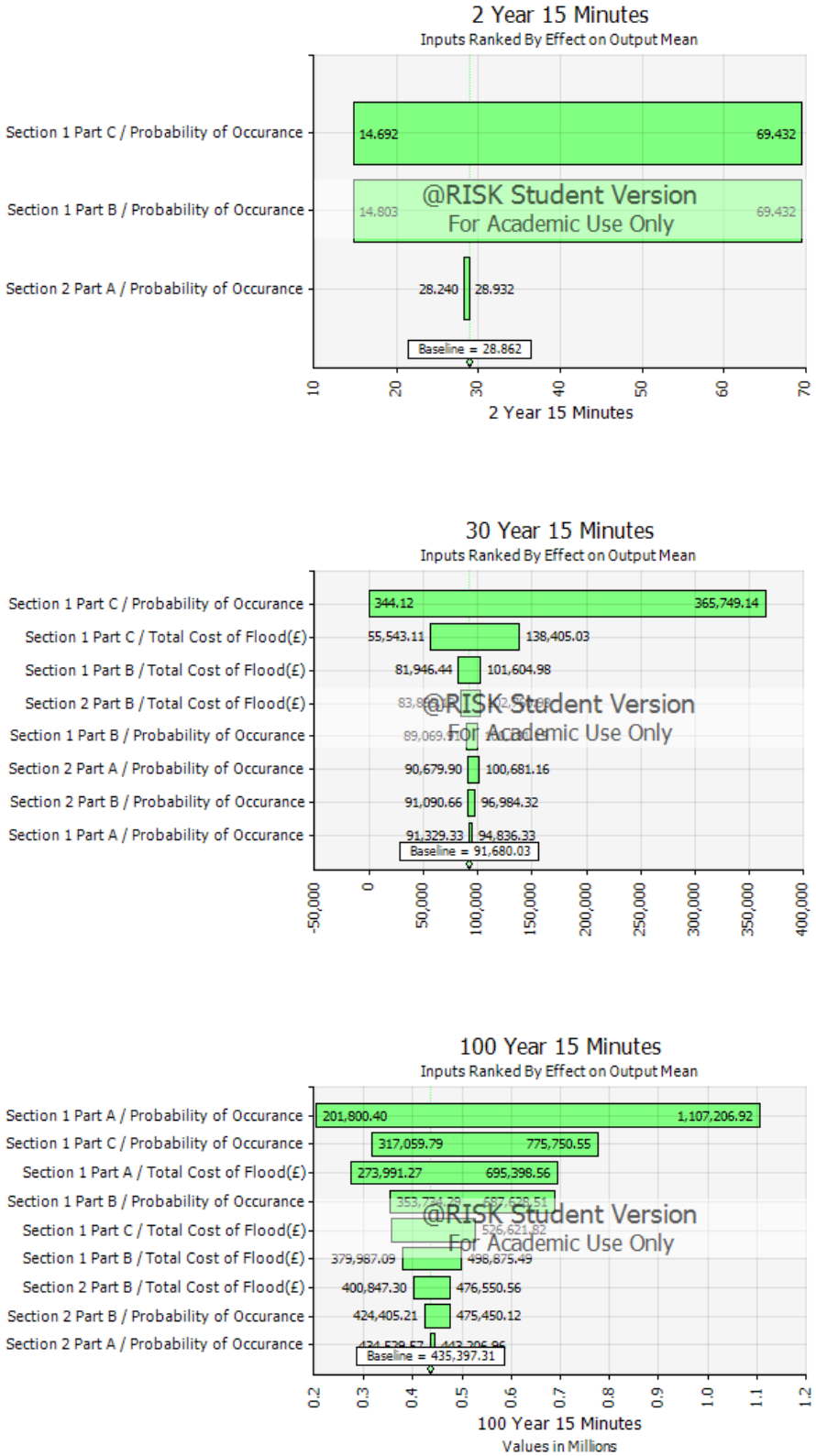


Figure 9-3 - @RISK(R) results (Current Design Standard - 15 minute duration)

Present Climate (Current Design 180 Minute Event)

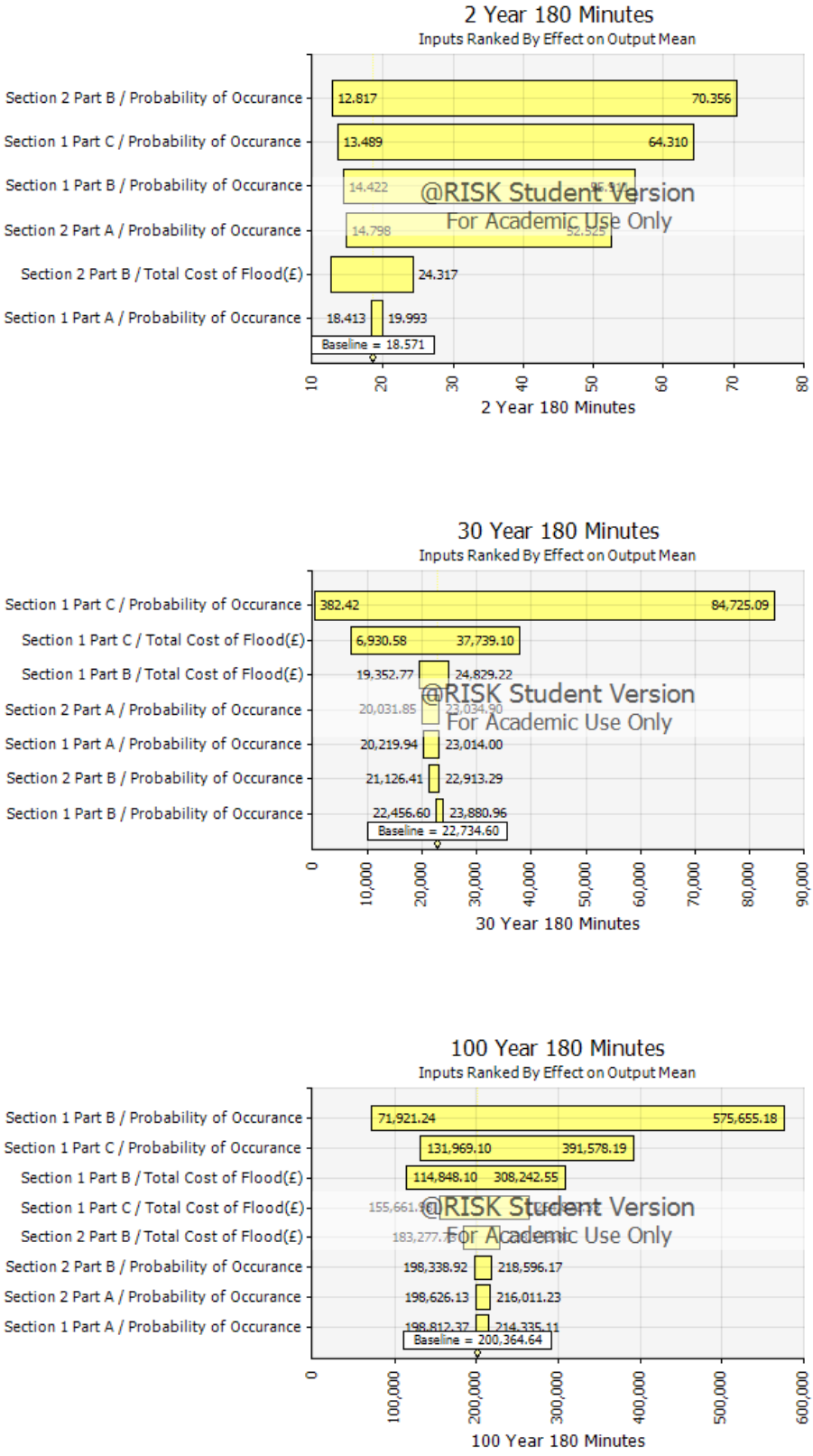


Figure 9-4 - @RISK(R) results (Current Design Standard - 180 minute duration)

