A DECISION-SUPPORT SYSTEM FOR THE DESIGN OF RETROFIT SUSTAINABLE URBAN DRAINAGE SYSTEMS (SUDS)

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Summary

Sustainable Urban Drainage Systems (SUDS) is a generic term that refers to various measures aimed at minimising surface runoff (and consequent flooding and pollution problems) from urban catchments. SUDS technologies include local infiltration, storage and storm-water re-use devices.

Although there is considerable international evidence of the successful incorporation of SUDS technologies in new developments, there is very little indication of the extent to which they represent a viable rehabilitation option for retrofit applications to problem urban catchments in the UK. It is believed that uncertainties about the design, hydraulic performance and cost of retrofit SUDS schemes, as well as some regulatory issues, have prevented UK engineers from exploiting the full potential of this approach.

This thesis presents two case studies in which retrofit SUDS have been evaluated against 'conventional' (i.e. in-sewer) drainage rehabilitation schemes. The case studies relate to the City of Leeds in Northern England, UK. In both cases it was found that SUDS technologies were viable, both in terms of hydraulic performance criteria (number and volume of CSO spills or flooding events) and in terms of comparative construction costs. Novel procedures were developed for evaluating hydraulic performance and SUDS scheme costings.

The identification of the most cost-effective from all feasible SUDS technologies for a given location is not straightforward. This thesis, therefore, proposes a design methodology for retrofit SUDS. The methodology comprises a decision making model (flow chart) that indicates whether SUDS-based approaches are likely to be viable, and cost-effective for a particular application. The flow charts make reference to SUDS design criteria (such as land-take, slope and infiltration capacity) and regulatory constraints (such as Building Regulations and local groundwater protection policies). Fundamental to the flow charts are hierarchies that characterise urban surface type, the treatment train concept, the disposal mechanism, and cost.

DECLARATION

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other institute of learning.

DEI GRATIA

(By the grace of God)

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SUMMARY

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This thesis presents two case studies in which retrofit SUDS have been evaluated against 'conventional' (i.e. in-sewer) drainage rehabilitation schemes. The case studies relate to the City of Leeds in Northern England, UK. In both cases it was found that SUDS technologies were viable, both in terms of hydraulic performance criteria (number and volume of CSO spills or flooding events) and in terms of comparative construction costs. Novel procedures were developed for evaluating hydraulic performance and SUDS scheme costings.

The identification of the most cost-effective from all feasible SUDS technologies for a given location is not straightforward. This thesis, therefore, proposes a design methodology for retrofit SUDS. The methodology comprises a decision making model (flow chart) that indicates whether SUDS-based approaches are likely to be viable, and cost-effective for a particular application. The flow charts make reference to SUDS design criteria (such as land-take, slope and infiltration capacity) and regulatory constraints (such as Building Regulations and local groundwater protection policies). Fundamental to the flow charts are hierarchies that characterise urban surface type, the treatment train concept, the disposal mechanism, and cost.

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ABREVIATIONS

AMP	Asset Management Programme
BRE	Building Research Establishment
CBA	Cost-Benefit Analysis
CIRIA	Construction Industry Research and Information Association
CSO	Combined Sewer Overflow
CSS	Combined Sewer System
EA	Environment Agency
EU	European Union
RwSC	Roof-water Source Control
RWU	Rain Water Utilisation
SEPA	Scottish Environmental Protection Agency
SRM	Sewer Rehabilitation Manual
SPZs	Source Protection Zones
SSO	Separate Sewer Overflows
SSS	Separate Sewer System
SUDS	Sustainable Urban Drainage Systems
UWWTD	Urban Wastewater Treatment Directive
UWWTR	Urban Waste Water Treatment Regulations
UPM	Urban Pollution Management
UDS	Urban Drainage Systems
WaPUG	Wastewater Planning Users Group
WWTW	Waste Water Treatment Works

1 OVERVIEW

1.1 BACKGROUND

In most UK cities, storm-water run-off from paved and roofed areas is generally directed into conventional sewerage systems. During times of high rainfall the capacity of these systems may be exceeded, resulting in catchment flooding, pipe surcharging, or in excess dilute sewage being discharged through combined sewer overflow structures into urban watercourses. In many cases these overflows cause unacceptable river pollution. The traditional means of resolving these problems is to upgrade the capacity of the existing infrastructure. However, such solutions can be costly, difficult to maintain and disrupt the natural water cycle.

The term 'Sustainable Urban Drainage Systems' (SUDS) describes a set of structural devices that are designed to drain surface water in a more sustainable fashion than conventional techniques. Example SUDS technologies include infiltration devices, permeable pavements, ponds and swales. SUDS generally operate by reducing, or attenuating, the peak storm-water runoff conveyed from the urban catchment to the sewer system. Flooding and pollution events can be prevented through the use of structural SUDS in conjunction with good site management strategies.

Although there is considerable international evidence of the successful incorporation of SUDS technologies in new developments, there is very little indication of the extent to which they represent a viable rehabilitation option for retrofit applications to problem urban catchments in the UK.

1.2 AIMS AND OBJECTIVES

This thesis aims to investigate the merits of applying retrofit SUDS as a rehabilitation strategy for conventional urban drainage problems, and to evaluate the practical and economic issues associated with their design and use in a UK context.

This thesis adopts the following objectives to achieve this overall aim:

- To undertake preliminary analysis (using existing literature sources and new case study data) to establish, in broad terms, whether retrofit SUDS approaches might represent a feasible sewer rehabilitation strategy – either when used on their own, or when integrated with conventional rehabilitation technologies. It is worth noting that subsequent objectives assume this to be the case.
- To establish those issues that affect in practical terms, the design and implementation of retrofit SUDS to existing UK catchments.
- To develop modelling procedures to enable the hydraulic effectiveness of retrofit SUDS to be evaluated and compared with conventional rehabilitation options.

- To explore the financial costs associated with the construction of retrofit SUDS, and develop costing procedures to enable the cost-effectiveness of retrofit SUDS to be evaluated and compared with conventional rehabilitation options.
- To develop a decision-making framework for the design and evaluation of retrofit SUDS.
- To demonstrate the application of the decision-making framework to a representative UK case study.

1.3 STRUCTURE OF THESIS

The following Sections highlight how the structure of this thesis reflects the key aims and objectives of this study.

1.3.1 Chapter 2 – Literature Review

The second Chapter of this thesis presents a review of the key literature that was considered to be relevant to this research project. This review explores:

1. The background to the UK's urban drainage problems
2. Conventional rehabilitation strategies that are generally employed to address these problems
3. The concept of sustainable water management
4. A range of alternative urban drainage rehabilitation strategies that are collectively known as Sustainable Urban Drainage Systems (SUDS)
5. The issues associated with implementing retrofit SUDS to a UK context

1.3.2 Chapter 3 – Gipton catchment

Chapter 3 investigates the implementation of retrofit SUDS to the Gipton catchment, the first of the two case-study catchments explored in this thesis. The main objectives of this investigation were to evaluate the potential for applying retrofit SUDS to this catchment, and to establish whether such measures could be used to eliminate the catchment's hydraulic problems. The secondary aims of this investigation were to develop preliminary design, costing and modelling methodologies for retrofit SUDS, that could subsequently be applied to the second of two case-study catchments, and ultimately used to derive a set of design guidelines for retrofit SUDS applications.

1.3.3 Chapter 4 – Design issues

Chapter 4 reviews the design issues that are considered to influence the viability of retrofit SUDS applications. This Chapter seeks to build upon the lessons learnt from the Gipton study, and the other SUDS studies highlighted in Chapter 2, in order to comprehensively explore the design issues associated with retrofit SUDS. The primary aims of this Chapter are to establish a list of factors that most influence the viability of retrofit SUDS (in terms of different technologies and applications), and to define basic guidelines for their design. These design

guidelines are subsequently applied to the Meanwood catchment, the second of the two case study catchments, in order to establish best-case catchment coverage scenarios for individual SUDS technologies.

1.3.4 Chapter 5 – Modelling issues

Chapter 5 presents modelling techniques that were developed to simulate the hydraulic performance of retrofit SUDS schemes. At the time these investigations were conducted, none of the main commercial urban drainage models contained direct procedures for the simulation of SUDS devices. The work presented in this Chapter assesses the potential for applying the HydroWorks model (Wallingford Software, 1994) to represent the hydraulic performance of retrofit SUDS. The Chapter reviews a number of alternative options for modelling retrofit SUDS using HydroWorks, and applies the most appropriate of these to the Meanwood catchment.

1.3.5 Chapter 6 – Economic issues

Chapter 6 develops methodologies for calculating the construction costs of a range of retrofit SUDS technologies. These costing methodologies are subsequently applied to the Meanwood catchment. Costs are presented in unit terms (i.e. per SUDS device) and for specific SUDS schemes (i.e. that serve a designated part of the Meanwood catchment).

1.3.6 Chapter 7 – Decision making framework

Chapter 7 presents a 'decision making' framework/methodology that develops the lessons learnt in the preceding Chapters. The methodology also draws from other work reported in Chapter 2 (Literature Review) and technical guidance provided in relevant UK design guidelines (CIRIA C522, 2000; CIRIA 124, 1992; CIRIA 156, 1996; BRE 365, 1991). This tool intends to address some of the problems/difficulties that were encountered whilst performing design work in conjunction with the case study catchments. It is envisaged that this framework could be used as a design tool to assist designers/engineers compile both retrofit SUDS and integrated (SUDS/conventional) solutions for comparison with conventional storm water management solutions. This design methodology is subsequently applied to the Meanwood catchment, and its performance assessed.

1.3.7 Chapter 8 – Conclusions and Recommendations for further work

Chapter 8 seeks to summarise the research that was undertaken in this thesis, draw a number of conclusions and highlight the potential for further work.

2 LITERATURE REVIEW

2.1 INTRODUCTION

This Chapter presents the literature review that was undertaken in conjunction with this thesis. Section 2.2 explores the background issues associated with problem urban drainage catchments in the UK. Section 2.3 investigates the conventional rehabilitation strategies generally employed to address urban drainage problems. Section 2.4 introduces the concept of sustainable water management, and Section 2.5 presents a range of alternative (more sustainable) stormwater rehabilitation devices that are collectively known as Sustainable Urban Drainage Systems (SUDS). Sections 2.6 and 2.7 investigate the issues associated with implementing SUDS technologies (in respect to global and UK contexts). Section 2.8 explores uncertainties associated with the hydraulic effectiveness of SUDS. Section 2.9 explores the cost/benefit issues associated with SUDS technologies, and Section 2.10 presents cost/benefit case studies for SUDS technologies.

2.2 BACKGROUND

2.2.1 Historical development of sewer systems within UK

Many of the UK's urban drainage systems date back to the Nineteenth Century. These systems were initially built in the central areas of large towns and cities, and were intended to carry surface storm runoff, industrial effluent and domestic foul sewage. These drainage systems were later followed by the development of sewage treatment works, which were introduced to improve the quality of wastewater discharged into local watercourses. However, in many cases, the capacities of these sewers and sewage treatment facilities were not sufficient to meet the demands of these growing cities. This led to the introduction of in-sewer detention tanks, and overflow structures to discharge excessive storm flows directly into receiving waters, without having to pass through the treatment works.

2.2.2 Basic definitions

Combined Sewer System (CSS) – Around 70% of the sewers in the UK are combined sewer systems (Andoh and Declerck, 1997). 'Combined' systems carry both foul sewage and storm water runoff (Figure 2.1). Most combined sewers were constructed at a time when it was considered acceptable to discharge untreated raw sewage directly into rivers. Today, it is customary practice for combined sewer flows to be treated at wastewater treatment plants. However, during heavy rainfall events wastewater treatment plants typically lack the capacity to treat all the flow conveyed through the sewer system. In such circumstances, excess flow is discharged directly to a receiving watercourse.

Combined Sewer Overflow (CSO) – CSOs are designed to prevent flooding from combined sewer systems by allowing excess flow to pass directly from the system into receiving

watercourses. Such overflows typically discharge during, or shortly after, periods of heavy rainfall, when it is hoped that foul sewage in the system is well diluted with surface water, and that levels within the receiving waters have also risen.

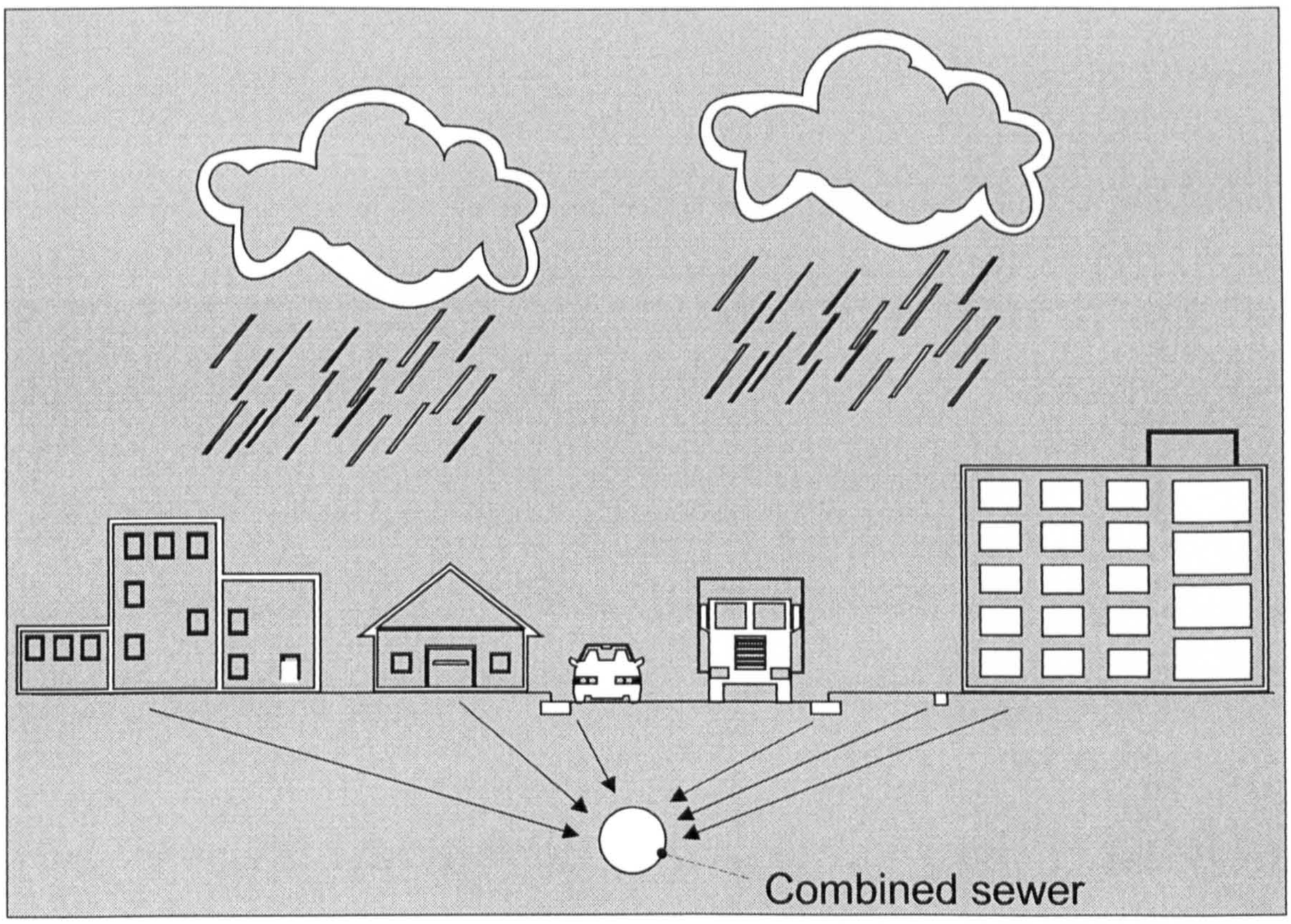


Figure 2.1 Combined sewer system

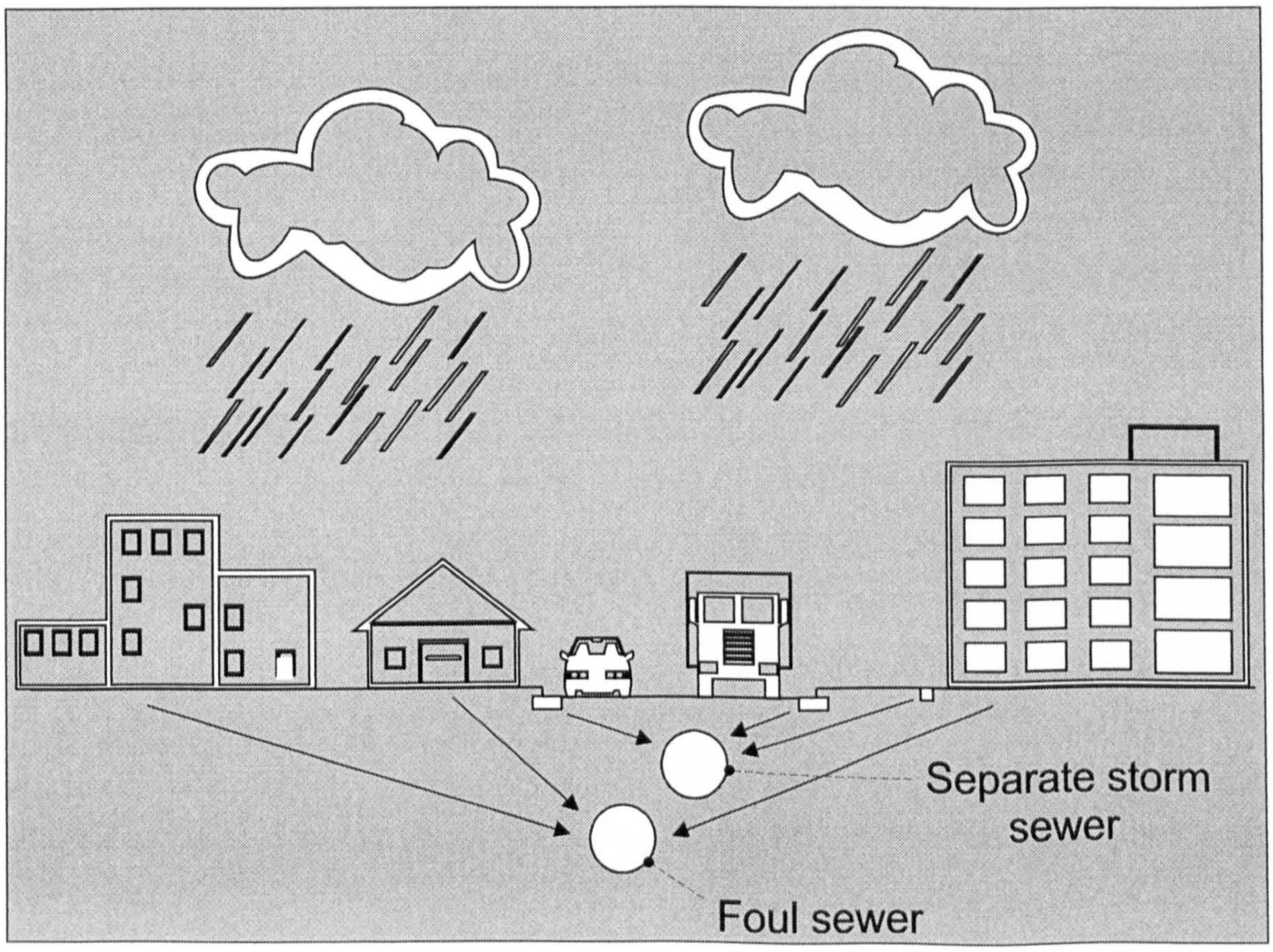


Figure 2.2 Separate sewer system

Bypass sewers – The by-pass sewer is another technique that has been adopted to address the problems of insufficient capacity within urban sewer systems. Such structures are generally

constructed in order to divert flows around overloaded sewer sections. However, this approach can often lead to problems being passed downstream through the system.

In-sewer Storage tanks – The use of in-sewer storage facilities to detain excessive storm flows has been an established practice since the early 1980s. Storage facilities may be used to control excessive storm flows upstream of problem sewer sections. The use of such storage can alleviate network flooding/surcharging and excessive CSO emissions. However, storage facilities are not without their own problems, these problems largely relate to the high costs associated with construction (i.e. due to their large volume, and location) and maintenance (i.e. due to sedimentation within the tank).

Separate Sewer System (SSS) – Separate sewer systems were developed to address some of the hydraulic and environmental problems associated with the traditional combined sewer systems. In a 'separate system' foul sewage is conveyed to treatment via a separate network to that which is used for the collection of storm water runoff (Figure 2.2). This avoids the discharge of untreated foul effluent into receiving watercourses during storm conditions. Separate Sewer Overflows (SSO) are generally used to convey excessive surface runoff directly to local watercourses.

2.2.3 Problems associated with conventional sewer systems

There are a number of problems associated with the use of conventional urban drainage systems. Most of these are the result of insufficient capacity during extreme storm events – and are exhibited in the form of excessive CSO/SSO emissions and network flooding/surcharging.

2.2.3.1 Problems associated with CSO/SSO emissions

The main problems associated with excessive CSO emissions from overloaded combined sewer systems are outlined below:

1. Health Problems – A variety of pathogens are present within raw sewage; and depending on rates of exposure and concentration, these may cause illness. Although sewage overflows are diluted by rain and river water, they may still represent a slight health hazard (FWR 1994).

2. Aesthetic Problems – Another major problem associated with CSO discharges is the release of unsightly material (e.g. condoms, sanitary towels) into the natural environment (Saul, 1997). This produces obvious public concern, and complaints to the responsible water authority.

3. Environmental Problems – Combined sewer overflows contain a variety of organic, chemical and industrial wastes. If the concentrations, or spill frequencies, of CSO discharges are significantly high then the receiving water and its aquatic life may be harmed.

Discharges from separate sewer systems can also pose pollution problems within receiving watercourses – especially in catchments with a high number of foul water misconnections into the surface water system, or where high levels of surface pollutants are conveyed into the stormwater sewer system.

It is evident, that in light of these problems, there are obvious benefits to be gained by eliminating, or limiting, CSO discharges. The main legislative issues associated with the control

of CSO discharges are discussed in Section 2.2.5, and the main design and planning strategies used to meet these standards within the UK are presented in Section 2.3.

2.2.4 Sewer Flooding/Surcharging problems

Network flooding and surcharging are further problems often associated with overloaded separate and urban combined sewer systems. These problems generally occur when the hydraulic capacity of the system is exceeded during extreme storm conditions. Flooding or surcharging events are considered problematic when they occur on a regular basis. This largely relates to the health risks associated with flooding from combined sewer networks, but also reflects the damage to property and general inconvenience that can result from flood events from both combined and separate sewer networks.

Acceptable levels of surface flooding from UK urban drainage systems are defined and monitored by levels of 'performance' and 'service' parameters.

Level of performance criteria – are used by design engineers to define unacceptable frequencies (in terms of design storms) for flooding or surcharging events from a given drainage system (See Table 2.1 and Table 2.2).

Level of service criteria – Monitored performance of drainage system in terms of actual recorded surface flooding.

CIRIA report 124 (1992) and the Sewer Rehabilitation Manual (WRc 1994) recommend acceptable 'levels of service' (See Table 2.1 and Table 2.2). Drainage systems with 'Levels of service' that do not conform to these criteria should be upgraded through appropriate remedial works. Recommendations on how such remedial works should be undertaken are presented within the Sewer Rehabilitation Manual (WRc 1994) (See Section 2.3.3).

Table 2.1 Suggested design 'levels of performance' criteria for stormwater drainage systems (CIRIA Report 124, 1992)

Land use	Design level of performance	Comments
Residential development	1 in 25 year	
Public open space	1 in 1 year 1 in 10 year	Dependent upon use
Non-domestic residential	1 in 25 years	Hotels, Hostels, etc
Retail trading, offices, industrial areas	1 in 25 years	

Table 2.2 Example Performance Criteria (Sewer Rehabilitation Manual, WRc 1994)

Aspect	Level		
	Trigger for early rehabilitation	*Target for upgrade*	*New design*
PUBLIC HEALTH Flooding Frequency: i) Inside occupied premises ii) Streets	 Twice in 10 years Twice per year	 1 in 30 years 1 in 20 years	 1 in 50 years 1 in 25 years
STRUCTURAL Frequency of Surcharge	N/A	1 in 1 year	1 in 2 years
RECEIVING WATER QUALITY CSO Operation	Unsatisfactory CSOs		

2.2.5 Legislative context

The UK is required to comply with EU water quality directives: these directives are usually incorporated into UK law. Within England and Wales, laws that relate to issues such as land drainage and the control of pollution within inland and coastal waters are established by Acts of Parliament. These acts establish a general framework, and provide authority to the Secretary of State to issue more specific regulations. However, where regulations are not made, as is the case for discharges into and from surface water sewers, then interpretation of the law is more difficult.

In practice, the sewer owners (e.g. the privatised water companies, the Scottish water authorities) and their environmental regulators (e.g. Local Authorities, the Environment Agency and the Scottish Environment Protection Agency) are responsible for administering the provisions of these Acts. This is achieved, in respect of the control of intermittent discharges, through the granting of consent orders, which impose limits upon the concentrations, volumes and rates of effluent that may be discharges through any given CSO/SSO.

2.2.5.1 Legislation – CSO Emissions

The Water Framework Directive (EU, 2000) is considered to be the most significant piece of international legislation that has been published in relation to the field of water management in recent years. This directive, unlike the Urban Wastewater Treatment Directive (UWWTD) described below, takes a more holistic view of water management, and may be applied to a large swath of the natural water cycle ranging from inland surface waters, groundwater, estuarine and coastal waters. Its three key objectives are: i) the prevention and enhancement of aquatic ecosystems/associated wetlands; ii) addressing the effects of floods and droughts; iii) the promotion of more sustainable water consumption patterns. These driving principles have been summarised by the single overriding objective of achieving good status in all waters (Chave, 2001).

The Water Framework Directive (EU, 2000) adopts the guidance provided in the Urban Wastewater Treatment Directive (UWWTD) (Directive 91/271/EEC, 1991) for the management of surface waters. The Water Resource Act (HMSO, 1991) and the Urban Waste Water Treatment Regulations (UWWTR) (HMSO, 1994) apply the UWWTD in the context of England and Wales. These acts adopt the following criteria to help define and control problem CSO emissions:

1. A dilution ratio between the quality of the sewer flow and that in the receiving watercourse

2. The capacity of the sewer system in relation to the dry weather flow

3. A specified number of overflows per year.

A guidance note on the UWWTR issued by the Department of the Environment in 1997, endorses the use of the UPM Manual (FWR, 1994/1998) as an appropriate planning tool for sewer and sewage treatment improvements within England and Wales. The UPM Manual is reviewed in Section 2.3, alongside a number of other conventional stormwater management

strategies. These tools are widely used by UK water companies to help achieve the improvements in CSO discharges, and river quality, required as part of the government's AMP (Asset Management Programme) periodic reviews of the privatised water companies. The third Periodic Review (AMP3), which covers the five-year period between 2000 and 2005, seeks an improvement in discharges from 3,800 unsatisfactory CSOs that pollute nearly 3,600 km of rivers.

2.2.5.2 Legislation – Land drainage/Urban Flooding

The legislation relating to drainage practices within England and Wales is complex. Few SUDS were in operation within the UK when this legislation was introduced, and as a result SUDS are not addressed directly. The following extract from CIRIA report 124 (1992) briefly outlines the legislation that relates to land drainage:

> The procedure for the approval of a planning application submitted in accordance with the requirements of the Town and County Planning Act 1990 provides the facility for informing the public and initiates a check of the drainage proposals by the relevant authorities. This check should ensure that the proposals meet the requirements of the Public Health Acts 1936 and 1961, the Land Drainage Act 1976, the Water Acts 1973 and 1989, the Control of Pollution Act 1974 and the Highways Act 1980.

See Volume 4 of CIRIA report 124 (1992) for further details.

CIRIA report C552 (2000) presents a more up-to-date list of legislation that affects the implementation of SUDS devices:

Highways Act (1980)
Sewers for Adoption (WRc, 1985)
Sewer Act (1989)
Town and Country Planning Act (1990)
Environment Protection Act (1990)
Water Industry Act (1991)
Water Resources Act (1991)
Land Drainage Acts (1991, 1994)
Environment Act (1995)
Policy and Practice for the Protection of Groundwater (EA, 1998)

See CIRIA reports C521, C522 and C523 (2000) for further details.

It should be noted that a new edition of Sewers for Adoption was published in 2001. This edition acknowledges the potential role of SUDS technologies in stormwater management, but excludes the approach from its recommended procedures due to uncertainties associated with their design, ownership and maintenance. The revised guidelines (WRc, 2001) also point out that sewer undertakers are generally only constrained to accepting pipe systems when adopting drainage from new developments.

2.3 CONVENTIONAL STORMWATER MANAGEMENT STRATEGIES

2.3.1 Introduction

There are three key publications that relate to the design of sewer rehabilitation schemes for the UK:

1. Urban Pollution Management (UPM) Manual (FWR, 1994/1998)
2. The Sewer Rehabilitation Manual (WRc, 2002)
3. FR0488 guidelines – Guide to the design of CSO structures (FWR, 1994)

A brief review of each of these publications is presented within the following Sections.

2.3.2 Urban Pollution Management (UPM) Manual

2.3.2.1 Definition

'Urban pollution management' has been defined as the management of wastewater discharges from urban sewer and sewage treatment facilities under wet weather conditions (taken from the UPM manual; FWR, 1994).

2.3.2.2 Purpose of UPM

The UPM manual was initially compiled in 1994 with the intention of creating a cost-effective strategy that could adequately protect natural receiving waters against pollution, without the over provision of storage or treatment capacity. Since then the UPM methodology has been developed and refined, by way of a second edition that was published in October 1998. The second edition presents a similar set of design procedures for the development of cost-effective sewer systems, but adopts a more generic tone than the original manual.

The UPM guidelines were developed through consultations with regulatory agencies (e.g. the National Rivers Authority, now part of the Environment Agency), and regulated bodies (e.g. water companies). This cooperative approach was adopted in order to help promote the UPM procedures as a standard tool within the UK water industry, and to promote common understanding for future negotiations between these two groups.

2.3.2.3 UPM manual – Basic Procedure

The basic methodologies described within the First and Second editions of the UPM manual (FWR, 1994 and 1998) are very similar (Table 2.3). Both methodologies start with an initial problem identification phase, then progress to data collection, model building, development and testing of a solution, and conclude with post planning issues, such as obtaining consents and undertaking detailed designs.

Table 2.3 Comparison of UPM Procedures: 1st and 2nd Editions

	UPM 1st Edition (1994)	UPM 2nd Edition (1998)
Phase A	Initial planning	Initial planning
Phase B	Assembling data and tools	Construct UPM tools
Phase C	Developing solutions	Test compliance
Phase D	Consenting and detailed design	Post planning study issues

The following Sections provide an overview of the UPM methodology using the original framework. Significant differences between the procedures contained within the 1st and 2nd editions of the UPM Manual (FWR, 1994/1998) are highlighted:

Phase A – Initial planning: The initial phase relates to assessing the existing 'wet weather' pollution problem; particularly in terms of the impacts that CSO discharges have upon receiving waters. This assessment is difficult to perform, as intermediate discharges are difficult to monitor, and their effects are usually of a short-term nature. The manual suggests a number of steps that can be taken to investigate the extent of such pollution problems. These procedures should indicate whether a problem is severe enough to be addressed. The manual recommends that environmental criteria be agreed between the quality regulator (e.g. the Environment Agency) and the sewer operator; these criteria should form the basis for the subsequent management and planning phases. These standards will typically define the level of performance required of the sewer and sewage treatment works (STW) to prevent harm to receiving waters. The stringency of these standards usually relates to the nature of the receiving water and its pattern of usage. Once these environmental standards have been established, decisions may then be made regarding the particular data and tools required to analyse the system.

Phase B – Assembling data and tools: The manual recommends that this phase involves the compilation of appropriate data (e.g. population and low river flow conditions) and of the tools/models required to simulate the wet weather performance of the urban drainage system. A number of techniques are suggested. These range from the use of simplistic models, such as SIMPOL (see Section 2.7), through to detailed deterministic urban drainage models such HydroWorks/InfoWorks (see Section 2.7). The second edition of the UPM manual is less prescriptive with regards to which specific urban drainage models should be adopted for this task, and recognises that a wide range of modelling packages is available. The second edition also contains guidance on the practical aspects of field data collection for the calibration and verification of detailed models.

Phase C – Development of solutions: UPM recommends that this phase should lead to the definition of appropriate environmental standards for the release of wastewater to receiving waters. Typical values representing ambient conditions (e.g. rainfall events, upstream flows and quality) are assigned for use with the modelling tool developed in phase B. This tool may then be used to simulate the performance of the system, and to compare this with the designated environmental standards. Repeating this process for different input data sets enables alternative solutions to be compared, and for the best solution to be ascertained.

The UPM methodology typically promotes the use of in-sewer storage facilities, or improved CSO screening, to address the problems associated with excessive CSO discharges. However, the UPM methodology does not rule out the use of SUDS-based solutions – i.e. provided that compliance can be demonstrated with the relevant performance criteria highlighted in Section

2.2. It is therefore important that relevant background data and models be collected in order to establish/simulate the performance of such SUDS-based proposals.

Phase D – Obtaining consent and detailed design: This phase should involve the application process for formal consent to discharge and the granting of appropriate consent conditions. The UPM procedure requires that this should be received before detailed engineering design works are undertaken.

2.3.2.4 Water quality standards

The UPM manual presents two sets of water quality standards for the protection of freshwater aquatic life from wet-weather pollution episodes.

- *Intermittent standards (Section 2.3.2.5)* – these are directly related to the characteristics of spill events that cause problems to river ecosystems. These standards are usually expressed in terms of concentration-duration thresholds with an allowable return period or frequency
- *High percentile standards (Section 2.3.2.6)* – these are based on 90/95 percentile water quality thresholds that are selected for the protection of river ecosystems.

2.3.2.5 Intermittent Standards

Discharges from CSOs are intermittent in nature, and the pollution resulting from them may have a range of harmful effects. Pollution problems may either be caused by acute incidents, which last for short periods of time, or by less severe incidents which are prolonged over the longer term. In response to this, the first UPM manual (FWR, 1994/1998) outlined a set of standards that have been developed to ensure protection of river aquatic life during short-term pollution events. These standards are often referred to as Fundamental Intermittent Standards, and are typically expressed in terms of DO and unionised ammonia (i.e. two parameters which have a significant impact upon the survival of aquatic life). However, as these are difficult parameters to deal with in practice, BOD and total ammonia are commonly used in their place. The second edition of the UPM manual contains a more comprehensive range of Fundamental Intermittent Standards than the original manual.

2.3.2.6 High percentile standards

The second edition also pays a greater emphasis to the potential use of high percentile standards. This relates to the fact that regulatory bodies, such as the Environment Agency, often specify percentile-based water quality standards to define river use classifications – e.g. the Rivers Ecosystem Classification (FWR, 1994). These standards include constraints for BOD, dissolved oxygen (DO), total ammonia and un-ionised ammonia, which are expressed in terms of percentile values (90 or 95 percentiles for BOD, ammonia and un-ionised ammonia and 10 percentiles for DO) – examples of percentile-based river quality standards are presented within Table 2.4.

Table 2.4 Example percentile-based river quality standards (FWR, 1994)

Class	Dissolved Oxygen % saturation 10 percentile	BOD (ATU) mg/l 90 percentile	Total ammonia mg N/l 90 percentile	Un-ionised Ammonia mg N/l 90 percentile
RE1	80	2.5	0.25	0.021
RE2	70	4.0	0.6	0.021
RE3	60	6.0	1.3	0.021
RE4	50	8.0	2.5	-
RE5	20	15.0	9.0	-

Note: Recommended standards for pH, Hardness, Dissolved Copper and Total Zinc are not illustrated.

2.3.2.7 Summary of UPM procedure

The UPM procedure is one the UK's main urban drainage planning tools for the protection of river quality/control of CSO discharges. It is claimed that these procedures significantly reduce the level of uncertainty associated with water quality impacts from proposals that are derived by traditional planning methods (Gent *et al.,* 1996).

The UPM methodology is widely used by UK's water industry and is endorsed by regulatory bodies (e.g. EA and SEPA) as a means of defining CSO discharge consents, and subsequently is of considerable importance to the application of retrofit SUDS in a UK context.

2.3.3 The Sewer Rehabilitation Manual (SRM) (WRc, 2002)

The Sewer Rehabilitation manual (WRc, 2002) was compiled for designers and planners involved with the rehabilitation of UK sewer systems. The manual contains a set of procedures and guidelines that were intended to assist the decision making process associated with such works. The aims of the Sewer Rehabilitation Manual (WRc, 2002) methodology are described as being able to produce:

1. Significant cost savings in necessary rehabilitation works
2. The ability to control the growth of future rehabilitation costs as the network gets older
3. The means of quantifying and justifying the financial requirements for future upgrading programmes

The SRM seeks to meet these aims by focusing investigation and planning resources on to 'core areas' within the sewer system. The term 'core area sewer' is used to describe: i) critical sewers where the consequences of structural failure are severe; ii) sewers where hydraulic performance problems are severe; and iii) other sewer sections that link the two previous types of sewer.