2040 Climate Scenario (15 Minute Event)

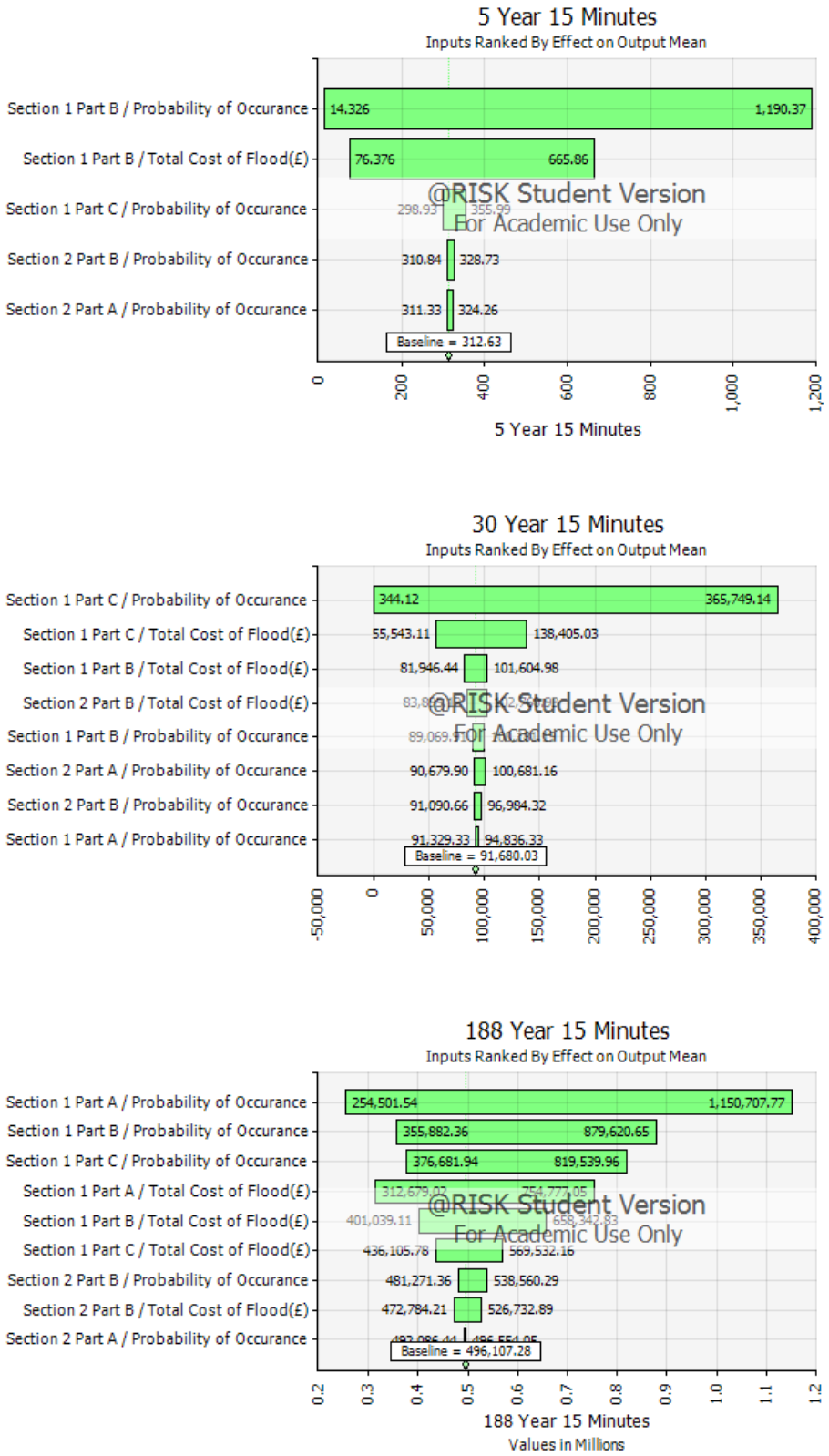


Figure 9-5 - @RISK(R) results (2040 climate scenario - 15 minute duration)

2040 Climate Scenario (180 Minute Event)

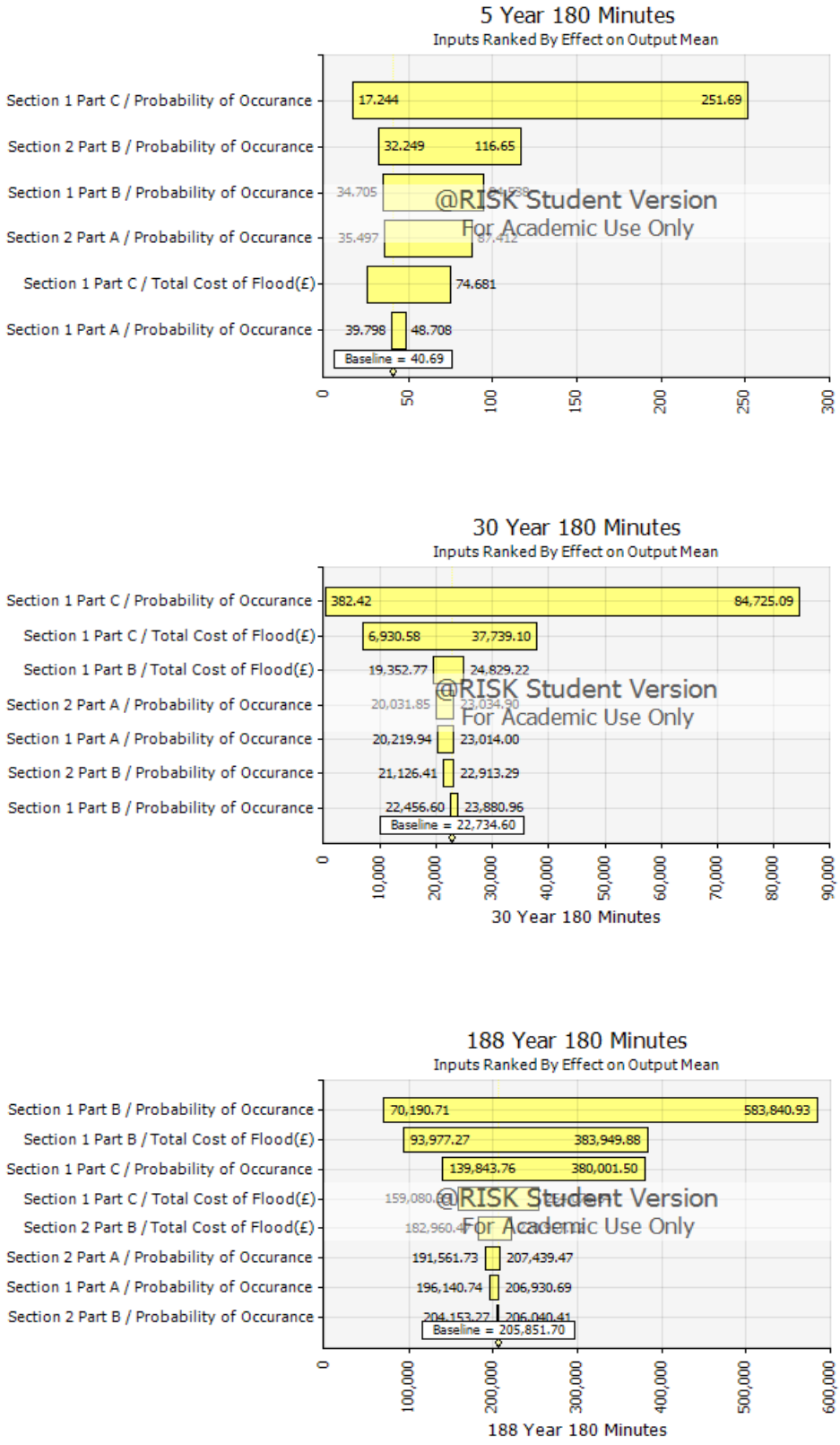


Figure 9-6 - @RISK(R) results (2040 climate scenario - 180 minute duration)

2060 Climate Scenario (15 Minute Event)

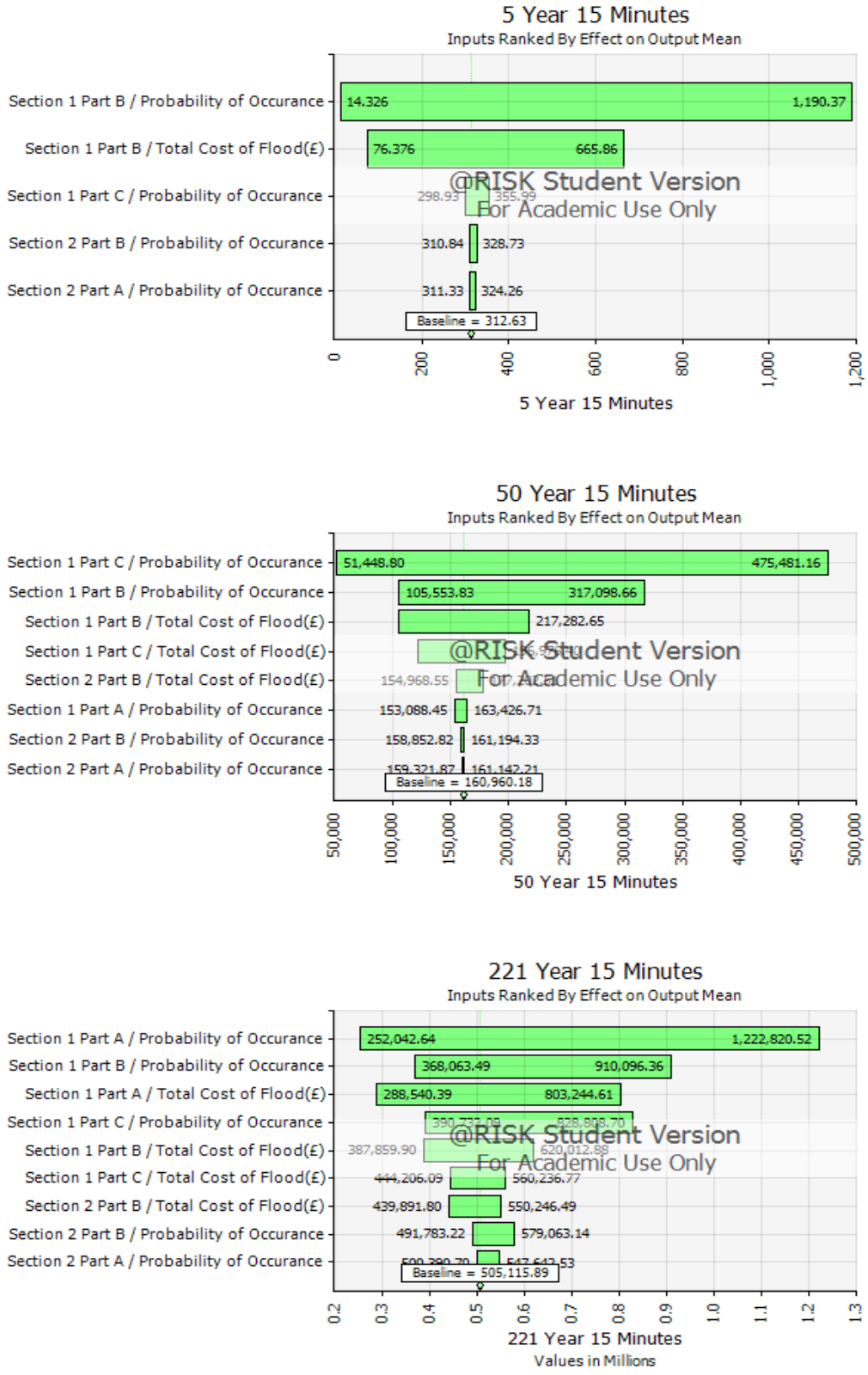


Figure 9-7 - @RISK(R) results (2060 climate scenario - 15 minute duration)