The Sewer Rehabilitation Manual (WRc, 2002) recommends the investigation of structural condition, hydraulic (e.g. flooding or surcharging problems) and environmental performance (e.g. CSO discharges) associated with each system. This approach is termed a 'full investigation' (Figure 2.3) and should lead to the development of a long-term 'drainage area plan' covering all 'identified needs' for the system.

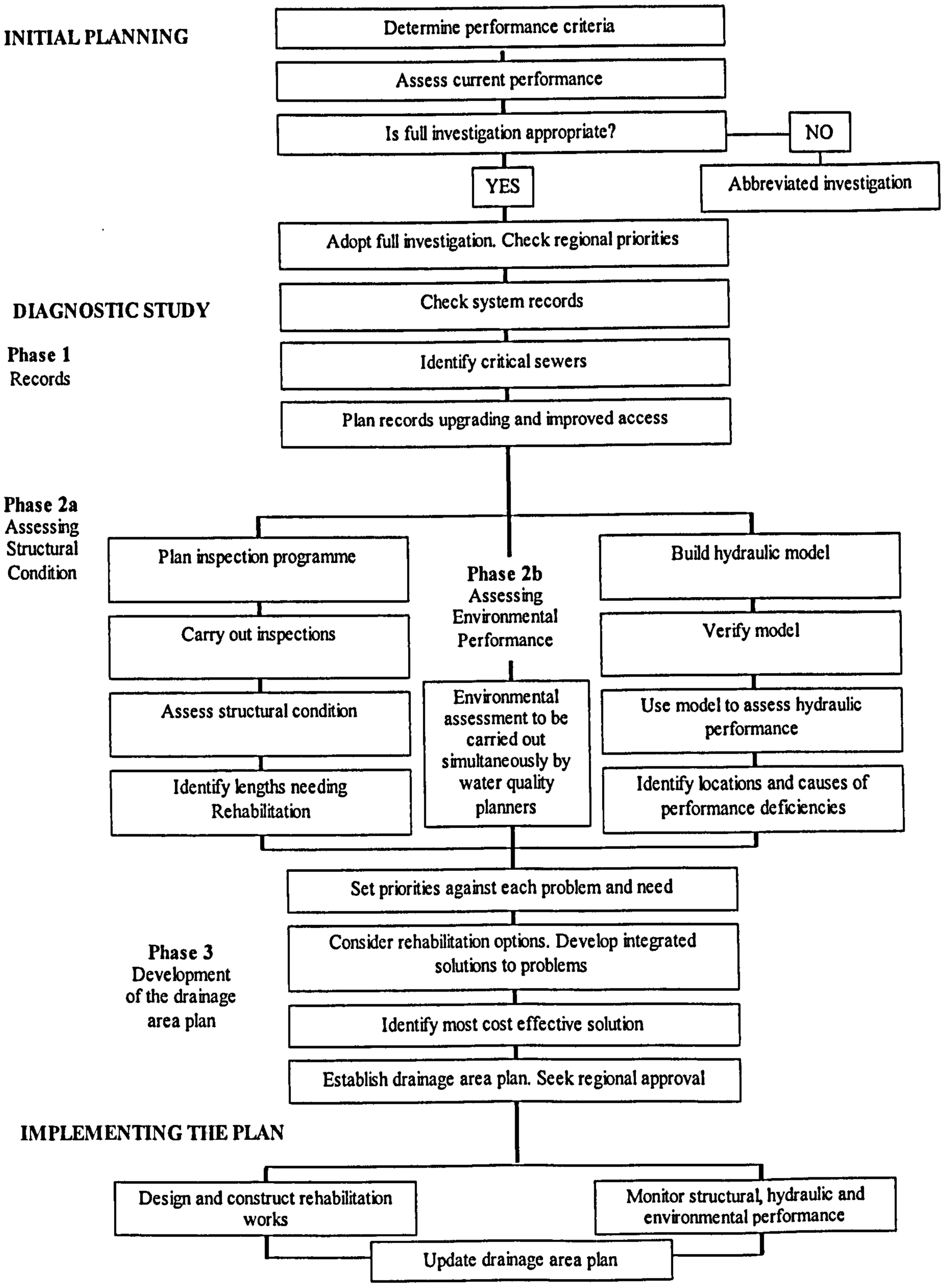


Figure 2.3 Sewer Rehabilitation Manual – Full investigation procedure (WRc, 1994)

It should be noted that although Phase 3 of the SRM procedure is generally used in practice for comparison of conventional rehabilitation proposal (e.g. upgrading in-sewer storage, or CSO facilities) there is no real reason why it could not be extended to include SUDS-based options (See Section 2.5). Phase 3 of the SRM procedure uses the term 'development of integrated solutions', to imply the combined use of different conventional sewer rehabilitation strategies (e.g. in sewer storage, upgrading CSOs and re-sewering). However, once again, there is no reason why this guidance could not be extended to include SUDS-based options.

2.3.4 FR0488 CSO design guidelines

The FR0488 guidelines (FWR, 1994) are widely used within the UK water Industry for the design of CSO structures. These guidelines complement the SRM (WRc, 2002) or UPM (FWR, 1994/1998) planning guidelines – both of which can be used to define 'acceptable levels' for CSO discharges. The FR0488 procedure specifically addresses the design of CSO structures – in order to meet the discharge targets specified by either the SRM (WRc, 2002) or UPM (FWR, 1994/1998) planning guidelines. These guidelines utilise the 'Formula A' methodology for defining CSO overflow settings (See Section 2.3.4.1).

It is worth noting that these guidelines have since been superseded by WaPUG's guide on 'The Design of CSO Chambers to Incorporate Screens' (WaPUG, 2001).

2.3.4.1 CSO design guidelines - Formula. A

The fundamental design parameter for CSO structures is the overflow setting. This defines the flow rate at which the CSO will start to spill. CSO settings were traditionally designed with reference to the downstream sewer sections, and the flow volumes that were appropriate to 'pass forward'. This led to the adoption of fixed pass-forward flow criteria, such as the 'Formula A' methodology (MHLG, 1970):

$$Q_c = DWF + 1360P + 2E \qquad \textbf{(Equation 2.1)}$$

Where: Q_c - *the continuation flow,*
DWF - *dry weather flow (l/day),*
P - *population,*
E - *industrial effluent (l/d)*

2.3.4.2 Alternative CSO design guidelines - SDD methodology

The Rivers Pollution Prevention Sub-Committee of the Scottish Development Department (SDD, 1977) presented a simplified design approach for establishing CSO settings that was based upon 'available dilution' within the receiving watercourse. This dilution parameter is calculated in relation to dry weather flow sewer effluent and minimum stream flow at the point of discharge (i.e. the mean daily discharge that is exceeded on 95% of occasions). The guidelines are presented in Table 2.5.

Table 2.5 Design guidelines for storm overflow installations (SDD, 1977)

Minimum dilution in terms of 95% exceedence mean daily discharge in receiving water course and sewer DWF	Approx. percentage of total polluting load of storm sewage spilled from sewer that may be discharge to stream (%)	Type of storm overflow installation
8	100	Overflow setting = Formula A, no tank
6	75	Overflow setting = Formula A + 455P, no tank, if sewer capacity available. Alternatively adopt next recommendation
4	50	Overflow setting = Formula A + tank of capacity 40 l per head.
2	25	Overflow setting = Formula A + tank of capacity 80 l per head.
1	12	Overflow setting = Formula A + tank of capacity 120 l per head.

This methodology defines a CSO setting that is equivalent to that calculated by Formula A, plus an additional storage volume of between 40 and 120 litres per head. The level of additional storage required is determined by the available dilution. Storage capacities within this range would typically store between 50 and 80% of the excess flow.

The SDD method does not predict the impact upon receiving watercourse – it simply attempts to reduce the impacts of spill discharges to acceptable levels. Whether this is achieved depends on the capacity or amenity classification of the receiving river. The SDD (1977) design guidelines generally produce more conservative solutions than the FR0488 methodology.

2.3.5 Review of conventional stormwater management strategies

It should be noted that all three of the conventional stormwater management strategies reviewed within this Section largely focus upon hard-engineering solutions, such as the construction of additional in-sewer storage facilities. However, this thesis seeks to demonstrate that in many cases innovative urban drainage technologies, which have been broadly classified as 'SUDS', provide a viable alternative. The following Section briefly introduces the concept of 'sustainable' stormwater management. Section 2.5 explains what SUDS are, whilst Section 2.6 explores the issues associated with retrofitting SUDS to urban catchments.

2.4 SUSTAINABLE STORMWATER MANAGEMENT

2.4.1 Sustainable development

"Sustainable development is that which meets the needs and aspirations of the present generation without compromising the ability of future generations to meet their own needs".

The Brundtland Report (WCED, 1987)

The subject of 'sustainable development' has received much attention in recent years. The global importance of this issue was highlighted by the findings of the Brundtland Report (WCED, 1987), and later reiterated at the Rio Conference in 1992 (United Nations, 1992). 'Sustainability' is consequently seen as having an important role to play with respect to the future of urban development. However, there has been some debate as to what the term 'sustainable' actually means in practice (Laursen and Gujer, 1997; Chen and Beck, 1997). Much of this confusion relates to the multidisciplinary nature of the topic. The popular view is that 'sustainability' is solely an ecological issue. However, this ignores the fact that a diverse range of social, economic and technical issues also impact the natural environment (Brooks, 1992).

Chen and Beck (1997) describe 'sustainability' in terms of an economic analogy, as a condition where the present generation bequeaths the next generation no less capital than it currently holds. This again, illustrates that 'sustainability' can be defined by any number of different criteria – since the term 'capital' in this analogy may be considered to represent a number of different factors (e.g. monetary, technological or environmental). It has been argued that 'sustainability' can be pursued to varying degrees; in its most rigorous form this would involve

the consideration of a large number of sustainability criteria, whilst its weakest would only consider those that are easily achievable (Chen and Beck, 1997).

It is therefore difficult to draw a precise definition for the word 'sustainability' from the current literature. However, there is broad agreement that the term 'sustainable development' implies characteristics such as durability, endurance and stability (Butler and Parkinson, 1997; Jeffrey *et al.*, 1997; WCED, 1987).

2.4.2 Sustainable urban water management

2.4.2.1 Background

It is debatable whether urban water management is, or can ever be, a truly sustainable technology (Laursen and Gujer, 1997). Indeed, it has been argued that since it may never be possible to derive a completely sustainable urban drainage system, resources would be better spent on identifying the least sustainable elements of conventional drainage systems and seeking to replace them with more sustainable alternatives. The benefits of such an 'incremental response' to the 'sustainability' question are that it avoids major economic, technical and logistical problems, which would otherwise be incurred by making dramatic changes to existing pieces of urban infrastructure (Butler and Parkinson, 1997).

2.4.2.2 Reported aims of sustainable urban water management

There have been a number of different reported aims for sustainable urban water management schemes over the last decade, and these have focused upon a wide variety of issues. Much attention has been given to the ecological aims of sustainable urban water management (Andoh, 1995; Kaiser, 1997; Niemczynowicz, 1994). Other proposed objectives that have been discussed in connection with sustainable urban water management relate to a range of economic, social and technical issues (Andoh and Declerck, 1997; Harremoes, 1997; Varis and Samlyody, 1997), and have addressed issues such as user acceptance, affordability and appropriateness.

There has also been some discussion as to whether 'flexibility' should be the prime characteristic of a truly sustainable technology (Jeffrey *et al.*, 1997). This is based on the premise that the challenges facing a system in the future may significantly differ from those it faces today. Therefore, if a system cannot be easily adapted to meet these new challenges, it is not truly sustainable. This may have particular relevance in light of the possible climatic changes that may accompany global warming (Bridgeman and Gregory, 1999; The Guardian, 24th Nov. 1998). This viewpoint is reinforced by Costanza (1996), who suggests that 'sustainability' may be more a matter of prediction rather than definition, since it will only be apparent that a system is truly sustainable at some point in the future.

These proposed objectives have been used to develop a number of more detailed Sustainable Urban Water Management strategies which are discussed in the following Section.

2.4.2.3 Development of Sustainable Urban Water Management strategies

A number of sustainable urban water management strategies have been developed in recent years (Butler and Parkinson, 1997; Krebs and Laursen, 1997; CIRIA Reports C521, C522 and C523, 2000). Unlike design procedures for conventional urban drainage systems, which tend to focus upon the specific issues of 'hydraulic performance' and 'water quality', these sustainable urban water management strategies advocate a more holistic design approach. In CIRIA Reports C521, C522 and C523 (2000) this holistic approach is illustrated by the '**urban triangle**' concept

(Figure 2.4), which views 'amenity value' as being of equal importance to the 'hydraulic performance' and/or 'water quality'. The urban triangle illustrates a key element of the SUDS design manual methodology – i.e. that sustainable systems should seek to balance urban drainage's three main impacts upon the local environment: quantity, quality and amenity (see Figure 2.4).

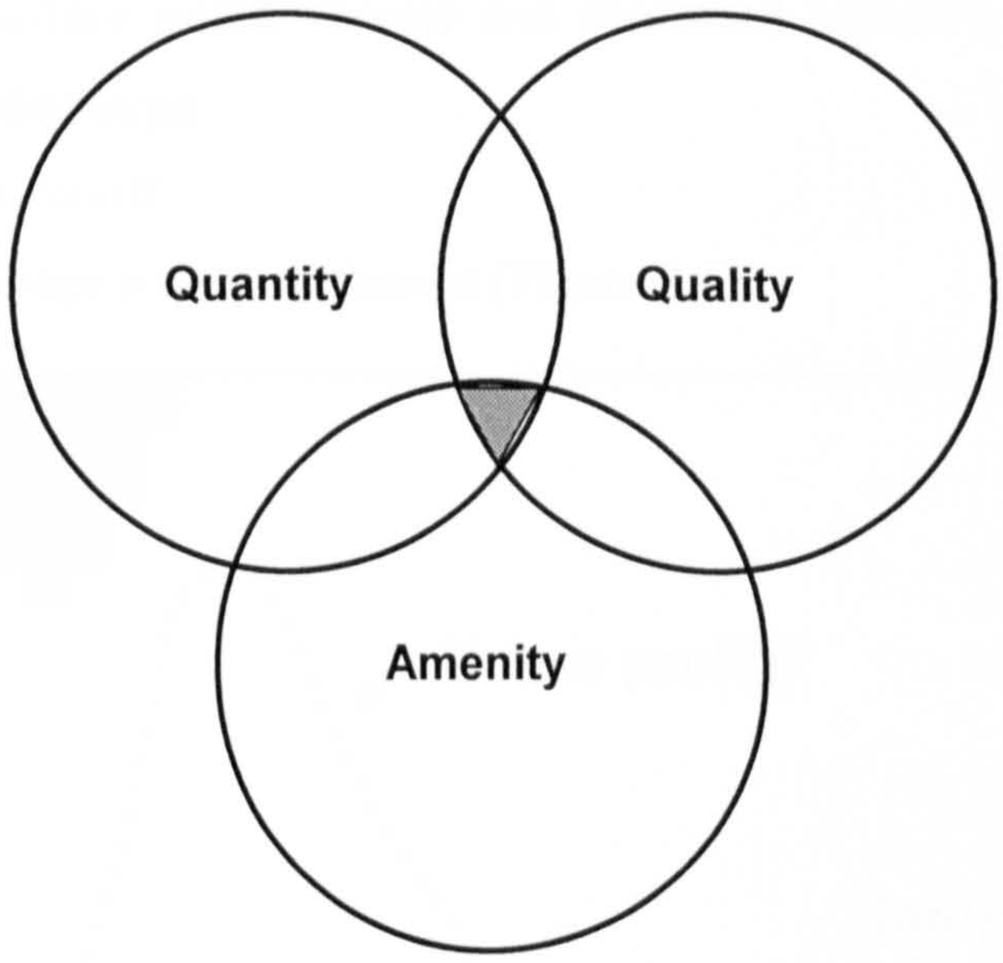


Figure 2.4 The urban triangle (from CIRIA Report C522, 2000) – balancing the impact of urban drainage on the environment

Each component of the urban triangle is briefly discussed within the following three Sections:

2.4.2.4 Quantity

Most urban drainage problems are associated with peak flow conditions within overloaded sewer systems. Traditional solutions to such problems seek to utilise conventional technologies such as upgrading CSO structures, sewer pipes or storage facilities, to detain or divert excessive flows once they are within the sewer system.

Sustainable urban drainage systems aim to alleviate peak flows within overloaded sewers by reducing all inputs (i.e. both foul flows and surface run-off) into the sewer network. The two main mechanisms used to achieve this alleviation of peak flows are: i) the promotion of 'natural catchment' conditions and ii) the reduction of water consumption rates.

The 'Natural catchment' – Natural catchment systems have various features that store and attenuate stormwater runoff before it is released into receiving waters. This mechanism has been

described as the '*natural distributed control system*' (Andoh, 1995). Urbanisation of a catchment disrupts the natural mechanisms that provide this 'distributed control', and as a result causes a number of adverse effects. The progressive urbanisation of a catchment (i.e. the introduction of roads, buildings, car parks, etc.) produces an increase in impermeable surface area. This in turn causes a reduction in the volumes of water infiltrated to the subsoil. Urbanisation will also tend to reduce the capacity of 'depression storage' that is available within a catchment. Similarly, evapo-transpiration will decrease when the urbanisation process involves the removal of vegetation. The cumulative effect of all of these factors will be to reduce the natural storage of stormwater within the catchment and subsequently increase the volumes of runoff entering the drainage system (Andoh and Declerck, 1997).

The idealised response of a natural catchment to a rainfall event is compared with that of an urbanised catchment in Figure 2.5. The main effects of urbanisation are summarised below:

1. Shorter response time (time of concentration) and steeper rising limb of hydrograph
2. Increased surface runoff volume and decreased baseflow contributions – overall increase in discharge
3. Higher peak runoff
4. Reduced storage within catchment (Figure 2.6).

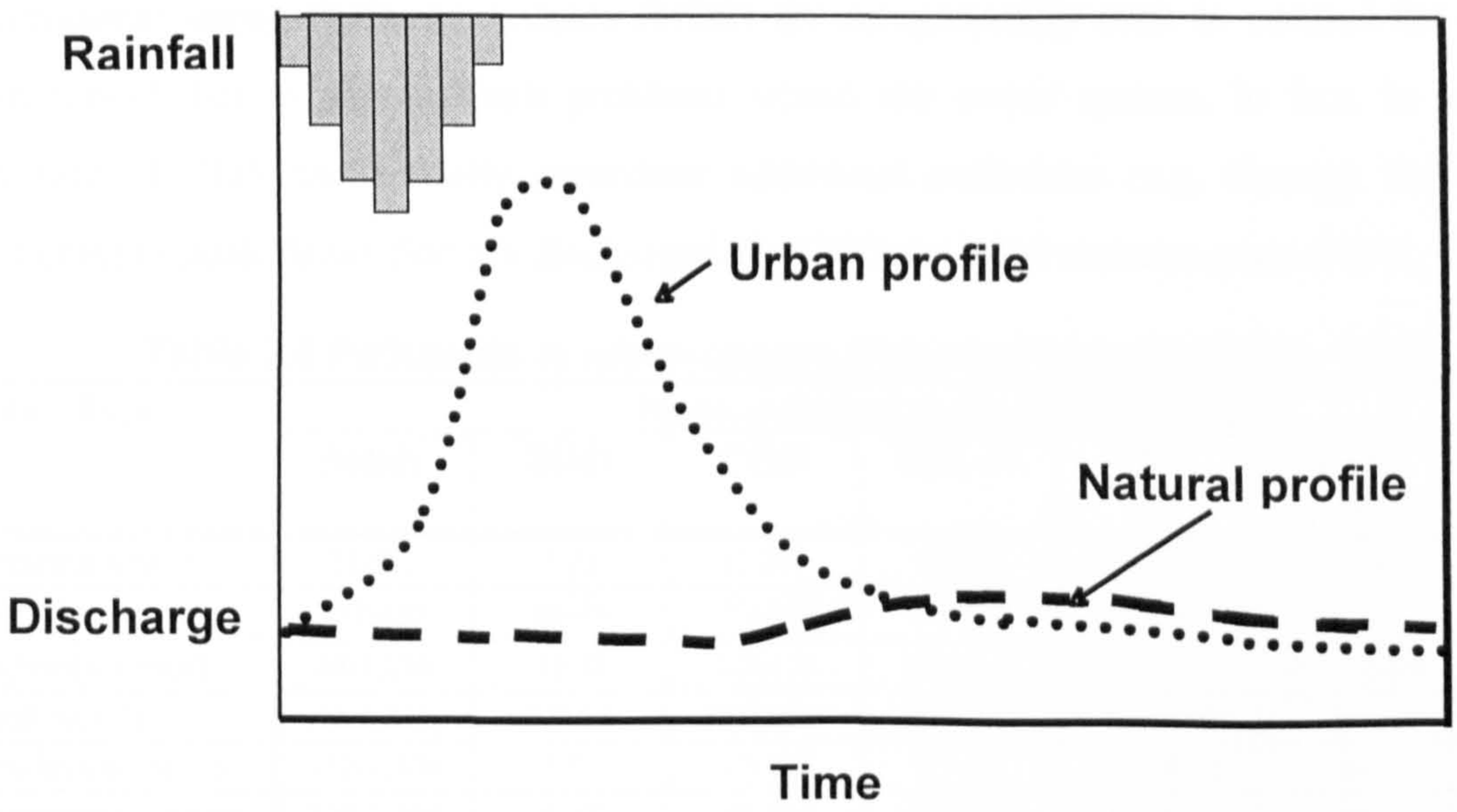


Figure 2.5 Schematic representation of natural and urban catchment hydrographs

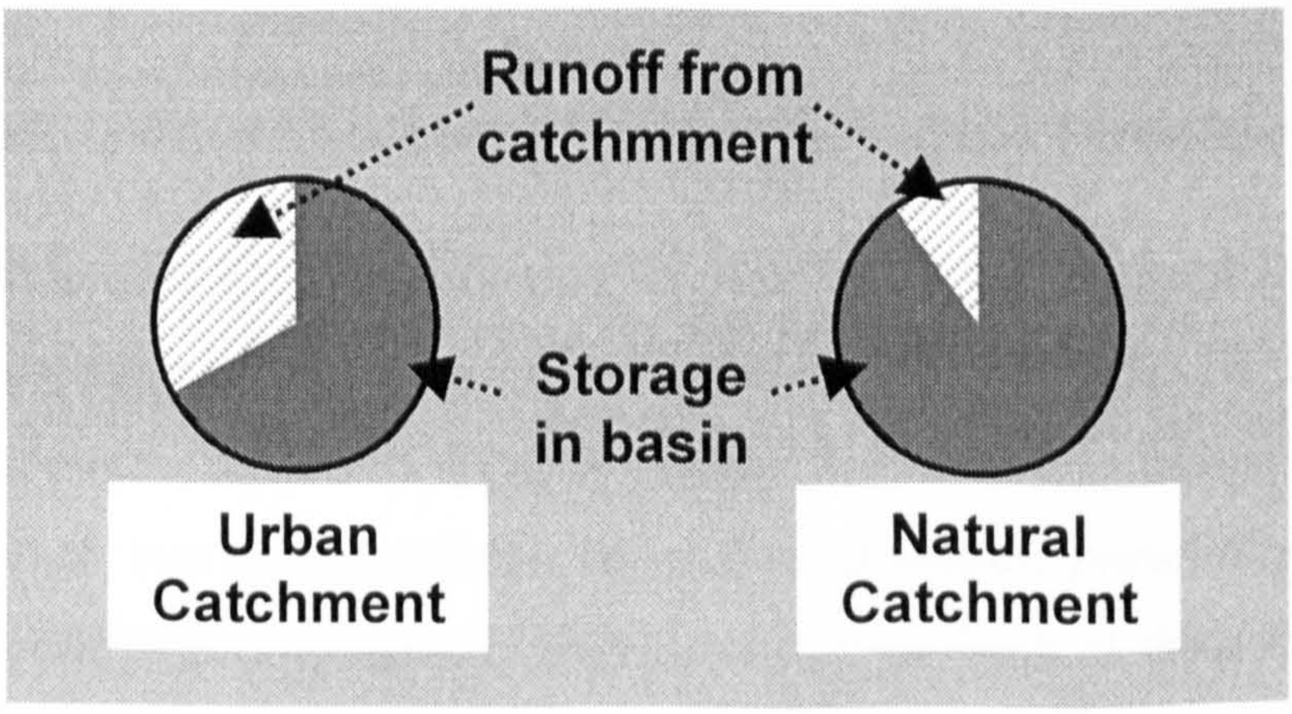


Figure 2.6 Runoff and storage characteristics of typical 'urban' and 'natural' catchments

Water consumption – It is reported that the average daily water consumption per capita in the UK has increased by approximately 65% in the last 30 years (Yorkshire Water, 2000; Southern Water 2000). Much of this increased water usage may be attributed to the growth in ownership of domestic and industrial water appliances (e.g. washing machines, dish washers). These developments have subsequently placed additional demands on urban drainage systems, in many cases exacerbating the problems of insufficient capacity. Reducing urban water consumption rates will therefore reduce the foul water input component to the sewer system, and may in some cases help alleviate overloaded systems. Strategies that may be pursued to reduce urban water consumption rates include grey-water and rainwater reuse schemes.

2.4.2.5 Quality

Storm runoff from urban surfaces can contain a range of pollutants (see Table 2.6). This largely relates to the dirtiness of most urban surfaces – for example, roads, car parks and industrial areas are generally contaminated with oil, rubber and other vehicle materials, as well as chemical spillages, mud, litter and organic matter. The cumulative effects of these mechanisms obviously represent a significant pollution problem at the catchment level, especially in terms of their impacts upon CSO discharges.

Conventional urban drainage systems (UDS) do not generally seek to control the quality of urban runoff, but to contain/limit problems within the sewer system. In fact, in many cases conventional UDS can actually contribute additional pollutants (e.g. through the erosion of sediments) to peak flows that are discharged via CSOs to local watercourses (FWR, 1998).

Table 2.6 Pollutants in urban sewers (Adapted from EA/SEPA, 1997)

Sewer Type	Mean pollutant concentrations (mg/l)						
	Solids	BOD	COD	NH_4-N	Pb	PAH (ng/l)	E Coli
Separate sewer	21-582	7-22	33-265	0.2-4.6	0.03-3.1	29-200	10^2-10^4
Combined sewer	237-635	43-95	120-560	2.9-4.8	0.15-2.9	12-215	10^4-10^6
Highway runoff	28-1,178	12-32	128-171	0.02-2.1	0.15-2.9	365-60,000	10-10^3
Roof runoff	12.3-216	2.8-8.1	57.9-80.6	0.4-3.8	0.001-0.03	na	10^2
Residential areas	112-1,104	7-56	37-120	0.3-3.3	0.09-0.44	na	10-10^3
Commercial areas	230-1,894	5-17	74-160	0.03-5.1	0.1-0.4	na	10^2-10^4

Notes:
BOD, COD = indication of oxygen required for degradation of pollutant
NH_4 = ammonia
Pb = lead concentration (non-degradable)
PAH = Poly Aromatic Hydrocarbons
E Coli = bacteria (presence of which can indicate sewage pollution)

It should be noted that in addition to the 'attenuation' and 'reduction' mechanisms highlighted previously, some innovative stormwater management techniques might also be used to polish urban runoff (i.e. to remove pollution from urban runoff). Improvements in runoff quality are usually achieved through four main pollutant removal mechanisms: *prevention, adsorption, filtration* and the *microbiological breakdown of organic matter.* Each of these mechanisms is discussed in greater detail within Section 2.5.5.6.

2.4.2.6 Amenity

Surface water management strategies affect a diverse range of issues. These include factors such as landscape, land use, wildlife, water resources and recreational issues. The SUDS design manual (CIRIA, 2000) groups all of these issues under one 'amenity' heading. However, in many respects, the 'amenity value' parameter is a somewhat subjective criterion, and hence difficult to quantify in practical terms. The 'quality' and 'quantity' design criteria are already widely used in association with the design of conventional systems and as a result are much easier to quantify. Therefore, all comparative studies between alternative urban drainage strategies undertaken in this thesis will primarily rely upon the use of these two quantifiable design parameters. Some reference will also be made to the amenity value of alternative strategies, however this will have a much lower bearing upon these comparative procedures due to the high level of subjectivity associated with this criterion.

It is evident that reducing or attenuating the peak levels of catchment runoff entering the sewer system will have a positive impact in terms of the 'quality' and 'quantity' design criteria highlighted above. Runoff polishing will also have a positive impact upon the 'quality' criteria, and possibly the 'amenity' criteria, but will have no affect upon 'quantity'.

Section 2.5 introduces a number of SUDS technologies, and outlines how they might be used to achieve a reduction or attenuation of peak catchment runoff. Section 2.5 also reviews the current UK design guidelines associated with each of these SUDS technologies.

2.5 SUDS TECHNOLOGIES

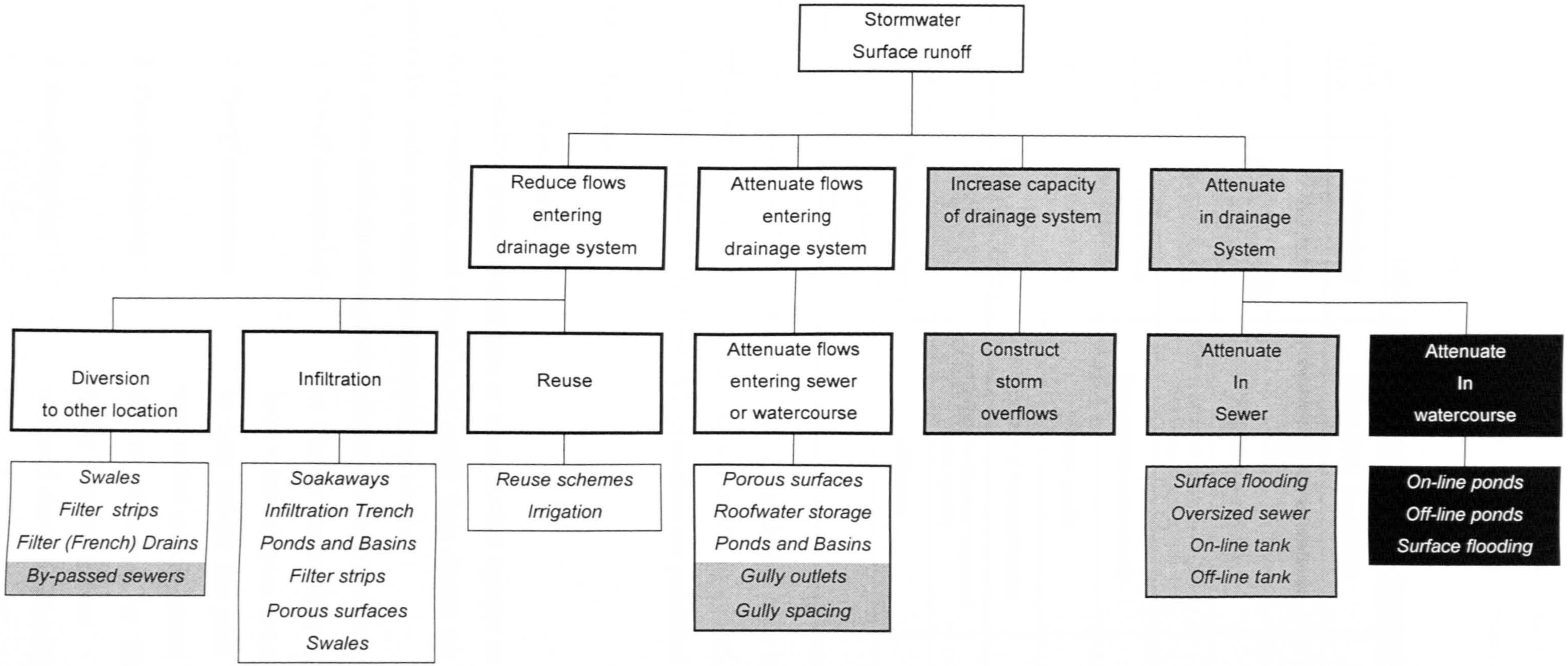
2.5.1 Background

Sustainable Urban Drainage Systems (SUDS) have been defined as a series of management practices and control devices that are designed to control stormwater in a more sustainable fashion than achieved by conventional techniques (CIRIA C522, 2000).

SUDS can be categorised as either being 'non-structural' or 'structural'. The term 'non-structural' SUDS describes an array of institutional, remedial and social issues that relate to the prevention of urban water pollution. Examples of non-structural SUDS include improved street-sweeping and public education on the disposal of oils. Structural SUDS are physical stormwater management devices that are generally used to reduce, or remove, the surface runoff component of peak storm flows that are conveyed through problem sections of the sewer system. Structural SUDS may also be used to improve the water quality of surface runoff conveyed to the sewer system, or as a public amenity.

This thesis seeks to investigate the merits of retrofitting structural SUDS as an alternative rehabilitation methodology for overloaded sewer systems.

Figure 2.7 presents a range of traditional and innovative urban drainage devices for the hydraulic control of peak storm flows (Note: SUDS devices are denoted as un-shaded options).



- *No shading denotes SUDS approaches*
- *Light shading denotes traditional approaches*
- *Heavy shading denotes watercourse-based stormwater strategies*

Figure 2.7 Traditional and Innovative urban devices for the hydraulic control of peak storm flows
(Adapted from CIRIA Report 124, 1992)

Details of each of these SUDS technologies are presented in the remainder of Section 2.5. The structure of this review is presented in Table 2.7. Note: the SUDS technologies displayed within Table 2.7 are grouped in terms of their primary functions for the hydraulic control of peak storm flows. The amenity value and the water quality polishing attributes associated with each of these technologies are also discussed.

Table 2.7 Review of SUDS Technologies

Primary Function	Technology	Secondary Functions	Further details presented in:
Conveyance: *Used to divert runoff flows to another location/ SUDS technology*	**Swales**	Amenity/attenuation of flows/ Infiltration/water quality	Section 2.5.2
	Filter (French) Drains	Infiltration/water quality	Section 2.5.3
	Filter strips	Attenuation of flows/conveyance/ Infiltration/water quality	Section 2.5.4
Flow reduction: *Infiltration devices*	**Infiltration Trench**	Conveyance/water quality	Section 2.5.5
	Soakaways	Water quality	Section 2.5.5
Reuse devices	**Irrigation/ Reuse schemes**	Attenuation of flows/infiltration	Section 2.5.8
Attenuation of flows	**Ponds and Basins**	Amenity/infiltration/conveyance/ water quality	Section 2.5.6
	Porous surfaces	Infiltration	Section 2.5.7
	Roof-water storage	-	Section 2.5.9

An overview of the key SUDS design guidelines/tools that have been developed for the UK is presented within Section 2.5.10. Further details on the design of these SUDS technologies is presented within Appendix 2A (Note: All appendices are presented on the attached CD).

2.5.2 Swales

2.5.2.1 Introduction

Swales are shallow grass-lined ditches or channels that operate as runoff conveyance channels during storm conditions, and return to an empty state during dry periods. The most common locations for swales are within roadside grassed verges.

In terms of urban drainage management, swales can be used in one of four roles:

1. *Runoff conveyance* to transfer storm-water away from urban areas into a local watercourse or sewer system
2. *Runoff attenuation* to help reduce the peak storm-water flows entering overloaded sewer systems
3. *Runoff treatment* due to settlement, or filtration through the swale's grassy channel surface
4. *Runoff disposal* achieved due to infiltration from the base of the swale

Figure 2.8 Examples of Roadside swales (UWTC, 2000)

2.5.2.2 Design issues

The following design guidance is largely taken from three key sources: SUDS design manual (CIRIA Report C522, 2000); A Guide to Sustainable Drainage (EA/SEPA, 1997); and the SUDS technical support CD (UWTC, 2000) compiled by the Urban Water Technology Centre at the University of Abertay, Dundee. There are a number of issues that influence the design of swales.

Conveyance – Swales should be designed in accordance with fundamental hydraulic principles to ensure sufficient capacity for the anticipated peak flows. Further details are presented within the following publications:

- Use of vegetation in Civil Engineering (CIRIA, 1990)
- Design of reinforced grass waterways (CIRIA, 1987)

Detention – Swales intended for extended detention or infiltration should be designed to drain from full capacity design conditions within a period of 24 hours (CIRIA Report C522, 2000). This literature review was unable to establish the origins or basis for this 'emptying within 24 hours' design criteria. However, this seems a sensible approach, as swales that empty shortly after a given period of a rainfall are ready to receive the next storm event.

Treatment – Swales utilise three main mechanisms to remove pollution: *adsorption* and *filtering* achieved within the vegetation on the base of the swale, and *microbiological breakdown of organic matter* in the upper soil layers. In order to allow adequate *adsorption* and *filtration* to occur, CIRIA Report C522 (2000) recommends that neither swale vegetation nor maximum flow depth should exceed 0.1 m, and runoff velocity should not exceed 0.3 m/s at the design treatment volume. The E.A.'s Guide to Sustainable Drainage (1997) recommends that the optimum depth of swale vegetation for treatment purposes is 0.15 m.

The width of the swale should not exceed 3.0 m (CIRIA Report C522, 2000) – as this should ensure that gullies are not formed, and a constant flow rate is maintained. Swales intended for treatment purposes should be designed to drain from full capacity conditions within a period of 24 hours.