2060 Climate Scenario (180 Minute Event)

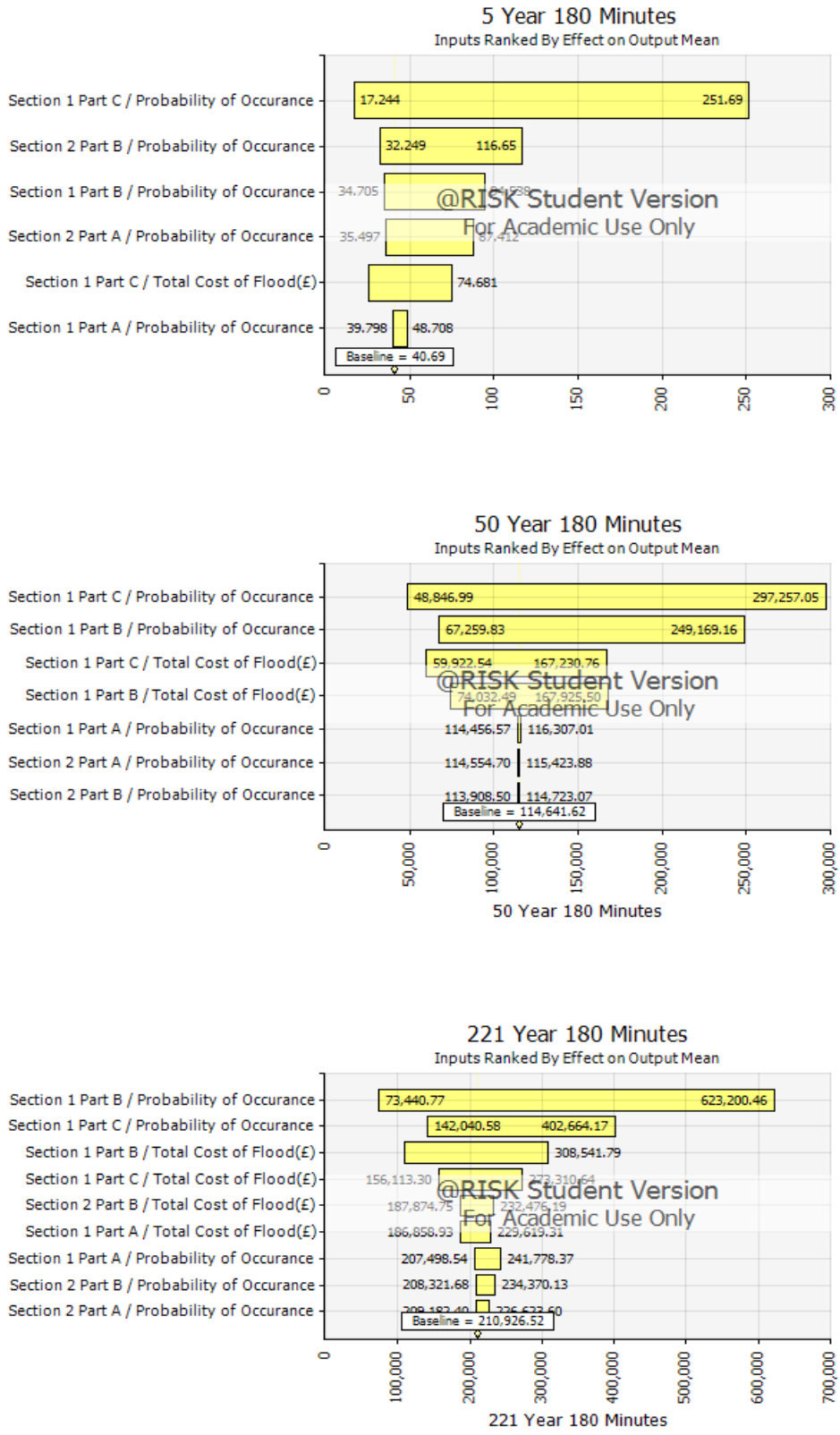


Figure 9-8 - @RISK(R) results (2060 climate scenario - 180 minute duration)

2080 Climate Scenario (15 Minute Event)

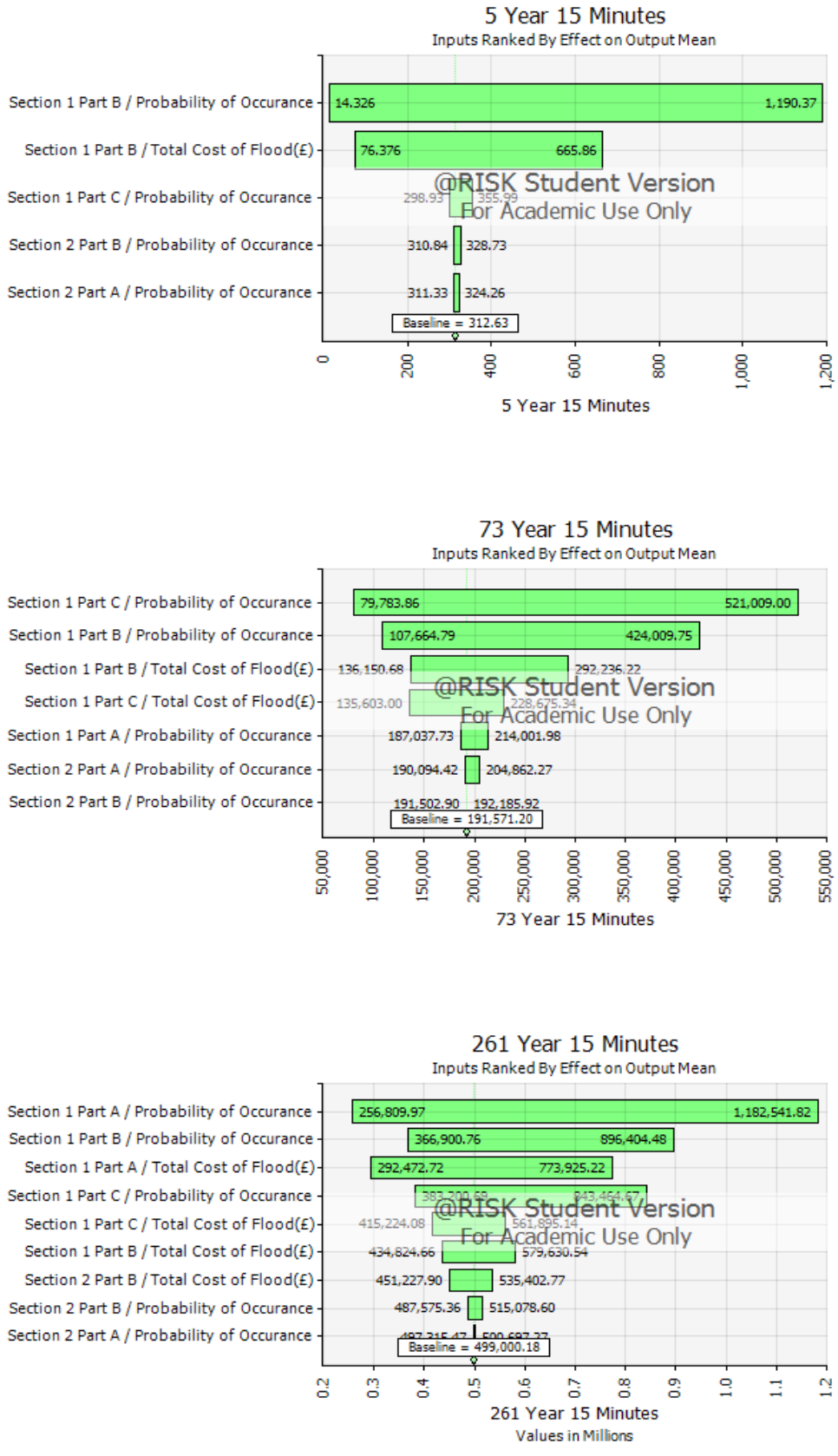


Figure 9-9 - @RISK(R) results (2080 climate scenario - 15 minute duration)

2080 Climate Scenario (180 Minute Event)

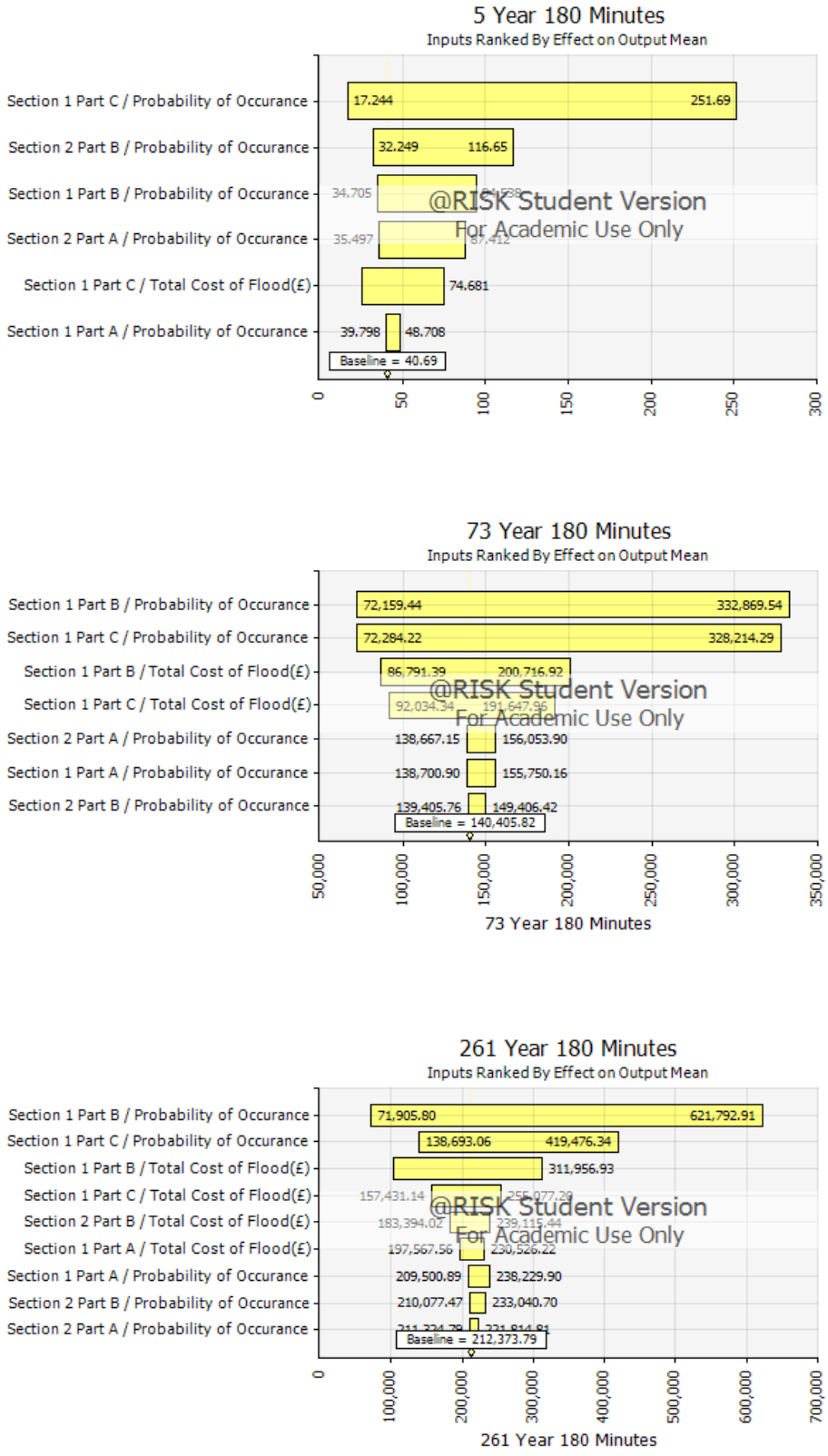


Figure 9-10 - @RISK(R) results (2080 climate scenario - 180 minute duration)

Table 9-12 - Summary of the most influential and second most influential variables having influence on the overall risks costs

Site Section	Probability/Impact	Climate scenario (Return Periods)																					
		Present						2040						2060						2080					
		2		30		100		5		30		188		5		50		221		5		73		261	
1 Part C	probability																								
	impact																								
1 Part B	probability																								
1 Part C																									
1 Part A	probability																								
1 Part C																									
1 Part C	probability																								
1 Part B																									
1 Part B	probability																								
	impact																								
1 Part A	probability																								
1 Part B	impact																								
1 Part C	probability																								
2 Part B																									
1 Part C	probability																								
1Part A																									
1Part A	probability																								
1 Part B																									

Key:	Duration (Mins)	
	15	180
Most influential variable as to risk costs (£)		
Second most influential variable as to risk costs (£)		

9.4.1.2 Section at greatest flood risk

An overall comparison of the sections of land within the study area identified which were at greatest flood risk, this was achieved by:

1. Tabulating the range of values of the most influential and second most influential for each return period.
2. Sorting the data was sorted by site section and part of section.
3. Using the figures obtained from (1) above then calculating the difference between the highest and lowest values for each site section and part of section.
4. Using the results of (3) the total for each site section and part of section was calculated to obtain the overall risk costs relating to each, thereby identifying the area at greatest flood risk.

The results of the 15 minute duration and 180 minute duration are shown in Tables 9.13 and 9.14.

Table 9-13 - 15 Minute comparison of the overall risk costs relating to each section and part of site

Influential Variable	Return Period	Lower Bound	Upper Bound	Difference
Section 1 Part A Probability	100 Year 15 Min	201,800.40	1,107,206.92	905,406.52
Section 1 Part A Probability	188 Year 15 Min	254,501.54	1,150,707.77	896,206.23
Section 1 Part A Probability	221 Year 15 Min	252,042.64	1,222,820.52	970,777.88
Section 1 Part A Probability	261 Year 15 Min	256,809.97	1,182,541.82	925,731.85
		Section 1 Part A TOTAL		**3,698,122.48**
Section 1 Part B Probability	2 Year 15 Min	14.90	69.43	54.53
Section 1 Part B Probability	5 Year 15 Min	14.33	1,190.37	1,176.04
Section 1 Part B Total Cost of Flood	5 Year 15 Min	76.38	665.86	589.48
Section 1 Part B Probability	50 Year 15 Min	105,553.83	317,098.66	211,544.83
Section 1 Part B Probability	73 Year 15 Min	107,664.79	424,009.75	316,344.96
Section 1 Part B Probability	188 Year 15 Min	355,882.36	879,620.65	523,738.29
Section 1 Part B Probability	221 Year 15 Min	368,063.49	910,096.36	542,032.87
Section 1 Part B Probability	261 Year 15 Min	366,900.76	896,404.48	529,503.72
		Section 1 Part B TOTAL		**2,124,984.73**
Section 1 Part C Probability	2 Year 15 Min	14.69	69.43	54.74
Section 1 Part C Probability	30 Year 15 Min	344.12	365,749.14	365,405.02
Section 1 Part C Total Cost of Flood	30 Year 15 Min	55,543.11	138,405.03	82,861.92
Section 1 Part C Probability	50 Year 15 Min	51,448.80	475,481.16	424,032.36
Section 1 Part C Probability	73 Year 15 Min	79,783.86	521,009.00	441,225.14
Section 1 Part C Probability	100 Year 15 Min	317,059.79	775,750.55	458,690.76
		Section 1 Part C TOTAL		**1,772,269.94**

NB: The costs presented in the table relate to the lower and upper bands that were randomly selected by @RISK®; consequently, the costs for each return period do not necessarily follow a sequential order.

Table 9-14 - 180 Minute comparison of the overall risk costs relating to each section and part of site

Influential Variable	Return Period	Lower Bound	Upper Bound	Difference
Section 1 Part B Probability	50 Year 15 Min	67,259.83	249,169.16	181,909.33
Section 1 Part B Probability	73 Year 15 Min	72,159.44	332,869.54	260,710.10
Section 1 Part B Probability	100 Year 15 Min	71,921.24	575,655.18	503,733.94
Section 1 Part B Probability	188 Year 15 Min	70,190.71	583,840.93	513,650.22
Section 1 Part B Total Cost of Flood	188 Year 15 Min	93,977.27	383,949.88	289,972.61
Section 1 Part B Probability	221 Year 15 Min	73,440.77	623,200.46	549,759.69
Section 1 Part B Probability	261 Year 15 Min	71,905.80	621,792.91	549,887.11
		Section 1 Part B TOTAL		**2,849,623.00**

Section 1 Part C Probability	2 Year 15 Min	13.49	64.31	50.82
Section 1 Part C Probability	5 Year 15 Min	17.24	251.69	234.45
Section 1 Part C Probability	30 Year 15 Min	382.42	84,725.09	84,342.67
Section 1 Part C Total Cost of Flood	30 Year 15 Min	6,930.58	37,739.10	30,808.52
Section 1 Part C Probability	50 Year 15 Min	48,846.99	297,257.05	248,410.06
Section 1 Part C Probability	73 Year 15 Min	72,284.22	328,214.29	255,930.07
Section 1 Part C Probability	100 Year 15 Min	131,969.10	391,578.19	259,609.09
Section 1 Part C Probability	221 Year 15 Min	142,040.58	402,664.17	260,623.59
Section 1 Part C Probability	261 Year 15 Min	138,693.06	419,476.34	280,783.28
		Section 1 Part C TOTAL		**1,420,792.55**

Section 2 Part B Probability	2 Year 15 Min	12.82	70.36	57.54
Section 2 Part B Probability	5 Year 15 Min	32.25	116.65	84.40
		Section 2 Part B TOTAL		**141.94**

NB: The costs presented in the table relate to the lower and upper bands that were randomly selected by @RISK®; consequently, the costs for each return period do not necessarily follow a sequential order.

The overall result showed that for a 15 minute storm duration Section 1 Part A was the area at greatest flood risk. Section 1 Part B was the area at greatest flood risk for 180 minute storm

durations. Section 1 Part A is shown in Appendix A1. These findings tally with the MicroDrainage™ results in Chapter 8. The complete alignment of these results is explained by the overall probability of flood being low and a high total flood impact (£) as an electricity sub-station was located within Part A. It is acknowledged that if the probability and impact associated with Section 1 (A, B, C) and Section 2 (A, B) change then this will have a direct impact on the risk analysis outcome.

9.5 Summary

This chapter identified the parts of the highway drainage infrastructure at greatest flood risk within the study area. Triangular distributions for the impact and probability relating to Section 1 (A, B, C) and Section 2 (A, B) were utilized within @RISK® for all return periods and storm durations. The total flood impact distribution consisted of the sum of each parameter (Equation 9.1), namely; non-residential properties, road disruption and emergency road maintenance.

The results of the @RISK® for a 15 minute storm duration (Table 9.13) identified that the three areas in order of greatest flood risk were; Section 1 Part A, Section 1 Part B and Section 1 Part C. The results of the @RISK® for a 180 minute storm duration (Table 9.14) identified that the three areas in order of greatest flood risk were; Section 1 Part B, Section 1 Part C and Section 2 Part B.

The following chapter discusses how the research objectives were achieved. The components of the Flood Risk Model; the risk management process and drainage network analysis are reviewed. Reflections are made on the development of the tool.

CHAPTER 10 DISCUSSION

10.1 Introduction

This research has explored the use of a risk based approach to better inform the decision making process used by highway drainage engineers when seeking to identify the parts of highway drainage infrastructure at greatest flood risk, Chapter 9 discussed the results obtained. It was evident from the findings of the literature review that a framework incorporating a risk based approach was appropriate to assess the uncertainties associated with highway drainage infrastructure flooding. The framework needed to include the risk management process and a drainage network analysis; Figure 5.1 shows this conceptually.