Infiltration – To ensure that effective infiltration can occur through the base of a swale, its longitudinal slope should not exceed 1 in 17. However, the longitudinal gradient should not exceed 1 in 50 to prevent erosion of the swale's base (UTWC, 2000). This literature review was unable to establish the basis for these gradient criteria.

Maintenance – The side slopes of a swale should not exceed 1 in 4, in order to allow mowing and access for maintenance personnel (CIRIA Report C522, 2000). This seems a sensible approach, as swales require regular maintenance, steeper side slopes would hinder maintenance access, and threaten the integrity of the swale.

2.5.3 Filter drains

2.5.3.1 Introduction

A filter drain is a perforated, or porous, pipe in a trench surrounded by a suitable filter material, such as gravel, and contained within a geo-textile membrane. Runoff may directly enter the gravel material, either through the top of the trench, or via an inlet pipe (Figure 2.9). The gravel material within the filter drain provides some filtering of runoff pollutants, and also enables some organic breakdown to occur. Furthermore, these devices may also be used to slow runoff velocities, to store runoff, and in some cases to infiltrate runoff to the surrounding sub-soil.

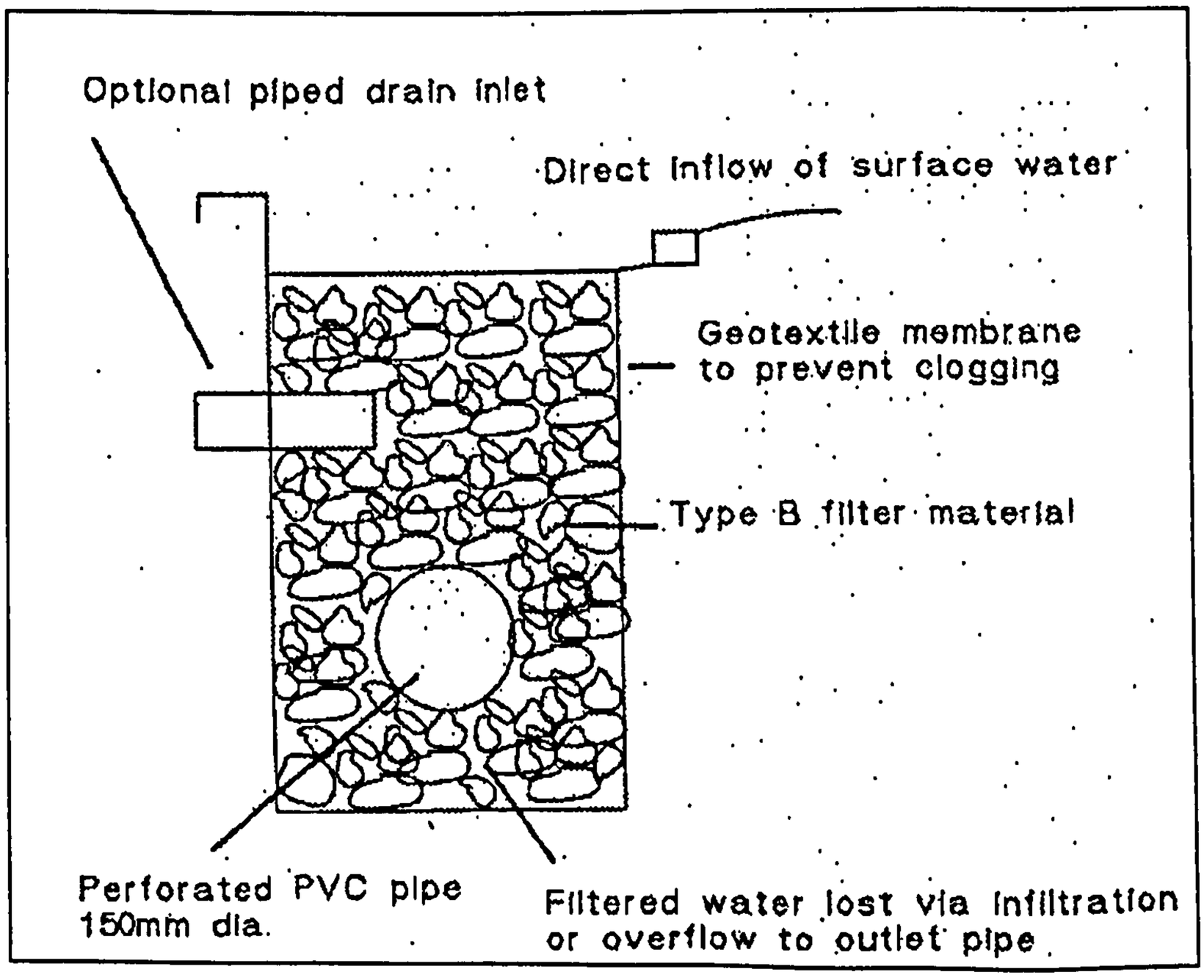


Figure 2.9 Cross Section through a Filter drain (from EA/SEPA, 1997)

Filter drains have traditionally been used to intercept surface runoff on road verges, preventing ingression onto the pavement construction by conveying it to an appropriate drainage outlet.

These devices are widely used by the Scottish Highways authorities for rural, urban and trunk roads (EA/SEPA, 1997).

2.5.3.2 Design issues

Filter drains are typically designed to store 10 mm of rainfall from the contributing area (CIRIA Report C522, 2000). The return period of the adopted design storm relates to the land use of the adjacent area, and the risks associated with system failure.

2.5.4 Filter strips

2.5.4.1 Introduction

Filter strips are vegetated areas of land over which runoff is directed. Filter strips are primarily used for slowing and filtering runoff. The filter strip's cover vegetation slows the flow, and traps silt and associated pollution. These structures are typically sandwiched between an impervious area and a surface water disposal system (e.g. a receiving water course, or a surface water collector, such as a swale – see Figure 2.10).

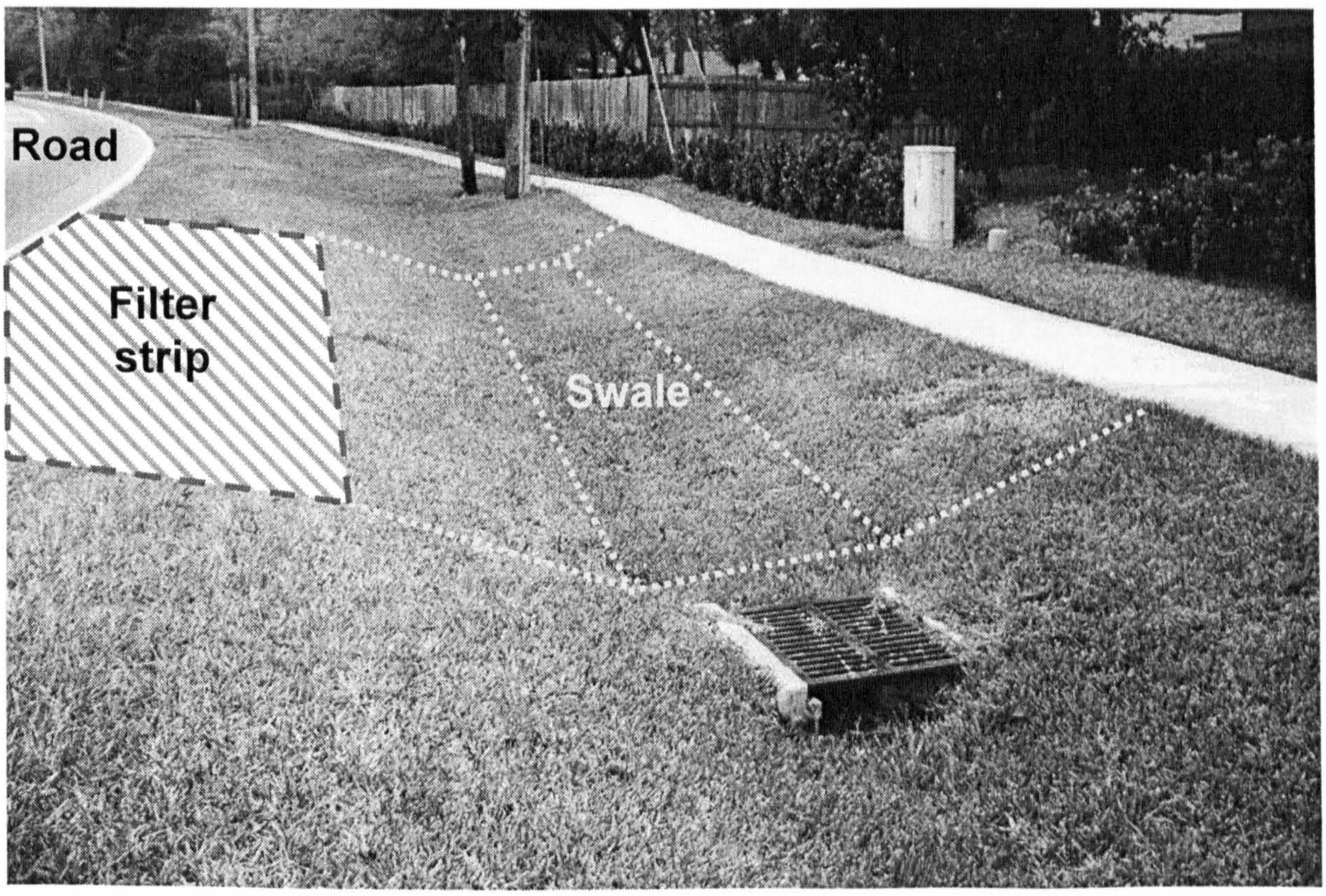


Figure 2.10 Example of filter strip and swale (Adapted from UWTC, 2000)

2.5.4.2 Design issues

Filter strips, like swales, should be designed in accordance with fundamental hydraulic principles, such as Manning's equation. The filter strip surface should be level and free from gullies, to ensure that erosion does not occur, and that a constant flow rate is maintained.

The performance of a filter strip is determined by a number of factors, including its slopes (longitudinal and cross), width and characteristics of its vegetation. The SUDS design manual (CIRIA Report C522, 2000) recommends that cross slopes should not exceed 1 in 20 and the minimum flow distance across a filter strip should be 6-7 m, however this may be reduced to 3

m if the flow travels to an infiltration trench. The same manual also recommends that effective filter strips are generally between 6 m and 15 m wide, whereas the EA's guide to Sustainable Drainage (1997) suggests a minimum width of 15 m.

A range of different vegetation types may be used for the cover material of filter strips, and these may vary from grass through to shrubs. The EA's guide to Sustainable Drainage (1997) suggests that effective filter strips should have a surface vegetation depth of 0.15 mm.

It is reported that in relation to infiltration purposes, the slopes of filter strips, like those of swales, should not exceed gradients of 1 in 17 (CIRIA C522, 2000).

This literature review was unable to establish the origins of the critical gradients and widths adopted for the design of these devices.

2.5.5 Infiltration devices

Infiltration devices are used in urban drainage management as a means of storm-water disposal (i.e. to reduce the levels of storm runoff emanating from urban areas). Examples include infiltration basins, trenches and soakaways. Such structures are only viable for areas with free draining ground conditions.

2.5.5.1 Soakaways

Soakaways are a traditional form of surface water disposal that can be applied to both paved and roofed areas. In the past, many poorly designed soakaways malfunctioned, giving the technology somewhat of a tarred image. However, properly designed soakaways can operate without problems.

There are two common forms of soakaway: i) the rubble, or stone filled pit and ii) the precast concrete ring unit or brick chamber. Both techniques utilise sub-surface storage, and infiltration to the local sub-soil.

2.5.5.2 Infiltration trenches

Infiltration trenches are essentially trenches that are filled with rubble or stone. Their mode of operation is similar to that of a soakaway, and like soakaways they can be applied to the disposal of both paved and roof runoff. But where soakaways require a vertical excavation, infiltration trenches require a narrow horizontal construction. It is worth noting that narrow trenches are more cost efficient in terms of construction costs.

Figure 2.11 Examples of Infiltration Trenches *(UWTC, 2000)*

2.5.5.3 Other SUDS infiltration devices

There are a number of other SUDS devices that can be used for infiltration purposes. These include: infiltration basins/ponds, filter strips (flat vegetated surfaces – also known as plane infiltration), porous surfaces and swales. Many of the generic design issues associated this type of device are presented within Section 2.5.5.4. More specific issues that relate to individual SUDS technologies are discussed elsewhere in Section 2.5, under specific technology headings.

2.5.5.4 Infiltration devices – design issues

There are two main UK design guidelines that relate to the design of infiltration-based SUDS:

- BRE Digest 365 Soakaway design (BRE, 1991)
- Infiltration drainage – manual of good practice (CIRIA 156, 1996)

Both of these methodologies investigate the hydraulic behaviour of the design proposal for a range of 10-year return period storms. This approach is based upon the design methods employed within the modified rational method (National Water Council, 1981).

The other important design issue associated with the design of infiltration-based SUDS is the infiltration rate of the local soil. Soil infiltration rates of at least 12.5 mm/hr are usually required for most infiltration devices to be considered feasible (EA/SEPA, 1997). It is important that site investigations be conducted prior to the design of an infiltration SUDS scheme in order to establish the soil infiltration rate at the location and depth of the proposed device, and to evaluate the geotechnical and hydro-geological characteristics of the local area. It is also worth noting that all infiltration devices should contain some form of inspection facility, to allow their performance to be monitored in the field.

Furthermore, infiltration devices should be designed as shallow constructions, so as to maximise the length of flow path to water table. Maximising this distance will effectively maximise the level of treatment received (or number of pollutants removed). The provision of pre-treatment of

runoff (see following Sections) entering the device is another strategy that can be used to help prevent contamination of the water table. This will also help to prolong the lifespan of these devices, through the removal of sediments that might otherwise clog/silt-up the device.

2.5.5.5 Infiltration devices – Water quality constraints

The infiltration of urban runoff presents a potential pollution risk to potable groundwater resources (e.g. wells, boreholes and springs). Source Protection Zones (SPZs) are defined by the Environment Agency (1998) to provide protection for potable groundwater resources against such threats; and restrictions are placed upon the infiltration of urban runoff within such SPZs (see Table 2.8). SPZs provide an indication of the risk to groundwater supplies that may result from potentially polluting activities and accidental releases of pollutants. Generally the closer the activity or release is to a groundwater source then the greater the risk. SPZs are generally subdivided into three zones (i.e. an inner, outer and total catchment zone), however in some instances a fourth zone (zone of special interest) is occasionally defined.

Pre-treating urban runoff prior to infiltration is considered to reduce the pollution risk posed to groundwater resources. The SUDS design manual for England and Wales (CIRIA C522, 2000) recommends different levels of pre-infiltration treatment for runoff emanating from different types of impermeable urban surface (Table 2.9) – this reflects the fact that some surfaces are more polluted than others. For example, runoff from paved areas is generally dirtier than runoff from roofs, due to vehicle pollutants, and will subsequently require additional treatment facilities prior to being infiltrated. The manual (2000) recommends different levels of pre-infiltration for runoff emanating from different urban surfaces, and in relation to a number of ground water classifications/source protection zones (See Table 2.8). This manual also recommends which SUDS may be used for pre-treating polluted urban runoff, and illustrates how these may be used individually or in series to treat runoff from different surfaces types.

Table 2.8 Summary of water quality design criteria for infiltration SUDS devices (Adapted from CIRIA, 2000 – Page 38)

Ground water classification/ Source protection zone		Surface Type from which runoff emanates						
		Roof drainage	Residential area, Amenity Area	Car park	Lorry park, garage forecourt – outside canopy	Major road	Industrial site, major commercial Site	Surface water sewer
Non-aquifer (infiltration possible to soil)				///	///	///	///	///
Other areas of aquifer outcrop	Deep water table			//	///	///	///	
	Shallow water table			//	///	///	///	
Ground-water protection zone II, outer zone	Deep water table			//				
	Shallow water table			///				
Groundwater protection zone I, Inner zone								

KEY

	Shallow infiltration to the soil zone, discharge to soakaway or discharge to a borehole soakaway may be acceptable
	Shallow infiltration to the soil zone, discharge to a conventional shallow soakaway may be accepatable
	Shallow infiltration to soil zone only may be acceptable
	No discharge to the ground; runoff must be conveyed to a more suitable area or discharged to a surface water body after treatment
///	Treatment required before infiltration; number of bars gives an indication as to the amount of pre-treatment required – i.e. more bars represent more treatment

Table 2.9 Levels of pre-treatment required prior to infiltration of runoff from 3 different surface types (Adapted from CIRIA, 2000)

Device	Residential	Non-residential	Industrial
Required Level of treatment	/	//	///
Prevention	☆	☆	☆
Containment	N/A	N/A	N/A
Permeable surfaces	/	/	/ (Contained)
Filter strips/treatment swales	/	/	//
Filter drains/pavement sub-base	/	/ or //	// (Contained)
Swales	/	/ or //	//
Extended detention basins	/	//	//
Retention ponds	/	//	///
Wetlands	/	//	///

KEY

☆ Always required

// Second level of treatment

/ First level of treatment

/// Third level of treatment

Table 2.9 illustrates how SUDS devices may be used to pre-treat runoff from three different urban surfaces: Residential, Non-residential and Industrial. For each surface type the number and order of potential SUDS treatment devices are displayed, with alternative drainage methods shown for each level. For example, runoff emanating from an industrial site is considered to require three levels of treatment. The first level of treatment may be provided by 'containment' or by using a lined permeable pavement; with the second level of treatment provided either by a filter strip, a filter drain or a swale; and the third level of treatment provided by retention ponds, or wetlands. The star denoted in Table 2.9 indicates that all sites should have good housekeeping (i.e. preventative measures).

2.5.5.6 Runoff polishing

As described previously, some SUDS devices also have the capacity to remove pollution from urban runoff. These technologies generally rely on one of three pollutant removal mechanisms: adsorption, filtration and the microbiological breakdown of organic matter (See Table 2.10).

Table 2.10 Summary of pollutant removal mechanisms utilised by SUDS technologies

Mechanism	Description	Examples
Adsorption	***Adsorption*** of pollutants by vegetation within the base of vegetated SUDS	Swales, filter strips, Wetlands, basins
Filtration	***Filtrating*** of larger pollutants flowing through vegetation on the base of vegetated SUDS	Swales, filter strips, wetlands, basins
Microbiological breakdown of organic matter	***Breakdown of organic matter*** in the upper soil layers of vegetated SUDS	Wetlands, ponds and basins

2.5.6 Basins and Ponds

Basins are surface features that store runoff under storm conditions, but which are completely free of water under dry weather conditions. Examples of this approach include infiltration basin, flood plains, detention and extended detention basins. Ponds contain water in dry weather conditions and are generally designed to receive more water under storm conditions.