The total possible risks associated with highway drainage infrastructure flooding were identified through a structured process involving a literature review augmented by expert opinion obtained from experienced highway drainage engineers and highway asset managers. The risk management process was successfully used to identify and analyse risk categories; as built condition of the infrastructure, asset maintenance undertaken, asset deterioration and predicted climate change. Each of these categories had associated risks.

Semi-quantitative risk analysis was used to identify the significance of each risk with a view to establishing the most influential risks. Experts assigned a score (1 to 5) for both the probability and consequence of each identified risk. Any risk considered too high from the semi-quantitative risk analysis process was further investigated through quantitative risk analysis. Quantitative risk analysis comprised of two processes; a process to determine the probability of a flood occurring and a flood impact model (see Section 5.5.2.2). This theoretical framework was then implemented through a case study, see Chapters 6 to 9.

This chapter discusses the progress made in the development of the analytical tool under the following headings:

10.2 - Achievement of objectives

10.3 - Risk Management

10.4 - Use of expert opinion

10.5 - Drainage Network Analysis

10.6 - Total flood impact

10.7 - Probability Distribution

10.8 - Monte Carlo Simulation

10.9 - The study area

10.2 Achievement of Objectives

10.2.1 Objective 1

Explore the current UK design procedure for highway drainage infrastructure

Drainage is a fundamental aspect of road design, it necessitates surface water being effectively removed from the carriageway to preserve safe functionality. Chapter 2 contains a comprehensive literature review in respect of the elements required to design a highway drainage system.

A placement with DCC allowed many hours of discussion with experienced highway drainage engineers and numerous site visits discussing current highway drainage infrastructure design procedures. This experience was augmented by discussions and demonstrations onsite.

10.2.2 Objective 2

Examine the current maintenance procedures undertaken by highway authorities in respect of highway drainage infrastructure

Chapter 3 contained a comprehensive literature review on the management and maintenance of highway drainage infrastructure. Drainage assets can be considered 'forgotten assets' primarily because they are buried, or even if above ground, elements frequently remain difficult to access. Drainage asset inventories have not been an industry priority, a situation which although improving, is expected to take some time to rectify given the size and complexity of formulating full records in respect of all sites. Many hours of discussion with experienced highway asset managers at DCC helped inform the research as to the current situation regarding the management of highway drainage infrastructure.

10.2.3 Objective 3

Investigate the uncertain threats associated with highway drainage assets which may cause them to flood

A comprehensive literature review identified 4 main risk categories; as built, maintenance, deterioration and climate change. The opinions of experienced highway drainage engineers and asset managers further confirmed these categories. Each category was composed of different individual risks; see Table 5.1. Lack of maintenance was readily identified by the engineers/managers as the main reason that a drainage infrastructure asset failed.

10.2.4 Objective 4

Explore the risk management literature to understand how risk management concepts have been used in disciplines related to that considered herein.

A comprehensive literature review identified risk management as a methodical process; comprising of communicating and consulting, establishing the context, identifying, analysing, evaluating, treating, monitoring and reviewing a risk, Figure 3.4 shows the risk management framework. The management of risk in industry is increasingly recognized as an important part of decision making; risk analysis helping managers better understand the risks and opportunities they face in order that they can evaluate better the options available. A review of previous studies relating to the use of a risk based approach is contained in Section 3.12.

10.2.5 Objective 5

Investigate whether the discipline of risk management can provide a suitable framework which can assist highway drainage management.

The framework should enable:

- **The identification of the threats which can cause flooding.**
- **In relation to these threats, the quantification of the likelihood of flooding on a highway network.**
- **The quantification of the effect, or impact of flooding on a road network**

This provided a theoretical framework from which a unique research methodological framework was devised. The framework integrated; (i) the risk management process and (ii) drainage network analysis. The risk management process allowed risk analysis to identify the threats which cause the greatest flood impact. The identified risks and their associated probability were investigated using drainage network analysis (MicroDrainage^{TM}), a flood cost model and @RISK® software.

10.2.6 Objective 6

Demonstrate the theoretical framework by means of a case study using data collected from a UK Local Authority

A placement with DCC enabled Markham Vale to be used as a study area. Markham Vale is a business distribution park located adjacent to J29A of the M1. Its selection was assisted by the fact there was a comprehensive electronic data set relating to the site, compatible with MicroDrainage^{TM}. The results of the case study clearly demonstrated the usefulness of the theoretical framework, albeit further refinements of the process are recommended for further research.

10.3 Risk Management

Table 5.1 shows 4 main processes within a risk management framework that can be used to assess uncertainties associated with road drainage flood risk; communication and consultation, risk assessment, risk treatment, monitoring and reviewing (Vose, 1997; ISO 31000, 2009). The research framework utilized the risk identification and risk analysis elements of the risk assessment process together with communication and consultation of the risk management framework. Inclusion of the other aspects of the risk management framework were considered beyond the remit of this research. Further discussion on the components included in the framework and their implementation within the Case Study are discussed in Section 10.8 and 10.9.

10.4 Use of expert opinion

In the absence of records identifying risks capable of causing a network to flood, a questionnaire was circulated to experts with a view to seeking their identification (see Section 6.3) (Vose, 2010). Various techniques on how to harness expert opinion were identified in Section 3.11.2.1. Despite the appeal of using the brainstorming technique, which offers the advantage of obtaining the information required in one session, it was recognized that it would be very difficult to get a large enough group of participants with the necessary knowledge to brainstorm answers together in one place for long enough. Similarly, the Delphi technique which is recognized as helping to remove bias was potentially an excellent method to use, however, it was rejected due to its disadvantages. These included possible difficulties in maintaining active participation with the experts throughout the process, and a possible large drop off rate; far more so than if respondents are asked to complete a one off questionnaire (BSI, 2010). As the research targeted a specific engineering expertise the number of interested participants was uncertain; a large number of respondents could consequently not be guaranteed. A large drop off rate would potentially have resulted in

extremely low number of participants. The Delphi technique was also recognized as time-consuming (Dunham, 1998).

As experts are human they have their own opinions; it is accepted that another group of similarly experienced engineers could potentially have identified a different set of risks and/or allocated different probabilities to them. However, as the questions related to a specialist field of engineering the range of answers from other experts would logically not be expected to be too dissimilar. The standard deviation of the identified risks overall was low (Table 7.2). Participating experts were unaware as to other responses and no bias was apparent. The use of expert opinion in research is discussed in Section 3.11.2.1, this clearly argues that there is no definitive number of experts that must be used.

10.4.1 Use of the questionnaire

The circulation of a single, purpose specific questionnaire was chosen as it potentially had the advantage of not attracting a high drop off rate. The main benefits of designing a questionnaire were that it could be specifically targeted at the area under examination, and was relatively easy and inexpensive to circulate. Similarly, it was considered quick to complete and analyse as well as being a familiar mechanism to the experts (Hurt, 2013; Vose, 1997; Bamford et al, 2008; BSI, 2010; Sackman, 1974).

Prior to distribution the questionnaire was approved by the ethics team at the University of Birmingham. In total 127 questionnaires were circulated, 73 to local authorities and 54 were circulated to consultancies; in total 24 replies (19 percentage of those circulated) were returned, see Section 5.5.1.2. However, respondents had freely volunteered without any coercion or incentive of reward; this was viewed as confirming their interest in the research, with answers well considered. However, as discussed in 3.11.2.1 the number of experts actually required for involvement in a qualitative survey is subject to many opinions, with a consensus view that a much lower number is required than if a quantitative survey had been

undertaken, Section 10.4.2 estimates the sample size required to provide a 95% confidence level using a population of 507.

Despite a disappointing response, the number was considered large enough for the research based on a scrutiny of the literature (Taylor and Bogdan, 1984; Patton, 1990; Spiggle, 1994; Maykut and Morehouse, 1994; Punch, 1998; Morse, 2000; Crouch and McKenzie, 2006; Glaser and Strauss, 2009; Creswell, 2012; Ritchie et al, 2013; Green and Thorogood, 2013). It is accepted that a wider circulation of questionnaires (to each LA and engineering consultancies indicating highway drainage expertise) may have resulted in a larger response rate and if this research were to be repeated a much larger distribution of questionnaires would be undertaken. Potentially this could be achieved through the assistance of the Local Government Association and the Chartered Institute of Highways and Transportation (CIHT) becoming involved with any future research. It is also recognized that the number of responses may well be increased if a financial incentive (e.g. offer of a book token) were to be offered; this option was not available as the research was self-funded.

10.4.2 Estimation of sample size

As stated in Section 5.5.1.2 there are 418 LAs in the UK (LGiU, 2015). The CIHT (2015) shows 89 engineering consultancies indicated they undertook 'related work in drainage', although this term is not further defined. Based on these figures and assuming one person is employed in each provides an estimated population size of 507 (418+89). A 95% confidence level is the most commonly used by researchers (Freund, 1972; Wonnacott and Wonnacott, 1972; Survey Monkey, 2015; Creative Research Systems, 2015). Assuming a finite population of 507 and using Equation 10.1 (Survey Monkey, 2015; Creative Research Systems, 2015) the sample size can be obtained.

$$Sample\ size\ (Finite\ Population) = \frac{Z^2 \times p(1-p)/e^2}{1 + \frac{Z^2 \times p(1-p)}{e^2 \times population}}$$

(10-1)

Z = Z critical value (1.96 for 95% confidence level)

p = percentage of accuracy required, expressed as decimal. When determining the sample size needed for a given level of accuracy the worst case percentage (50%) must be used.

e = margin of error (e.g. 0.05, ±5% for 95% confidence level).

Population = 418 local authorities in the UK (LGiU, 2015) and 89 engineering consultancies specialising in drainage (CIHT, 2015), total estimated population = 507

$$Sample\ size\ (Estimated\ Finite\ Population) = \frac{1.96^2 \times 0.5(1-0.5)/0.05^2}{1 + \frac{1.96^2 \times 0.5(1-0.5)}{0.05^2 \times 507}}$$

$$Sample\ size\ (Estimated\ Finite\ Population) = \frac{0.9604/0.0025}{1 + \frac{0.9604}{1.2675}}$$

$$Sample\ size\ (Estimated\ Finite\ Population) = \frac{384.16}{1.757712}$$

$$Sample\ size\ (Estimated\ Finite\ Population) = 218.557 = 219$$

If future work is undertaken regarding this methodology it is important that a minimum sample size of 219 is obtained in order to achieve a 95% confidence level. However as discussed in Section 3.11.2.1 the number of experts actually required for involvement in a qualitative survey is subject to many opinions, with a consensus view that a much lower number is required than if a quantitative survey had been undertaken.

10.4.3 Risks for drainage network analysis

The findings of the semi quantitative analysis were identified in Section 7.3, Table 7.3 shows 92% of the identified risks had a standard deviation of less than 5. As shown in Section 5.12.3.2 it is possible that these risks could interact with each other in ways not predictable from examining each one individually (Vose, 2010). Consequently, there was a need to identify the total number of possible scenarios to be modelled in MicroDrainage™. It was found that 27 scenarios existed for the case study, but due to the problems experienced within MicroDrainage™, 24 scenarios were chosen to be modelled.

The climate risk category and its associated risks could not be included within MicoDrainage™, (return period, duration of storm and rainfall intensity), on an individual basis. Consequently, to ascertain the effect of precipitation on a drainage network a return period and its duration was used as a test condition utilizing the other identified risks, the results are in Chapters 8 and 9.

The risks identified through semi quantitative analysis for inclusion in quantitative analysis are shown in Section 7.4. However, maintenance and deterioration, and quality of workmanship were not so straightforward to include. Quality of workmanship was identified by 92% of the experts as having the most influence on the flooding of highway drainage infrastructure. Unfortunately, this research could not include this risk within the sensitivity

analysis as it could not be modelled within MicroDrainage™ which only allows specific parameters, for example; pipe diameter, pipe gradient, pipe roughness, pipe length, diameter of manhole. Non-inclusion of this risk must have affected the accuracy of the total flood cost and hence the final results of the Monte Carlo simulation. However, the inaccuracy of the overall results would be small as 95% of the experts considered quality of workmanship to be good or very good. If this opinion changed to poor or very poor then this would adversely affect the deterioration rate of the asset and increase the overall flood risk.

96% of experts identified deterioration of an infrastructure asset was strongly influenced by the standard of maintenance received, confirming the literature (HMEP, 2012; Spink et al, 2014; O'Flaherty, 2008; Olesen and Rollings, 2012a). The limitations of MicoDrainage™ necessitated the maintenance and deterioration risks being combined to form one risk (sedimentation depth). The estimated loss of function (%) within the pipe was provided by the experts based on frequency and type of estimated asset maintenance. Although the substitution of the sedimentation depth parameter may have detracted from the overall accuracy of the quantitative analysis; it is impossible to say by how much. The use of sedimentation, as a parameter, replicated a restriction of flow within the network, this could be argued to be a reasonable compromise as the literature suggests that sediment deposition is the most common cause of asset failure, and one which ultimately results in the loss of the asset from a total blockage. This is exacerbated when pipes and channels have insufficient gradient to be self-cleansing, and when an asset is structurally poor, and poor maintenance effects the invert causing ponding (Spink et al, 2014; Olesen and Rollings, 2012a; O'Flaherty, 2008).

10.5 Drainage Network Analysis

10.5.1 UK Rainfall

Although it is not universally accepted that climate change is happening (see Section 4.3). The findings of the IPCC (2007) and UKCP09 are accepted by many governments around the world including the UK. The overwhelming evidence suggests climate change predictions indicate extreme weather events such as heavy rains will increase in the future. In the UK there are two well established methodologies used to produce an IDF relationship namely the FSR and the FEH. This research used the FEH method as is supersedes the FSR and uses more recent data (1961 to 1990), (MicroDrainage, 2012a) and hence is considered more reliable. Unlike the FSR, the FEH allows for regional and local variations of rainfall frequency (Butler 2008). Another reason for choosing the FEH was the fact that the study area was greater than 50ha (Butler 2008). Although it is acknowledged that the FSR could have been used; Allitt et al (2009) found this method consistently underestimated the rainfall intensity when compared to the FEH.

Heavy rainfall events in winter have increased for all areas and effect the reliability of existing IDF curves, which play a vital role in determining surface runoff (Section 4.4). The data set used by the FSR/FEH is dated. Lumbroso et al (2011) suggested that ideally a new IDF curve should be created for each new development. Whilst it was considered beyond the scope of this research to create a new IDF curve in relation to the study site, further research could investigate the feasibility of such a process.

As noted in Section 4.4 Sanderson (2010) examined how rainfall return periods are expected to change in 2040, 2060 and 2080. Section 6.4.7 explained that climate data used within this research was extracted from Sanderson (2010). The study area was analysed under two storm durations (15 minutes and 180 minutes), as suggested by participating experts. Various climatic scenarios were used namely; (2, 30, 100 year events), 2040 (5, 30, 188 year events),

2060 (5, 50, 221 year events) and 2080 (5, 73, 261 year events). These climatic scenarios were considered to provide an adequate representation of current and predicted future changes.

10.5.2 Drainage network details

The catchment area used in the initial design was unknown; therefore, it needed calculating. Section 6.4.4.1 describes how this was done for use in the surface runoff equation (Equation 5.3). This is the method used by experienced highway drainage design engineers at DCC, it was adopted as it was considered to be accurate, reliable and the most appropriate (Russell, 2013; Boyack, 2013; Millership, 2013). Its use was also supported by the literature (Olesen and Rollings, 2012a; t). As noted previously, this research modelled the drainage infrastructure as a complete system, namely; gully pot, gully connector, carrier pipe and manholes. The cover levels in respect of the gully connector were unknown and also needed calculating, as no alternative method of calculating cover levels was discovered in the literature review, the one used by experienced drainage design engineers at DCC was accepted as an accurate method (Section 6.4.4).

10.5.3 Flood Flow Analysis

Table 8.3 and Table 8.4 shows an increase in the number of times an ID floods for the same return period over 24 simulations. An example of how the number of scenarios changed over different return periods is shown in Table 10.1.

Table 10.1 – An example showing the number of times the A632 flooded over 24 scenarios

Return Period	**Number of scenarios**
100	18
188 (2040)	20
221 (2060)	21
261 (2080)	23

Walters (2009) and Spink et al (2014) identified this trend; recognizing that as climate change impacts develop so will the lack of capacity within the drainage network; resulting in more flooding in particular locations; and hence an increase in associated costs. The developed tool can assist decision makers on how best to allocate resources for example towards infrastructure improvements, maintenance or preventative measures.

10.5.4 Reflections

Several problems were encountered with the network modelling, specifically with the software, namely:

- Whilst constructing the 24 scenarios for the case study it was surprising to find that MicroDrainage™ did not allow the user to copy and paste columns from other software (Microsoft Excel). An otherwise straight forward task was made extremely time consuming and laborious. It necessitated the range of values for each risk to be changed individually throughout the network; this involved 31,464 amendments for both site sections. Since completion of this mammoth task and based on feedback to MicroDrainage™ regarding the problem, and including comments from other users a copy/paste function feature has been incorporated within the software. This feature will greatly reduce the implementation of the proposed framework.
- Gullies had to be simulated by adjusting the size of a manhole to the same size as a gully pot; this was the only way within the software that a gully pot could be modelled. This adjustment was considered to accurately model gully pots. If MicroDrainage™ included a function to directly incorporate a gully pot within the network, then the results of the proposed framework would need to be revised. If this situation arises then a comparison could be made to determine the difference in adjusting the size of the manhole to that of the actual gully pot. It is acknowledged

that a gully pot and a manhole have a slightly different shape, the manhole having slightly more capacity. If a software enhancement becomes available it would be expected to show a very slight increase in the extent of flood.

- In order for the gully connections to be modelled the connection at which it joins the main branch had to be installed as a manhole, hence invert levels had to be calculated for each connection using the process described in Section 6.4.5. In reality this manhole does not exist, as it is a pipe to pipe connection within the software. This is how pipe to pipe connections are modelled within the software (MicroDrainage, 2012h).
- In order for flood flow analysis to be run, a terrain model must be loaded onto the network under examination. However, due to software limitations, the terrain model must not include any Xrefs, this meant that both the terrain model and OS Map had to be combined in AutoCAD so that it could be uploaded for flood flow to run. It would be very advantageous if an AutoCAD drawing containing Xrefs could be uploaded directly in order for flood flow analysis to be performed for use in this framework.
- A similar problem existed when the network was modelled using the climate change sensitivity tool. Although this initially identified which of the 24 scenarios had flooded under each climatic event, flood flow analysis had to be performed separately on each flooded scenario. It would be very advantageous if flood flow analysis could automatically link with the results of the climate change sensitivity tool for use in this framework.

10.6 Total Flood Impact

10.6.1 Flood Cost Model

This research solely concentrated on quantifying direct tangible flood losses resulting from highway drainage infrastructure flooding. It would have been possible to create a set of depth damage functions to obtain the total cost of flood (Messner et al, 2007). However, this was considered beyond the scope of the research. The creation of a depth damage function would have been a mammoth task and is not considered necessary when using the MCM (Hall et al, 2003). The FHRC has produced a regularly updated database of absolute damage functions since 1977 (MCM). This was accepted as providing accurate data (Hall et al, 2003; Tapley et al, 2009; Plate, 2002). Consequently as all ID types were identified in this well accepted reference manual, it was used to calculate the flood losses for each section and part of the site. The results in Chapter 8 showed only non-residential properties, the roads through the site, one agricultural field and some wasteland flooded.