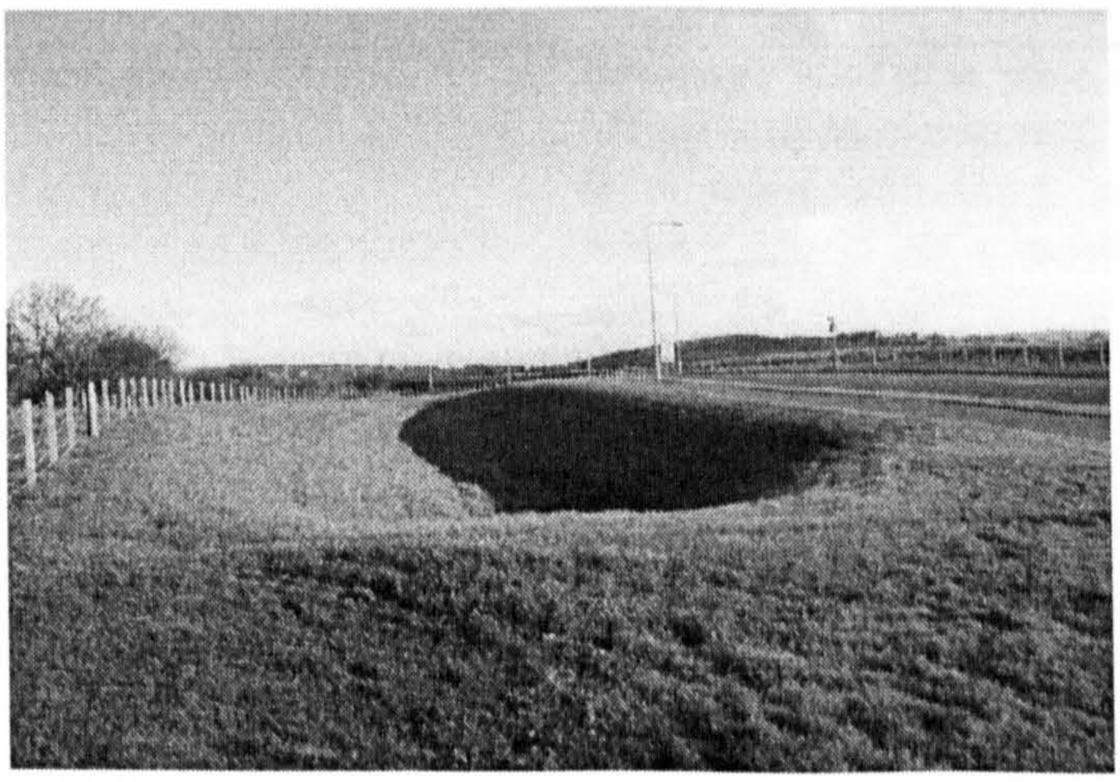


Figure 2.12 Roadside Detention basin (UWTC, 2000)

Basins and ponds may both be used to attenuate excessive surface flows (i.e. storing floodwater, and releasing it when the risk of flooding has reduced). For example, in balancing ponds, flow is generally released via a controlled outlet, whereas in infiltration ponds flow is released through

the process of infiltration. The volume of stored water will obviously vary under different weather conditions, therefore ponds and basins should be designed to operate in both dry and wet conditions. Overflows are generally added to most basins and ponds for the disposal of excessive storm flows.

Basins and ponds can be used to treat runoff using a variety of mechanisms. The first mechanism is by the settlement of solids that occurs within calm water conditions. The presence of aquatic plants can promote calm water conditions and therefore settlement. The second way that basins and ponds can improve runoff quality is by absorption into aquatic plants, and the third is through the biological activity that occurs within the ponds.

Basins and ponds may also be used to enhance the urban landscape. Basins can be used for sporting and other recreational activities. Wet ponds may be used to store water for reuse, and as wildlife habitats.

Figure 2.13 Retention pond (UWTC, 2000)

Table 2.11 and Table 2.12 present a brief overview of the different basin and pond types, as well as highlighting relevant design guidelines.

Table 2.11 Types of basin

Basin Type	Description
Natural or constructed flood plains	Dry majority of time, store water for short periods of time after severe storms
Detention basins or balancing ponds *Design of flood storage reservoirs (CIRIA, 1993)*	Store water until flood has receded. Restricted outlet – allows basin to fill under severe rainfall conditions.
Extended detention basin *Design of flood storage reservoirs (CIRIA, 1993)*	Designed to detain flood volumes for longer times periods (e.g. around 24 hours). Longer retention times allow more settlement to occur. Structures therefore used for a combination of attenuation and treatment.

Table 2.12 Types of pond

Pond Type	Description
Balancing ponds or flood storage reservoirs *Design of flood storage reservoirs (CIRIA, 1993)*	Used to store runoff until flood peak has passed, and as a result has limited treatment capacity compared with ponds that have longer retention times
Lagoons	Used to provide still water conditions for the settlement of solids, but do not utilise biological treatment processes
Retention ponds *Design of flood storage reservoirs (CIRIA, 1993)*	Have detention periods of up to three weeks. Provide a greater degree of treatment than extended detention basins
Wetlands *Review of the design and management of constructed wetlands (CIRIA, 1997)*	Wetlands operate by allowing low levels of runoff to continuously flow through aquatic plants – these structures used to attenuate and filter the flow. Wetlands have detention periods of up to 2 weeks, and are generally more efficient at treating pollutants than retention ponds.
Infiltration ponds	Store water and allow it to gradually infiltrate through the soil of the basin floor.

It is important that ponds and wetlands receive a constant base flow to prevent them drying out. However, excessive storm flows may damage wetland plants and other adequate life, and should therefore be routed around the ponds.

2.5.7 Porous/permeable surfaces

2.5.7.1 Introduction

Permeable surfaces are 'load-bearing' paving constructions that allow runoff to permeate through a top surface layer through to an underlying sub-base construction. The surface material may be formed by a porous coating layer, or by a series of blocks. These blocks may either be permeable or impermeable. If impermeable blocks are used, runoff can still enter the sub-base through joints or spaces in the blocks. The key element of permeable surfaces is that runoff can be stored and conveyed through the sub-base structure.

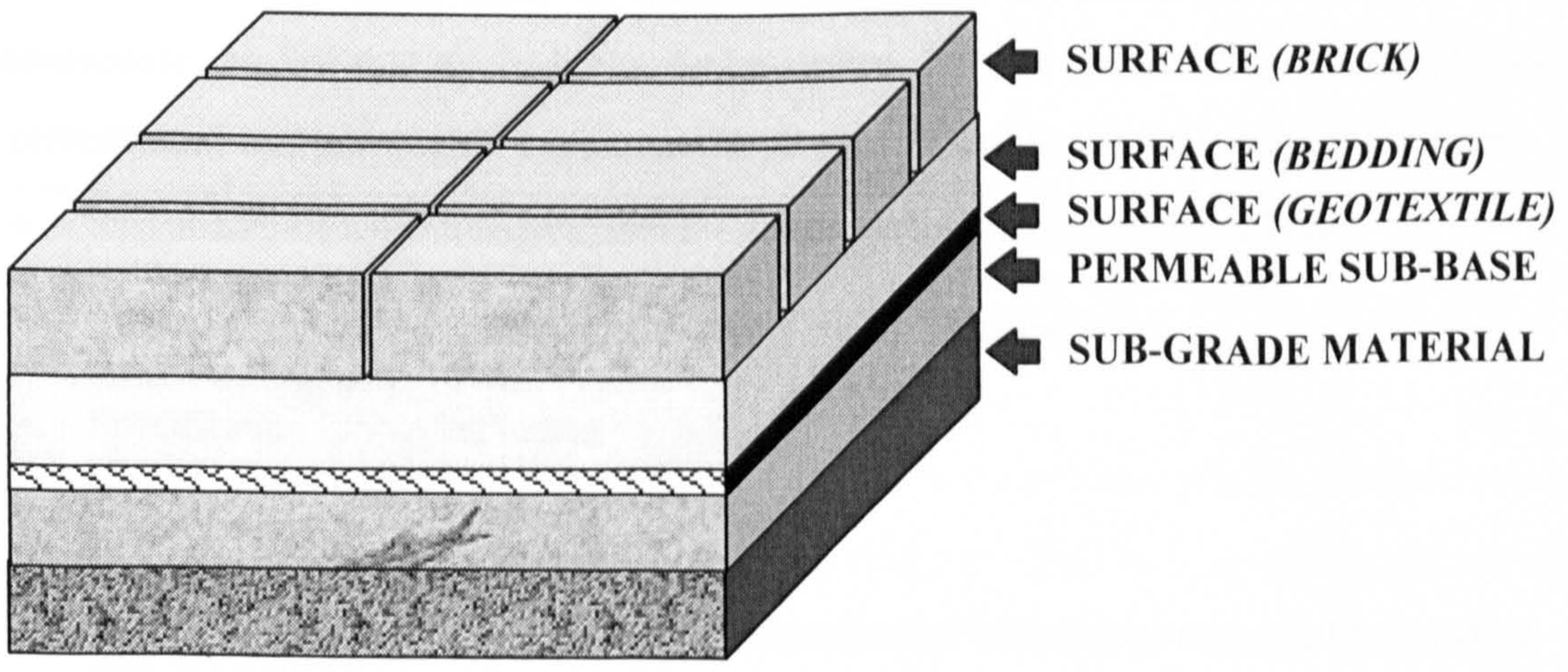


Figure 2.14 Cross Section of permeable paving

Figure 2.14 illustrates how permeable surfaces are generally formed from three separate layers: Layer 1 - Surface materials, Layer 2 - Sub-base (underlying layers, in which runoff is stored), and Layer 3 - Sub-grade (supporting soil).

Permeable surfaces can be utilised to fulfil a number of different roles (CIRIA Report C522, 2000):

1. To detain surface water runoff within the sub-base for flow attenuation purposes
2. To detain surface water runoff within the sub-base for reuse purposes
3. To reduce or eliminate the costs of conventional site drainage
4. To provide treatment to surface water runoff prior to disposal
5. To infiltrate water into the local sub-grade for disposal, or to maintain the soil moisture content

Permeable pavements are another SUDS technique that can be used as an infiltration device. However the runoff collected by most permeable pavements should receive some form of treatment prior to being infiltrated to the local sub-soil (See Table 2.8) – this is particularly important if there is a high level of surface pollutants.

The degree of treatment required for runoff emanating from less trafficked paved surfaces would be less than required for highway runoff, and would be determined by the surface's exposure to pollutants. For example, runoff emanating from an industrial area is likely to be heavily polluted, and hence require additional treatment than runoff emanating from a residential property.

2.5.7.2 Design issues

This Section highlights a number of issues that relate to the design of permeable surfaces. Firstly, it is important that the surface is strong enough to support the loadings associated with its intended use. Secondly, the surface should be designed to adequately capture, store and discharge the volumes of runoff associated with the design storm event. Thirdly, provision should be made for some form of overflow structure, or additional storage – in order to accommodate rainfall that exceeds the design storm. Further information relating to the design of conventional and permeable pavements is presented within the following guidelines:

- Sustainable Urban Drainage Systems – design manual for England and Wales (CIRIA Report C522, 2000)
- Manual of contract documents for highway works Volumes 1-3 (Highways Agency, 1998)
- Specification for paving blocks (BS 6717Part 1 1993)
- Specification for pavers (BS 6677 Part 1 1986)
- Guide for structural design of pavements constructed with clay or concrete block pavers (BS 7533 1992)
- Code of practice for laying precast concrete paving blocks and clay pavers for flexible pavements (BS 7533 Part 3 1997)

2.5.8 Reuse schemes

Roof-water reuse schemes have the potential to reduce the volumes of roof runoff conveyed to the sewer system, and in that sense they constitute a source control methodology. There are a variety of reuse options for roof-water (i.e. the stormwater runoff emanating from roofs); these include non-potable domestic water usage (e.g. toilet flushing and washing), industrial and irrigation purposes. It has been speculated that between 30 and 60% of a typical household's total annual water consumption could be supplied by stormwater collected from its roof (Herrmann and Hasse, 1997).

Roof water collection systems have already been successfully implemented within a number of countries (CIRIA Report 124, 1992). In Japan, more than one hundred large buildings have on-site roof water utilisation systems (Sakakibara, 1996). Most of these are corporate and public buildings, but it is thought that such devices could soon begin to be used in residential properties. Herrmann *et al.* (1996) report the widespread use of 'Rain Water Utilisation' (RWU) systems within Germany. Roof water reuse programs are now beginning to appear within the UK (The Scotsman, 1998; Cooper, 2001; Wearing *et al.*, 2001).

Grey-water systems – The term 'grey-water' is commonly used to refer to water emanating from 'non-foul' domestic usage (e.g. water from baths, showers, hand basins and washing machines). Grey-water systems collect water that would otherwise be directed into the local sewer and then reuse it for a further application (typically for toilet flushing). Grey-water systems can achieve reductions both in terms of the volumes of water conveyed to the sewer system and the demand for potable quality water. Grey-water systems do not require the use of roof-water, but it is possible to combine the two techniques within an integrated system (Dixon *et al.*, 1999).

Irrigation – The informal reuse of roof water for irrigating gardens is also a relatively common practice within the UK. This is typically performed on an individual basis, in residential properties that have installed a water butt to store runoff from roof guttering. The increased use of water butts to collect roof runoff for irrigation purposes within the UK has coincided with the gradual introduction of domestic water metering, and financial incentives offered by Water Companies for customers that disconnect their roofs from the local sewer system (Yorkshire Water, 2000). These trends have demonstrated the viability of retrofitting water butts.

2.5.9 Roof water storage

Roof-water storage facilities, as the name suggests, are used to collect and store runoff from roofed areas. Examples of roof water storage devices are: water butts, ponds, porous pavements and tanks (above or below ground). Roof-water runoff collected within such facilities may be used for a variety of purposes, such as irrigation, car washing and domestic reuse (e.g. toilet flushing or laundry purposes). The overflow from such devices can either be: i) Returned to the local sewer system; ii) Disposed of locally (e.g. by infiltration or discharged into a local water course) or iii) Conveyed to another location.

2.5.10 SUDS design methodologies/selection tools

This Section highlights two generic SUDS design methodologies that have been presented in previous UK guidelines. The first is taken from the CIRIA C521, C522 and C523 (2000) guidelines and the second from CIRIA Report 124 (1992). Both procedures were primarily developed for new SUDS applications.

2.5.10.1 CIRIA C521, C522 and C523 guidelines (2000)

'Surface water management train' – The SUDS design methodologies adopted in CIRIA Reports C521, C522 and C523 (2000) are based upon the 'management train' format. The 'surface water management train' (CIRIA, 2000) is a concept that illustrates how integrated SUDS-based systems might be used to alleviate/eliminate flooding and pollution problems. It demonstrates how SUDS technologies can be used in series to progressively change the quality, or quantity, of surface runoff passed down through the urban drainage catchment

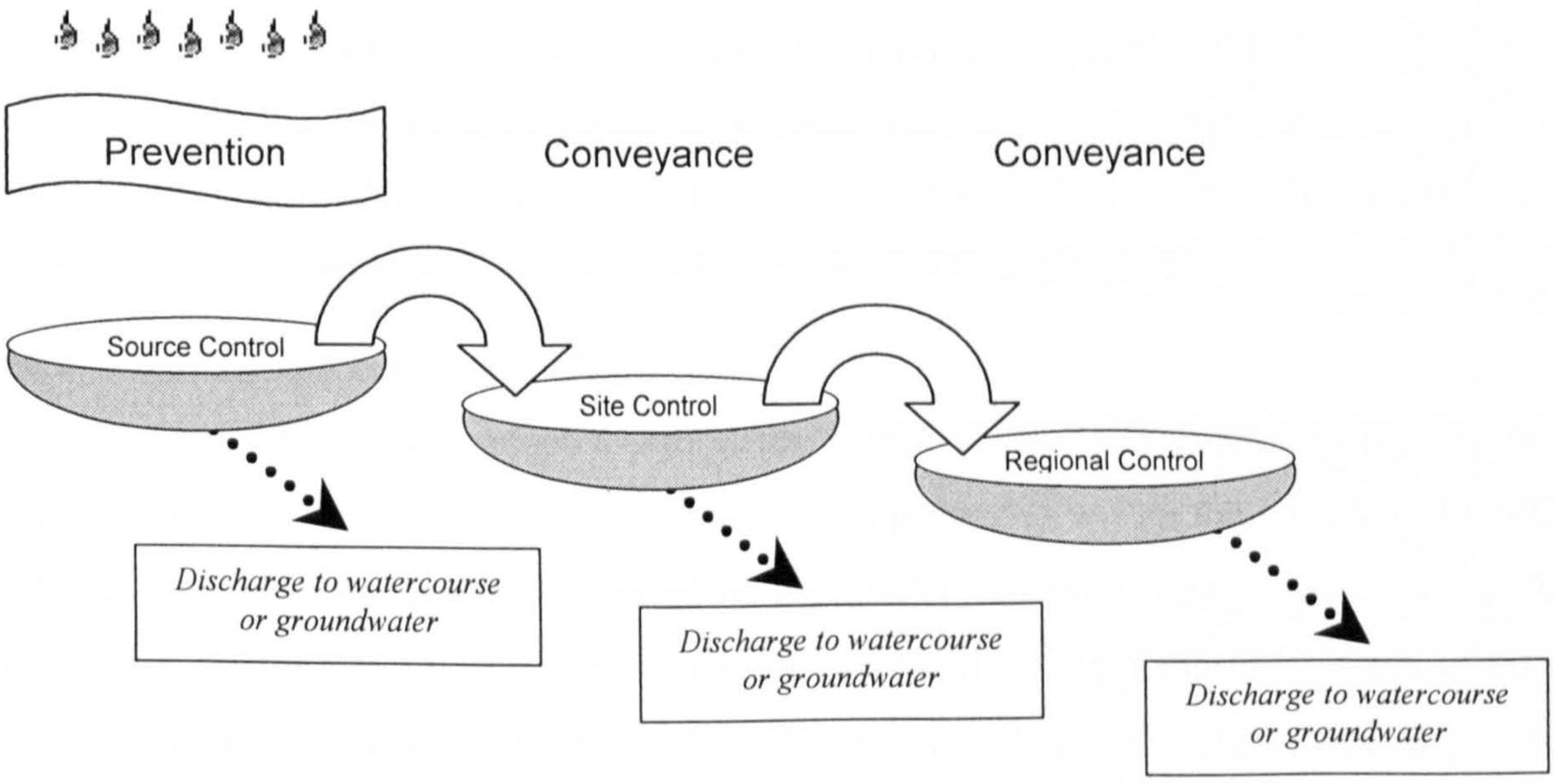


Figure 2.15 Surface Water Management Train (Adapted from CIRIA, 2000)

The first element of the management train is 'prevention' (e.g. good housekeeping measures implemented at individual properties), then local 'source controls', followed by larger 'offsite' (e.g. 'site' and 'regional controls') at progressive points downstream.

It is considered that SUDS techniques are generally most effective when located in the upper reaches of the urban catchment (i.e. as close as possible to the point where the rainfall falls) since they provide attenuation, and some degree of water quality treatment, of stormwater runoff flows – SUDS used in this capacity are often termed as '**source controls**' since they control runoff at, or near, its source. SUDS technologies that can be used to manage runoff further downstream in the urban catchment system are described as '**site controls**' and '**regional controls**' – these techniques deal with runoff on a catchment scale rather than at source. The scale of SUDS schemes generally increases with distance down the surface water management train. Runoff does not have to pass all the way along the management train. It

could be conveyed directly to site or regional control structures – however, it is generally better to deal with runoff at a local level – returning it to the natural drainage system as close to source as possible.

Selection tool – The design procedure/selection tool adopted within the CIRIA C521,C522 and C523 guidelines (2000) is based upon four key principles:

- Drainage techniques are best used in series to meet design criteria
- Drainage techniques are generally preferable at the top end of the management train rather than in more downstream locations
- There is no single correct solution
- The drainage system should be inspired by the natural/original drainage pattern

The design/selection procedures presented within the CIRIA C521-C522 guidelines (2000) take the form of recommended flow-paths for the SUDS design process. It should be noted that these procedures are not prescriptive, as the guidelines acknowledge that other catchment specific issues should also influence the design process. The advice presented within these guidelines appears to be sensible, based upon sound basic principles, and clearly represents a significant advance in the SUDS design within the UK. However it should be recognised that these procedures were not specifically developed for retrofit SUDS applications

2.5.10.2 CIRIA 124 Guidelines (1992)

The SUDS design procedures adopted within the CIRIA C521-C523 guidelines (2000) were developed from earlier concepts, many of which were presented within the CIRIA 124 (1992) guidelines. The principle factors considered by the CIRIA 124 (1992) guidelines to affect the selection and viability of SUDS technologies are presented within Table 2.13. Each of these issues is discussed in more detail within Volume 3 of CIRIA 124 (1992). Once again, the advice presented within these guidelines appears to be sensible and based upon sound basic principles. However, this advice was not specifically developed for retrofit SUDS applications, and in light of this fact it is recommended that further work be undertaken to develop more appropriate guidelines for retrofit applications. It is considered that many of the issues associated with the design of conventional SUDS are also applicable to retrofit applications (e.g. the permeability of local soils, local topography and water table level) – however it is evident that there are other issues that more relevant to the design of retrofit SUDS (e.g. available space).

Table 2.13 Selection tool for stormwater control devices (Adapted from CIRIA 124, 1992)

	Attenuation in water course			Attenuation in sewer				Controlled entry to sewer			Infiltration					Diversion
	OFF-LINE PONDS	ON-LINE PONDS	CONTROLLED SURFACE FLOODING	SURFACE STORAGE PONDS	OFF-LINE TANKS	ON-LINE TANKS	CONTROLLED SURFACE FLOODING	CONTROLLED GULLEY SPACING	CONTROLLED GULLEY OUTLET	CONTROLLED FLOW IN DOWNPIPES	TRENCH INFILTRATION	SOAKAWAYS	SWALES	BASIN INFILTRATION	POROUS PAVEMENT	DIVERSION TO OTHER CATCHMENT
Application *(Suitable for:)*																
Flat or gentle gradients	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Steep gradients	-	-	-	-	●	●	○	-	-	●	○	○	-	-	-	●
Pervious soils	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Impervious soils	●	●	●	●	●	●	●	●	●	●	-	-	-	-	-	●
High groundwater table	●	●	●	●	○	○	●	●	●	●	-	-	-	-	-	●
Limited land availability	-	-	-	-	●	●	-	●	●	●	●	●	-	-	●	●
Alleviation of existing flooding	●	●	●	●	●	●	●	-	-	-	-	-	-	-	-	●
Very low permitted runoff	-	-	-	-	-	-	-	-	-	-	●	●	●	●	●	●
Design considerations (*Necessary for:*)																
Limit ingress of silt	-	-	-	○	○	●	○	○	○	-	●	●	●	●	●	-
Consider low flow channel	-	●	-	●	-	●	-	-	-	-	-	-	-	-	-	-
Provide for maintenance	●	●	○	●	●	●	○	-	-	●	-	○	●	●	-	-
Consider consequences of design flows being exceeded	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Design openings to avoid blockage	●	●	○	●	●	●	○	-	●	●	-	-	-	-	-	-
Include screens																-
Operation & Maintenance *(may:)*																
Require periodic refurbishment	-	-	-	-	-	-	-	-	-	-	●	●	●	●	●	-
Have limited life (e.g. 10 years)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	●	-
Have low maintenance requirements	-	-	●	-	-	-	●	●	●	●	●	●	-	-	●	●
Have high maintenance requirements	●	●	-	●	●	●	-	-	-	-	-	-	●	●	-	-
Others *(may:)*																
Pollute groundwater	-	-	-	-	-	-	-	-	-	-	●	●	●	●	●	-
Be designed to flood public areas	-	-	●	-	-	-	●	●	●	-	-	-	●	●	●	-
Improve discharge water quality	●	●	-	-	-	-	-	-	-	-	●	●	●	●	●	-
Be the responsibility of private individuals	-	-	-	●	●	●	●	-	●	●	●	●	●	●	●	-
Sustain groundwater recharge	-	-	-	-	-	-	-	-	-	-	●	●	●	●	●	-
Be abused by owner	-	-	-	-	-	-	-	-	●	-	-	-	●	●	-	-
Minimise downstream impact	-	-	-	-	-	-	-	●	●	●	●	●	●	●	●	-
Have amenity/recreation use	●	●	●	-	-	-	●	-	-	-	-	-	●	●	-	-

●	Most suitable/appropriate/necessary
○	Possibly suitable/appropriate/necessary
-	Unlikely to be suitable/appropriate/necessary

2.5.11 Overview

It is clear that SUDS technologies have the potential to provide full or partial solutions to most urban drainage problems (Section 2.2), and therefore represent an alternative design approach to the conventional 'hard engineering' approach. It is also acknowledge that advances have been made towards the development of design guidelines for SUDS applications, most noticeably in the form of CIRIA Reports R124, C521, C522 and C523. These guidelines provide a useful framework for the SUDS design process, and present basic design advice/calculations for a number of SUDS technologies. However, these guidelines fail to specifically address issues relating to the design of retrofit SUDS. These guidelines are also weak in relation to practical advice on the financial costs associated with SUDS, and the provision of detailed feedback from existing UK SUDS schemes.

The following two Sections therefore examine the extent to which SUDS technologies have already been adopted both within the UK, and abroad, and will also highlight any real or perceived barriers to their widespread implementation (Section 2.7).

2.6 IMPLEMENTATION OF SUDS-BASED STORMWATER MANAGEMENT STRATEGIES

2.6.1 SUDS implementation to date

2.6.1.1 Background

The uptake of SUDS technologies within the UK has been somewhat limited in comparison with many other parts of the world, most notably Australia, Germany, Japan, Scandinavia and the USA. Most of Britain's SUDS devices serve new developments. In fact, this literature review failed to uncover any documented cases of large-scale retrofit SUDS schemes within the UK.

SUDS have been promoted in Scotland since the mid-1990s, and during this period over one hundred Scottish SUDS installations have been constructed (Jefferies *et al.*, 1999; Ashley, 1999). Most of these have been stand-alone installations, or part of small scale integrated schemes, that serve new housing, leisure or industrial developments. Jefferies *et al.* (1999) reported on an on-going assessment programme that was attempting to establish what specific issues have most affected the performance of approximately ninety of these existing SUDS installations. Many of the inspected devices were found to be performing well, whilst others were not as successful. This study indicated that poor performance amongst 'hydraulic control' type SUDS could generally be attributed to one of three key factors:

1. Lack of suitable land on which to install system
   (unsuitable land would have excessively steep slopes, or low soil permeability)
2. Administrative and Institutional issues
   (i.e. particularly relating to maintenance access, ownership and safety issues)
3. Poor design, construction or maintenance

By comparison with Scotland, there are relatively few documented uses of SUDS devices (Kearns, 1999; Today, 2001) within the rest of the UK. This illustrates the positive effect of the SUDS promotional activities that have been undertaken in Scotland in recent years.

2.6.1.2 Retrofit SUDS

As highlighted within the previous Section, this literature review failed to identify any documented evidence of large-scale retrofit SUDS schemes within the UK. However, there are a number of documented schemes from other parts of the world, most notably within North America. A number of examples from the USA are presented within the ensuing Sections:

2.6.1.3 City of Portland, USA

The City of Portland, Oregon, USA introduced a 'downspout disconnection program' in an attempt to address the ecological problems caused by frequent overflows from the city's combined sewer system into the Willamette River and Columbia Slough (City of Portland, 1998). The scheme encouraged local residents to disconnect their roofs from the sewer network, and to redirect the roof runoff into a 'water butt' or onto their garden. A financial incentive of US$ 53 was paid to every household that participated in the program (note: this payment was made after the 'disconnection' has been inspected by the local authority). Disconnections were performed by the householder, contractors or approved 'neighbourhood associations' (e.g. schools, churches and other community groups). These 'neighbourhood associations' received a token 'fund-raising' payment of US$ 13 for every downspout they disconnected. It was hoped that involving the community in this way would promote the program, and help educate local residents about the issues surrounding 'sustainable water management'. By March 1998, 5200 properties had been disconnected through this scheme, with roughly one third of these disconnections being performed by about 1600 volunteers.

A cost benefit analysis that was conducted in conjunction with this study is presented within Section 2.10.1.

2.6.1.4 Other American examples

Another example is the scheme currently in operation within the Austin City, Texas, USA. The Austin City website contains a statement encouraging its residents to collect, reuse or irrigate their roof runoff (Austin City Council, 2000). An incentive of a 30% 'water bill' rebate (i.e. up to a total of US$ 500) is offered to all domestic and industrial consumers who participate in the program.

Similar schemes have been conducted within a number of North American cities, including Edmonton, Minneapolis, Pittsburgh, Portland (Maine) and Toronto (Norris, 1999).

2.6.1.5 Implications for the UK

Although the previous examples demonstrate that retrofit SUDS have proven to be viable within a North American context – it does not necessarily follow that they would also prove to be viable within a UK context. There are a number of differences between these two nations that

might significantly influence the viability of this approach in a UK context. These differences relate to factors such as climate, urban landscape (i.e. urban areas within the US are generally not as built up as those within the UK), and institutional arrangements (i.e. within many US cities the local municipality is responsible for the provision of water services, highways, public areas and town planning – whereas in the UK each of these roles are the responsibility of different agencies).

It is worth noting that over the time-span of this thesis, a number of UK water companies have begun to offer financial incentives, in the form of reduced water bills, to customers that disconnect their roofs from the local sewer network. This indicates that these companies have undertaken some form of cost/benefit analysis to assess the merits of these schemes. However no details of such studies have yet been released into the public domain. It is likely that these would have been generic studies, and not focused upon specific problem catchments, such as described previously within Section 2.6.1.3. This assumption is based upon the fact that these companies offer financial incentives across their whole network, not just in problem areas.

The following sub-Sections describe two previous feasibility studies that were undertaken to assess the viability of retrofitting SUDS to UK catchments. These feasibility studies are both presented in two distinct parts with performance issues (e.g. hydraulic performance of the existing systems, and alternative future proposals), being considered in the following Section. Cost issues for these two catchments are discussed in Section 2.10.

2.6.1.6 Previous UK retrofit feasibility studies - Balmforth and Bailey (1985)

Balmforth and Bailey (1985) investigated the potential use of on-site roof water storage as a source control methodology. This desktop study explored the impacts of installing attenuation devices at the base of 'gutter' down-pipes to collect roof-runoff from every house in a 'typical' UK housing estate (12 ha). The total roofed area of this estate was 1.6 ha, and the total number of required 'on-site' attenuation tanks was calculated as being 320. A 350 l capacity PVC tank was modified to provide attenuation, rather than storage (Figure 2.16) and then subjected to both laboratory and field trials over a one-year period. The hydraulic performance of this system was then investigated using a deterministic model for a range of storm events, each of 2 year return period. It was subsequently found that the peak flow reduction achieved by the installation of 320 on-site attenuation tanks was roughly equivalent to that of a 85 m^3 on-line underground storage tank located downstream in the sewer system.

It's is worth noting that the appropriateness of adopting 2 year return period storms to form the rainfall input for these simulations is somewhat questionable in relation to issues of water pollution caused by excessive CSO discharges. The use of design storm events is appropriate for the investigation of a sewer system's hydraulic performance (i.e. whether it floods or surcharges). However, for the simulation of water quality parameters, such as BOD and COD, a time series rainfall input representing a 'typical year' would be more appropriate (FWR, 1994/1998).

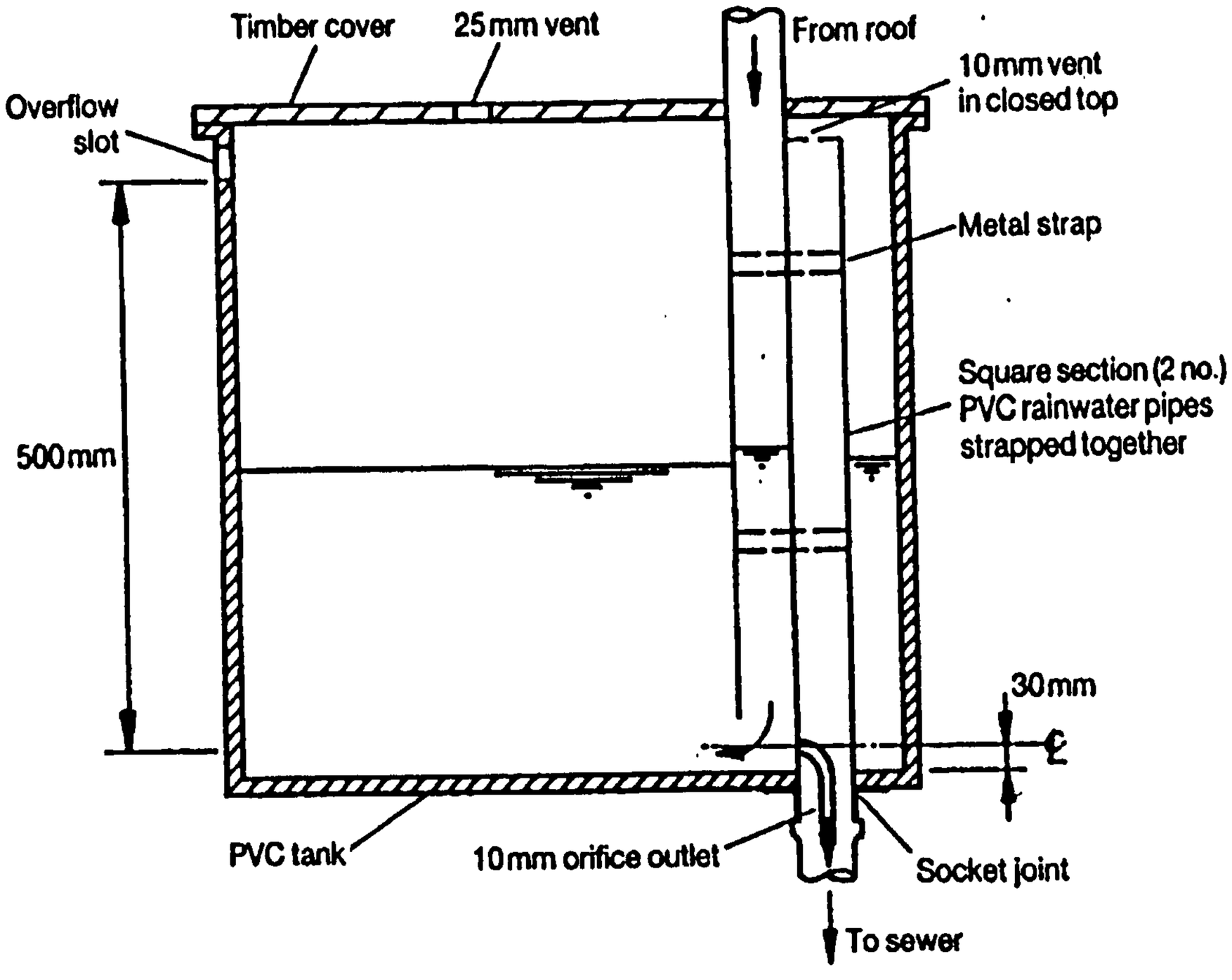


Figure 2.16 Section through 'roof downpipe' attenuation tank (From Balmforth and Bailey, 1985)

The Roof-water Source Control (RwSC) device proposed by Balmforth and Bailey (1985) was essentially little more than a modified 'water butt'. There is some speculation that 'water butts' are not entirely appropriate flow reduction devices, for in the absence of supportive legislation there is nothing to prevent a house-holder from removing or modifying such devices (Balmforth and Bailey, 1985). It has subsequently been suggested that on-site underground tanks might be seen as a more permanent and acceptable solution by the relevant regulatory authorities (CIRIA, 1992). However, if roof water were stored and reused to supplement a property's 'metered' domestic water supply the likely financial savings to the occupant would probably serve as an incentive not to remove the device.

An important issue associated with RwSCs, is that of 'user acceptability'. This is of particularly importance when RwSCs are used as a retrofit technology. It has been speculated that this will strongly determine both the size and appearance of 'on-site tanks'; and whether such tanks are located above, or below ground level (Balmforth and Bailey, 1985).

A cost benefit analysis that was conducted in conjunction with this study is presented in Section 2.10.

2.6.1.7 Previous UK retrofit feasibility Studies - Catchment X (2001)

It should be noted that the catchment names and locations associated with this case study have been withheld at the request of the UK water company that contributed this data. The contributor has also requested to remain anonymous – as they consider some of this information to be industrially and politically sensitive.

Catchment X is a 5775 ha suburban catchment located in one of the UK's major cities. The catchment contains two main watercourses. The south of the catchment is formed on a chalk 'downland', and the catchment gently slopes down in a South to North direction. The catchment encompasses four local authorities, and has a resident population in excess of 400,000. Some areas of the catchment are served by combined sewers, and other areas by separate foul and surface water systems. Figure 2.17 shows a typical residential area from this catchment.

Figure 2.17 Typical residential area from Catchment X

A major upgrade of the catchment's infrastructure was conducted in 1999. This work involved linking two previously separate catchments (**Catchment X1** and **Catchment X2**) via the construction of a new combined sewer tunnel (**X Tunnel**), and up-grading the new combined catchment's only receiving WWTW. The new catchment's sewer system has a history of flooding (foul and storm-water) events. In December 1999 flooding also occurred at the **X Tunnel**.