10.6.1.1 Non-residential properties

Each non-residential property that flooded was assumed to have flooded to a depth greater than 0.25m; this assumption allowed for the maximum flood costs to be included in the model. The MCM provides costs in 0.25m increments, and for flooded sub-ground areas (0m); however, the latter was considered to under estimate the actual flood impact. Consequently, costs associated with a depth of 0.25m were used as they were considered to better reflect the cost of flooding.

10.6.1.2 Road disruption cost

Penning-Rowsell et al (2013) sets out 4 methods to calculate the financial costs associated with road disruption namely; the diversion value method, speed-time limit, origin destination, and delayed hour method; the first 3 are ranked by the refinement of data provided.

The delayed hour method was used in this study as it is the most commonly used method by LAs for costing floods on small developments (Russell, 2013; Bache, 2013; Boyack, 2013; Daniels, 2013; Green, 2013; Wells, 2013; Doorman, 2013; Millership, 2013).

The other methods were considered inappropriate for the following reasons:

1. Ideally, the study would have used the origin destination method as it is the most sophisticated method of assessing road traffic disruption costs. It utilizes an origin-destination matrix and complex traffic modelling results. The use of such a matrix for the area then enables transport models for example SATURN, a general traffic assignment model or PARAMICS which provide a micro-simulation model to be used to calculate the traffic flows on the different roads (Bache, 2013). However, this method has complex requirements and a specialist experienced transport modeller is needed to use it (Olesen and Rollings, 2012t). Such analyses were therefore considered beyond the scope of this research.
2. The drainage analysis results presented in Chapter 8 showed that the flood only lasted one hour under the 15 minute duration, and 6 hours under the 180 minute duration whilst the flood depth remained on average less than or equal to 36mm. Consequently the 15 minute storm duration would have produced very little disruption; similarly the 180 minute storm duration although lasting longer the depth was also safe to drive through (Jordan, 2014). As a result the road disruption cost varies for each site section as shown in 9.2.
3. The diversion value method was therefore rejected as the roads remained open; had this not been the case and traffic had been diverted then this method would have been appropriate. Similarly the speed-time limit was considered inappropriate as the flood depth did not close the road and the alteration in speed would have been minimal (although reduced) and not significantly affected the values given in the MCM.

10.6.1.3 Other flooded IDs

Although the agricultural field and several pieces of wasteland flooded, the costs, if any, associated to this type of land were not included within the cost model as the flood depth was less than 100mm. Penning-Rowsell et al (2013) allowed for costings in relation to flooded agricultural land, however 80% of agricultural damage costs are associated with loss of production or additional production costs incurred, 20% are associated with damage to property or equipment. Costs are available for flood events 'for a few days to one or more weeks'. No animals, property, or crops were considered to occupy the land. The MCM does not provide costs in respect of flooded wasteland. However, future work could include this ID if water remained on the surface and was stagnant as it could be considered an environmental hazard but would require an environmental impact assessment (Penning-Rowsell et al, 2013).

10.6.2 Emergency maintenance costs

The flood flow analysis results identified that flooding would only last for 1 hour under a 15 minute duration and 6 hours under a 180 minute duration, with flood depth remaining constant at less than100mm for both. The following assumptions were made within the developed framework; namely the flood would be reported, the LA would comply with its statutory requirements to ensure a road is safe for road users, and a highway inspector would visit the flooded road and assess the costs associated with the maintenance required; the modal hourly inspection rate of £12 was used (provided by the experts). Any increase in: the number of flooding events, hourly rates paid, number of workers required to respond, and time taken to complete a job would add to the overall cost. These increased costs would need to be included within the Monte Carlo simulation. Following the results of the semi quantitative analysis a sensitivity analysis was undertaken. The results showed climate

change was the most influential risk to impact highway drainage infrastructure flooding followed by sedimentation depth.

10.7 Probability distribution

The MicroDrainage results clearly illustrated that the higher the return period the more flooding occurred, and consequently a greater number of scenarios were affected (Appendix B4 to B7). Consequently, the probability associated with each section and part of site changed accordingly (Table 9.8 and 9.9). As mentioned in Section 5.5.2 a probability distribution rainfall intensity associated with climate change, although mentioned in the theoretical Flood Risk Model (Equation 5.3) was not utilized within the case study. It is recognized that inclusion of climate change risk may have impacted the overall flood risk of particular assets and also possibly the ranking of areas of a site at greatest flood risk. It is therefore recommended that research which focuses on the implications of climate change on a particular site should examine climate change risk as provided for in the Flood Risk Model (Equation 5.3) developed herein.

10.8 Monte Carlo Simulation

@RISK® calculated the model to a pre-defined 5000 iterations (number of times model was run), to generate a frequency distribution. The number of iterations performed affects the simulation execution time and the quality and accuracy of the result. Less iterations would have detracted from the quality and accuracy of the results, however, the literature review indicated 5000 iterations would provide accurate results (Vose, 2010). It was necessary to ensure that the results were accurately obtained as this would have fundamental implications on achieving the aim of the study.

10.8.1 Risk quantification

This research explores the use of a risk based approach to better inform the decision making process used by highway drainage engineers when seeking to identify the parts of the highway drainage infrastructure at greatest flood risk. The overall risk cost distribution (see Figure 9.2) from the Monte Carlo simulation would not have satisfied the aim of the research. This type of output from Monte Carlo could be created for each climate scenario and site section to ascertain the probability associated with the overall cost to that section. If the decision maker needed to identify the probability of a flood cost occurring under a certain climatic condition (for each section of site) then this type of distribution would incorporate climate change implications within the current decision making process.

10.8.2 Sensitivity analysis

Tornado charts were produced for each climate scenario; they identified the sections and parts of site most at flood risk. This fulfilled the aim of the research. The tornado charts displayed the input variables Section 1 (A, B, C) and Section 2 (A, B) together with their associated overall risk cost distributions, they are ranked in order of greatest influence on the overall risk cost. The findings show that the probability of occurrence had more influence on the overall risk cost than the cost of flood (impact). This was due to the probability of occurrence being low for each section of site and the total cost of a flood being high. If the probability associated with the range of values for each risk assigned by the experts changed, this would affect the Monte Carlo simulation results and the overall maintenance decision. For example; the probabilities associated with the as built situation, in respect of the risks; pipe diameter (most likely), pipe gradient (most likely) and maintenance (minimum) was high for each risk as the study area was only developed in 2005. This meant that the probabilities associated with the other values were low.

However, had the study area not had an accurate asset inventory then there would have been more uncertainty as to value of each risk, consequently the probability associated with each value would have been higher, resulting in an overall higher risk cost. This demonstrated the importance of having an up to date accurate asset inventory when trying to assess and cost flood risk see Section 3.4.1.

10.8.2.1 Section at greatest flood risk

The results of the @RISK® for a 15 minute storm duration (Table 9.13) ranked the three areas in order of greatest flood risk; Section 1 Part A, Section 1 Part B and Section 1 Part C. The results of the @RISK® for a 180 minute storm duration (Table 9.14) ranked the three areas in order of greatest flood risk; Section 1 Part B, Section 1 Part C and Section 2 Part B. The 15 minute results were consistent with the topography of the area; Section 1 Part A contains the electricity substation, the flooding of which has significant financial implications. More IDs flooded in Section 1 Part B than Section 1 Part C, consequently a greater flood impact occurs in Section 1 Part B. The 180 minute results were also consistent with the topography.

10.8.3 Remote Condition Monitoring Systems

The use of technology to assist monitoring highway drainage assets is an undeveloped area, although CCTV cameras are used by Highways England and LAs, see Sections 3.4.1 and 3.4.2. The development of low cost, walk over the ground, survey methods that do not use CCTV are in their infancy. Remote control monitoring is an undeveloped area of research, although its importance is recognized and progress in development is being made as described in Section 3.8. Ideally this developed technology would enable highway drainage assets above and below ground to be monitored continuously, reporting asset failure and providing early warning as to possible future asset failure. This would potentially greatly improve the understanding of asset health, so helping reduce the risk of sudden asset failure

and associated costs. The developed Flood Risk Model could be better informed as to asset condition, thereby for each identified risk the probability and range of values used for drainage network analysis (within the Flood Risk Model) could potentially be more accurate, so improving the determination of flood risk.

10.8.4 Reflections

For the case study, the input variables within the Monte Carlo simulation all had high impact and low probability scores (for the reasons suggested above). Vose, (2010) considered that in such circumstances Monte Carlo simulation may not always be the most suitable form of analysis. If the developed tool is used in the future another type of risk analysis tool may be considered more appropriate for cases where the impact is high and probability of occurrence low. Further research comparing different forms of analysis would help ascertain the most suitable.

10.9 Case study area

As discussed in Chapter 6 the study area was located in Derbyshire adjacent to Junction 29A of the M1. This site was chosen as it contained three roads, a diverse range of offices, warehouses, industrial units, a field, land for further development and some residential properties. This mix of land and structures was considered a good representation of a typical urban environment. Development on the study area was completed in 2005, with site data available in electronic format. The accuracy of the data was confirmed by the senior project engineer. The developed tool was successfully demonstrated using the case study area. The availability and accuracy of the case study data is not typical, however the proposed framework can be applied to any site not benefitting from such a comprehensive data set, irrespective of its age. This is possible as UKCIP09 details climate projections covering the whole of the UK at 5km and 25km gridded resolutions. Various emission scenarios (low, medium and high) are available; the choice of which directly relates to the level of flooding

attributable to climate change; for example a high emission scenario would result in a high level of flooding and associated higher levels of cost when compared to the use of a low level emission scenario. The appropriate emission scenario to use depends on future climate trends; with greater costs associated with using a high emission scenario.

If the methodology is applied to another site, experts would need to be provided with relevant site information in order to complete the designed questionnaire. If applied to an area not benefitting from electronic documentation, and/or with unknown highway drainage infrastructure assets then a site investigation would be necessary, however, this is a time consuming and expensive process (Millership, 2013). The need for LAs and Highways England to have a complete inventory of underground assets is recognized and being addressed. This will increasingly enable the tool to be used and the range of values for each identified risk and their associated probabilities more accurately identified.

10.10 Summary

This chapter discussed the techniques and software used to develop a tool to assist the highway engineer to identify parts of highway drainage infrastructure at greatest flood risk. The focus of the chapter was associated with lessons learnt from using the tool through the case study.

The advantages of the tool have been discussed in the particular context of the case study, and where appropriate suggestions made to enable improvements to the tool to be effected in future work. The tool utilized a recognized risk based approach as an appropriate framework to use in assessing the uncertainties associated with highway drainage infrastructure flooding. The tool incorporated the risk management process and drainage network analysis.

The next, and final chapter, describes the accomplished work within the thesis and makes recommendations as to possible future work. The contribution of the research to the wider risk literature is also identified.

CHAPTER 11 CONCLUSIONS AND FURTHER RESEARCH

11.1 Accomplished Work

The work presented in this thesis may be regarded as the first stage in the development of a tool designed to assist the highway drainage engineer/asset manager identify parts of the highway drainage infrastructure at greatest flood risk.

The research study focused on establishing the feasibility of assessing the degree of flood risk to road drainage infrastructure using a risk-based approach that utilized data from drainage network analysis software. To this end the developed framework implemented through a case study provides the structure for use in any area to ascertain the part of area at greatest flood risk.

11.1.1 Conclusions

The main conclusions of the research are:

1. A risk based approach is suitable for identifying and quantifying the risks associated with highway drainage infrastructure flooding.
2. Drainage Network Analysis can assist in risk quantification relating to flooding of highway drainage infrastructure by ascertaining the extent of flooding in relation to a drainage network.
3. In order for the tool to complete the risk management process, its further development needs to incorporate, risk evaluation, risk treatment, and monitoring and reviewing.

11.1.2 Findings

The Flood Risk Model could successfully be used to identify which area of a site is at greatest flood risk, this information could be used as a decision support tool by asset

managers/ highway maintenance engineers to help identify the parts of a drainage network that need examination with a view to maintenance strategies being implemented.

11.1.2.1 Suitability of case study area

As noted in Section 10.9 the developed tool was successfully demonstrated using the case study area. However, this area was a relatively recent development (2005) and the associated asset inventory could unusually be considered up-to-date. This was advantageous as the comprehensive electronic inventory provided accurate as built data for consideration by the experts. However, up-to-date documentation meant that the most likely values were less uncertain, attracting high associated probabilities. Consequently, if the developed Flood Risk Model was used to analyse a site not having such an up-to-date asset inventory then the uncertainties in relation to the most likely values would be higher and the probabilities lower. This would result in higher individual risk scores and consequently an overall larger risk cost.

11.1.2.2 The use of experts

The use of experts to assist the risk management process is a well-recognized approach in the absence of historical data relating to complex problems. The lack of historical data relating to highway drainage flooding means the use of expert opinion to confirm the risks identified in the literature review, and subsequently modelled was a relevant approach to undertake. Section 3.11.2.1 identified a variety of views as to the appropriate sample size required; Section 10.4 further discusses the sample size required if a confidence level of 95% is to be attached to the data.

11.1.2.3 Risk identification and semi quantitative analysis

The literature review identified 4 main risk categories; as built, maintenance, deterioration and climate change. The risks within each category were subsequently confirmed by the experts as being inclusive (Table 5.1). The 26 risks were refined using semi quantitative

analysis (Table 5.3) enabling only risks considered to highly influence highway drainage infrastructure flooding to be analysed using quantitative analysis. This process ensured that the most influential risks were further investigated. Some risks needed to be amalgamated so that MicroDrainage ™ analysis could take place. To further improve the accuracy of the results all risks identified in Table 5.1 should have been included in the model however inclusion was impossible as MicroDrainage™ was not designed for this purpose. Despite this the risks included within the model were a good representation of the overall risks identified.

11.1.2.4 Quantitative analysis (Monte Carlo Simulation)

Monte Carlo is a well-known, tried and tested method for analysing uncertainties, however, as noted in Section 10.8.3 the input variables within the simulation had high impact and low probability scores due to the low uncertainty associated with the as built site (Section 11.1.2.1.). Vose (2010) suggested that in such cases Monte Carlo may not necessarily be the most suitable form of analysis to use, possibly another type of risk analysis tool may be more appropriate if the impact was high and there was a low probability of occurrence. To ascertain if there is a more suitable form of analysis further research needs to be undertaken.

11.1.2.5 Drainage network analysis

MicroDrainage™ successfully modelled the risks chosen for quantitative analysis to ascertain the extent and depth of flooding. Although it was not designed to incorporate some of the risks identified by semi quantitative analysis, a similar problem would have existed using any other non-bespoke commercial software package.

11.2 Future work

To enable a fully working tool to be developed which identifies the areas of a highway drainage network to be at greatest flood risk, other work needs to be done as specified below:

11.2.1 Risk Management

1. Risk evaluation, risk treatment, and monitoring and reviewing were three elements of the risk management process not incorporated into the model. Their inclusion would further refine the process and enable it to provide a more comprehensive risk management process. However, not including them in the research did not detracted from accurately analysing the risks identified.
2. The feasibility of obtaining the involvement of the bodies responsible for roads in the UK in further research needs pursuing; such involvement could potentially lead to a far larger number of experts identifying and quantifying the risks inherent in a drainage network. In turn the provision of more risks and their associated values are likely to further improve the chance of having captured all risks relevant for inclusion within the model.
3. Progress made in remote control monitoring of sites similarly needs to be accounted for within any developed model.

11.2.2 Drainage network analysis

1. Network analysis should ideally be undertaken utilizing up-to-date IDF curves in respect of each new development. Currently IDF curves are mainly based on historic rainfall data only. Climate change predictions which include an increase in extreme weather events such as heavy rains may well adversely impact on highway drainage infrastructure designs, this means that the current type of IDF curve may well be insufficiently accurately advised. The composition of a site specific IDF curve needs

to incorporate predicted climate change scenarios to improve the accuracy of the decision making process.

2. The approach used in this study could be extended to include other types of highway drainage infrastructure. This research utilized gullies, carrier pipes and manholes; other assets such as surface water channels and combined kerb and gully could be incorporated into the tool.
3. The feasibility of developing a tool which is capable of assigning a probability of flood to each asset within a drainage network, so enabling the probability of other assets within the network to be calculated, needs to be examined.
4. The feasibility of developing a bespoke drainage network analysis software capable of including other identified risks, for example quality of workmanship, frequency of maintenance and deterioration needs to be examined. This would reduce any inaccuracies caused by having to substitute these parameters within the model.

11.3 Contribution of the research to the wider risk literature

The research proposed a unique methodological framework that integrates the risk management process and drainage network analysis. Other studies have proposed models to examine a variety of aspects of highway drainage including associated managerial related issues; some have been informed by expert opinion. However, this research was uniquely confined to the identification of parts of a highway drainage system at most flood risk in an identified area. The methodology can be applied to any defined area in the UK as UKCIP09 details climate projections covering the UK at 25km and 5km gridded resolutions. Various emission scenarios (low, medium and high) are available; the choice of which directly relates to the level of flooding attributable to climate change. The results produced by the model could potentially improve in tandem with advancements in asset management recording.

11.4 Model Validation

Sargent (2013); Schlesinger et al (1979) identified that a model developed for a specific purpose needs to have its validity determined with respect to that purpose; ideally, each model component should be separately validated. Ideally this should include an examination of overall efficacy including checking that input data is verified as coming from a reliable source. The efficacy of a model can be determined by how well it provides an objective assessment of the closeness of the simulated behaviour to the observed measurements; ultimately field tests provide a good assessment of accuracy**.**

11.4.1 MicroDrainage™ Validation

The drainage network analysis aspect of the research framework (Figure 5.2) was undertaken using MicroDrainage™. MicroDrainage™ is recognized throughout the highway drainage design industry as the market leading software and therefore it has been assumed that the product has been fully validated.

As the study area was concerned with a developed site, this would enable a visual and measured (mm) physical inspection of any flooding. The level of flood occurring in each of the identified parts and sections of site could then be directly compared to the simulations produced by the model. Due to the time limitations of an individual research degree no measurements were taken in a time of flood and no previous measurements relating to flooding were available.

11.4.2 @RISK Validation

Table 9.3 to 9.6 show that the impact distributions associated with each climatic scenario and section and part of site followed a pattern of descending values with no outliers present, a checking process recommended by (Moore et al, 2014). This pattern of descending values had been anticipated in line with the principles of the IDF relationship (see Section 2.3). The

impact distribution included in @RISK consisted of NRP and road disruption from the MCM, together with the cost of emergency maintenance (provided by experts). This research assumed the values provided by the MCM were accurate at the time of the study. It is noted a different group of experts could potentially provide a different cost regarding emergency maintenance.

Had remote control monitoring (see Section 3.8) of the site been available it could have assisted experts when assigning a probability of occurrence; this in turn would have increased the accuracy of predicting the overall probability of a flood event.

@RISK was used to undertake Monte Carlo simulations with 5000 iterations used. 5000 iterations were used as the literature suggests that this number is appropriate for a Monte Carlo simulation linked to risk analysis as conducted here in. However, it is recognised that further work could verify whether 5000 is appropriate by comparing the outputs as a function of the number of iterations. The minimum number of iterations required is that when the outputs of the model do not change for one number of iteration compared to the next (e.g. 5000 compared to 5100).

To complete the validation of the results produce by MicroDrainage™ and @RISK would require the methodology to be repeated; this would entail additional research project(s), both of which were beyond the scope of this research project.

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APPENDICIES