The local water company conducted a pilot study to assess the potential for retrofitting SUDS to this catchment in order to remedy these flooding problems. The aims of this study were to identify whether retrofit SUDS/source controls could be used to significantly address the hydraulic problems associated with this catchment, and to estimate the costs associated with implementing any such SUDS option.

An InfoWorks model of **catchment X** was used to simulate the effects of disconnecting different sources of storm runoff using retrofit SUDS, on the peak flows reaching the overloaded **X Tunnel** after a (M10-360 winter) critical design storm. Simulations were run for best-case disconnections scenarios for both roofed and paved areas. However, the results of this analysis indicated that these best-case retrofit SUDS scenarios would have limited effect upon

the critical peak flows through the **X Tunnel**. It was hence decided that there was little value in investigating other, more realistic retrofit SUDS options.

2.7 BARRIERS TO THE IMPLEMENTATION OF RETROFIT SUDS IN THE UK

This Section and Section 2.8 outline the main barriers that are considered to stand against the implementation of retrofit SUDS within the UK. These obstacles need to be addressed before retrofit SUDS are viewed as viable form by large parts of the UK water industry.

It should be noted that the views expressed in this Section are not widely documented, but have repeatedly emerged in project discussions with industrial contacts.

2.7.1.1 Attitudes within Water Industry

The UK water industry retains a strong reliance upon conventional rehabilitation solutions for urban drainage problems. This attitude is characterised by the industry's widespread use of the UPM methodology to generate 'hard engineering' solutions for CSO related problems. There is a reluctance to move away from these conventional solutions, especially to explore the use of SUDS, which are viewed as being 'untried' and 'untested' technologies. This reticence owes much to the 'familiarity' of conventional 'hard engineering' design methods, coupled with a lack of retrofit SUDS costings data and/or design guidelines. Conventional solutions are often used in preference to SUDS schemes, because of designers' familiarity with the design and costing procedures involved in their development. The water industry generally favours projects that incur a short-term capital expenditure (construction costs) with fixed maintenance costs. The novelty of SUDS type solutions means that there is more uncertainty associated with their construction and maintenance costs, than those of conventional solutions.

These attitudes are in stark contrast to those of the Environment Agency and SEPA, both of whom have been actively promoting the use of SUDS since 1997 (Protecting the Quality of our Environment - A guide to Sustainable Urban Drainage, 1997).

2.7.1.2 Lack of relevant design guidance

The shortcomings of the existing UK guidelines for SUDS design were highlighted within Sections 2.5.10 and 11. These manuals neglect the design issues associated with retrofit SUDS schemes, in terms of the specific factors that relate to the implementation of SUDS within existing urban catchments rather than new developments. These manuals also contain very little data that relates to the financial costs of SUDS technologies (i.e. costs of construction, operation and maintenance). It is felt that both of these issues need to be addressed before retrofit SUDS will be given serious consideration by the water industry.

2.7.1.3 Issues relating to ownership/adoption

The issues of ownership and responsibility are further barriers to the implementation of SUDS technologies. Due to their novelty, there are no clear precedents within the UK relating to the

ownership, maintenance and operation of SUDS technologies once constructed. This ambiguity leads to reluctance, particularly among developers, to adopt SUDS solutions, as they are unsure as to what their future responsibilities towards the technologies might be. For example, take the case of a house developer considering whether to include a network of grass roadside swales within a new housing development. The developer's obvious questions will relate to who will own, maintain, and operate this network after its construction? Until these questions are answered, the developer will be reticent about pursuing this scheme, and will therefore opt for a conventional solution – for which these future roles and responsibilities are well understood and clearly defined. It therefore seems necessary to establish clear roles and responsibilities for the ownership, maintenance and operation of SUDS schemes – this ideally needs to address the problem from the perspective of a number of different affected agencies (e.g. the Developer, Local Authority, affected Property owners, Sewer operator and Environmental Regulator). Although the example used in this Section relates to implementing SUDS to a new development, there are many parallels that may be drawn with the introduction of retrofit SUDS.

2.7.1.4 Uncertainty in cost effectiveness

Another factor that limits the adoption of SUDS within the UK is the degree of uncertainty that relates to their financial costs (i.e. the costs associated with their construction and operation and maintenance). However, even if such costs were available, it is apparent that the costs of implementing specific SUDS technologies would be significantly different for retrofit, as opposed to new-build, SUDS. For example, whereas a porous pavement car-park might be readily (and cheaply) installed as part of a new development, the replacement of an existing, conventionally drained, car park with a porous pavement is likely to be significantly more expensive, due to the additional costs associated with disruption and loss of operational revenue. Equally, the introduction of filter strips and swales to drain roads in residential areas may become prohibitively expensive when disruption to existing services located within the road verges are considered.

The uncertainty that surrounds the costs of SUDS is exacerbated by the limited experience of applying such schemes within the UK, and the lack of published UK costing data for SUDS devices. The SUDS design manual (CIRIA C522, 2000) acknowledges that cost is an important factor in the evaluation of conventional and alternative SUDS proposals, but fails to provide any specific information as to how those costs might be obtained. Furthermore, the manual provides no indication as to the comparative costs of the different SUDS technologies that it presents.

The financial costs associated with the construction and operation of conventional urban drainage are well understood, and documented. The uncertainty relating to the costs of SUDS obviously make them a much less attractive option than conventional approaches to the majority of UK urban drainage design engineers.

In summary, although SUDS might be shown to be hydraulically effective and environmentally more sustainable than conventional sewer rehabilitation strategies, it seems inevitable that, in the context of the current economic climate, cost-based comparisons will be required to justify the use of retrofit SUDS. Hence there appears to be a need for a selection tool that is specifically aimed at the evaluation of retrofit technology options and which give due recognition to the importance of cost assessment. It is likely that this would need to utilise some form of Cost Benefit Analysis (CBA). Section 2.9 explores the fundamental principles behind CBA, and Section 2.10 presents two previous studies that have utilised CBA to investigate the merits of implementing retrofitting SUDS techniques to case study catchments. The following Section explores the uncertainties associated with the hydraulic effectiveness of SUDS, and the role that modelling packages might play in defining these issues.

2.8 UNCERTAINTY RELATING TO HYDRAULIC EFFECTIVENESS OF SUDS

English and Welsh sewer operators are generally required to demonstrate the compliance of proposed rehabilitation schemes for problematic CSO discharges with stipulated discharge consents, defined by the Environment Agency (Section 2.2.5). Similarly, proposed solutions for sewer flooding problems are usually designed to meet the performance criteria laid down within the Sewer Rehabilitation manual (WRc, 2002). In both instances, compliance with the required standards is typically assessed through the use of urban drainage software packages. There are two main types of urban drainage model: detailed deterministic models and simplified models. Deterministic urban drainage models, such as HydroWorks™ (Wallingford Software, 1994), InfoWorks™ (Wallingford Software, 1998) and Win-Dap Ver.W.7™ (MicroDrainage, 1998), are widely used within the UK water industry. Complex deterministic urban drainage models are considered to produce relatively accurate hydraulic simulations when compiled and calibrated correctly against monitored flow data. However, the lack of appropriate quality data can also lead to difficulties when calibrating and verifying such models (Harremoes, 1997). Simplified urban drainage models such as SIMPOL (FWR, 1994/1998) are also widely used within the UK.

2.8.1 Need for SUDS modelling packages

The absence of previous UK retrofit SUDS schemes, means that modelling exercises still offer the most viable means of analysing the performance of such schemes, both in terms of their respective performance, and for comparison with conventional rehabilitation schemes. The ensuing Sections present a number of documented models that have been used to model various SUDS proposals.

2.8.2 Modelling SUDS using detailed deterministic modelling tools

Over the duration of this research project, work has been underway to upgrade the source-code of existing deterministic urban drainage models to allow the simulation of various SUDS

techniques. For instance, MicroDrainage's new Source Control module is now a fully integrated part of the WinDes suite of urban drainage modelling tools, and it is claimed that this can support the design and analysis of a number of source control devices, including infiltration trenches, ponds, porous pavements, soakways and swales. However, this software was not available early enough to be utilised within this study.

However, many earlier versions of traditional deterministic urban drainage models (such as HydroWorks and MOUSE) have been used in their existing state (without the need to upgrade the software source code) to simulate the hydraulic impacts of most source control technologies (Andoh and Declerck, 1997). This was achieved by utilising the existing model input parameters in such a way as to represent the hydraulic behaviour of SUDS techniques.

For example, Monster *et al.* (1998) describe how the runoff component of the HydroWorks software package was amended to enable the hydraulic simulation of a number of SUDS techniques. This up-dated package was then used to analyse a new housing project in the Dutch Town of Zeewolde. Similarly, Linde and Mikkelsen (1998) report that an amended MOUSE-SAMBA (v.3.20) model was used to investigate the impacts of retrofitting, Real Time Control (RTC) and stormwater infiltration approaches to stormwater management for an hypothetical catchment.

2.8.3 Modelling SUDS using simplistic modelling tools

SIMPOL is one of the UK's most widely used simplistic urban drainage models. The SIMPOL model is a spreadsheet model that combines many of the key processes from the urban drainage cycle, in a simplified way, so that simulation times are kept to a minimum. It incorporates both hydraulic and water quality elements and is designed to assist in the implementation of the UPM Procedure (FWR, 1994/1998). The main use of SIMPOL is as a key element of the UPM methodology, to allow the performance of potential sewer rehabilitation schemes to be rapidly compared against the environmental and emission standards. SIMPOL was designed for use in conjunction with conventional stormwater management proposals, but there is nothing to stop it from also being applied to model the behaviour of SUDS-based schemes.

2.8.4 Modelling SUDS using specialised SUDS models

In recent years, a number of models have been specifically developed for representing the behaviour of an array of SUDS techniques. These models have generally been based upon simplistic modelling approaches, such as mass-balance flow analysis conducted over large, aggregated, time steps (Ashley *et al.*, 1998; Ristenpart, 1998). These models tend not to be as sophisticated as the deterministic type models discussed previously. The following paragraphs contain a brief description of some of these models, together with details of their reported application to relevant case study modelling exercises:

MIDUSS98 is a rainfall-runoff software model that incorporates a set of 'decision support' design tools (Smith, 1998). The **MIDUSS98** model comprises both hydrological and hydraulic

modules. The hydrological component is adaptable, and allows the user to select from a variety of methods for 'storm description, rainfall loss estimation and overland flow routing'. The hydraulic component provides design tools for both centralised stormwater controls such as ponds and outflow devices; and on-site controls such as rooftop storage, parking lot storage, oversized pipes and infiltration trenches. Rainfall inputs are limited to single event storms.

ERWin is a 'rainfall-runoff' software model that supports a variety of SUDS, including storm tanks, ponds, Rain Water Utilisation (RWU) systems, soil filters and both centralised and on-site infiltration systems. The **ER-Win** model is able to perform long-term simulations as well as simulations for single storm events. Both types of storm event may be generated from either continuous historic, or time variable synthetic, rainfall data.
Ristenpart (1998) describes how the **ER-Win** model was used to predict the effects of implementing various SUDS approaches to a 27 ha catchment in Berlin-Mahlsdorf, Germany. The adaptability of the ER-Win has been highlighted by Ashley *et al.* (1998), who report that the **ER-Win** model has been used to analyse a case study drainage problem in accordance with both UK and German design practices for infiltration devices.

SMUSI is a conventional storm-water balance/pollution load model. The package is specifically designed for performing simulations driven by long-term rainfall input data (SMUSI website, 2002) and as been updated to include a number of SUDS techniques. The hydraulic and quality performance of each SUDS technology were analysed by **SMUSI** for long-term simulations conducted for a hypothetical drainage system (Mchlur and Ostrowski, 1998).

The **SWIFT** package is an urban drainage software tool constructed around the hydrological transport and pollution load module of the **SMUSI** model (Bente, 1998:a). **SWIFT** has the ability to simulate the effects of implementing a variety of stormwater management measures. The **SWIFT** model is essentially a decision support tool that enables the comparison of a range of both conventional and alternative stormwater control measures in relation to a variety of economic and ecological factors. Alternative approaches accommodated by **SWIFT** are decentralised stormwater infiltration and roof water usage schemes. The package may also be used to investigate the effects of a range of user 'up-take' and usage scenarios for such technologies.

Bente (1998:b) describes how the 'SWIFT' model was used to investigate the effects of introducing a variety of roof water storage and infiltration techniques to 3 case study catchments in Germany. This exercise involved simulating the disconnection of roofed areas from the sewer system. An array of roof-water disconnection scenarios was investigated, ranging from the collection and storage of roof water from only the largest buildings (e.g. schools, hospitals and office blocks) in the catchment, through to the collection of water for every roofed area in the catchment. The findings of this study seem to indicate that there would be some value in

conducting similar investigations to encompass a greater number of case study catchments; with a more diverse set of catchment and rainfall characteristics.

2.8.5 Modelling SUDS – Discussion

Previous modelling exercises have attempted to assess and quantify the catchment level effects associated with the widespread application of SUDS schemes (Vaes and Berlamont, 1999; Bente, 1998:a; Bettmann and Ostrowski, 1996; Herrmann *et al.*, 1996). The findings of these studies have been inconclusive, and somewhat contradictory. Some of these studies have indicated that such schemes would constitute an effective rehabilitation technique for problem urban drainage systems (Vaes and Berlamont, 1999; Bettmann and Ostrowski, 1996; Herrmann *et al.*, 1996), whilst other work has questioned this premise (Bente, 1998:a).

Most of the existing catchment-based studies investigating the implications of source-control SUDS have relied upon predictions from simplified 'urban drainage' modelling tools. The use of simplified models implies that modelling compromises have been made. For example, most simplified urban drainage models tend to use large, aggregated, time steps (e.g. of 1 hour) in conjunction with mass-balance analysis to represent catchment rainfall, runoff and sewer hydraulic processes.

In the context of the current research it is believed that the use of a detailed urban drainage analysis software package, such as HydroWorks™ would offer a more rigorous form of analysis. For instance, HydroWorks offers the possibility of high-resolution simulations (e.g. HydroWorks may accept rainfall input data with 5 minute timesteps and produce results with 1 minute timesteps). One advantage associated with conducting higher resolution urban drainage simulations is that the impacts of pumps, and other components of the sewer system, can be incorporated within the analysis. The level of output produced by detailed models, such as a HydroWorks, is generally far more comprehensive than that generated from most simplified models. HydroWorks also offers an array of alternative models to represent the runoff, infiltration and pipe flow processes. HydroWorks is widely used within the UK water industry, and compatible catchment data is readily available.

A major disadvantage associated with the use of HydroWorks relates to its lack of transparency in terms of the precise modelling processes used to produce urban drainage simulations. Another potential problem relates to the fact that HydroWorks only considers traditional urban drainage management techniques, and has no direct procedures for representing the effects of SUDS approaches. However, this problem could potentially be addressed by amending conventional HydroWorks modelling techniques in such a way as to represent the impacts of SUDS. For example, Monster *et al.* (1998) report that HydroWorks' runoff component was amended to enable the hydraulic simulation of a number of alternative Stormwater Management techniques.

HydroWorks was selected as the main modelling tool for urban drainage simulations conducted in relation to this thesis. The HydroWorks/InfoWorks model packages are well established

within the UK water sector, and consequently have a large pool of experienced users and existing catchment data. This was the key factor in the selection of HydroWorks – since this has meant a wider range of catchment data from which case studies could be drawn. However, most of the verified HydroWorks catchment models currently are hydraulic models. The lack of appropriate quality data has lead to difficulties when calibrating and verifying the water quality component of such models (Harremoes, 1997).

2.9 COST-BENEFIT ANALYSIS (CBA)

2.9.1 Introduction

There are two sets of considerations associated with every potential activity; one set relates to the demands for a given service (i.e. the desired benefit or benefits); whilst the other focuses on the resources required to achieve that activity (i.e. the costs) (Laursen and Gujer, 1997).

Cost-Benefit Analysis (CBA) is a decision-maker's tool that enables the comparison of alternative options or investments. CBA has been defined as a set of procedures that are used for the definition and comparison of project costs and benefits (Zerbe and Dively, 1994). CBA may also be extended to enable consideration of issues such as risk and uncertainty (Pearce and Nash, 1982).

2.9.2 Costs

The costs considered within a CBA can be classified in a number of different ways. Some authors speak of 'Primary' and 'Secondary' costs (Zerbe and Dively, 1994), others of tangible and intangible costs (Ashley *et al.*, 1998). In practice, the range of costs included within any given analysis is dependent upon a number of factors, such as the purpose of the study and its logistical constraints (e.g. time, financial and available data). Projects may incur a whole range of different costs, examples of which include investment, overhead and running costs.

2.9.3 Benefits

In simplistic terms 'profit' may be defined as 'income' minus 'costs'. Therefore benefits may be expanded by either increasing income or reducing costs, or by any combination of the two. As with costs, both the range and type of benefits included within a CBA may vary greatly from project to project. The way in which benefits, like costs, are classified also varies on a project basis.

2.10 COST/BENEFIT ANALYSIS - EXAMPLE STUDIES

This Section presents two documented cost-benefit studies that have utilised urban drainage modelling techniques to investigate the merits of retrofitting source control techniques to case study catchments.

2.10.1 Assessing the benefits of Combined Sewer Overflow Abatement Measures (Attanasio, Hemphill and Lee, 1994)

Attanasio *et al.* (1994) report the findings of an investigation conducted on behalf of the City of Portland. This desk top study investigated the hypothetical costs and benefits of introducing a variety of 'interim' measures to address the ecological problems within the Willamette River posed by discharges emanating from 42 of the city's 55 combined sewer outfalls (CSOs). The major water quality problem within the Willamette River relates to the persistent violation of bacteriological (i.e. permissible e-coli) standards. The PULSEQUAL model was utilised to investigate the in-stream e-coli levels at 6 points along the river, and in particular to establish whether failure criteria of 400 counts per 100 ml had been exceeded. A variety of 'average year' model simulations were generated in which the annual 'baseline' CSO load was reduced by between 0 and 90%. These simulations indicated that prevalent e-coli levels were not significantly reduced until CSO loads were lowered by at least 40%. However, for the purpose of comparing alternative stormwater management proposals, CSO reductions were confined to between 0 and 20% - since these values reflected the anticipated performance of the proposed techniques.

A range of proposals were then evaluated in terms of their predicted effectiveness in reducing CSO loadings and assumed costs of implementation. These two factors were then equated to give the 'cost per hour of water quality violation avoided' - a parameter that allowed direct comparison between each of the alternative options.

Table 2.14 Range of alternative proposals and their comparative costs (Adapted from Attanasio R. , Hemphill B. and Lee L.E., 1994)

Alternative proposals investigated	Cost per hour of water quality violation avoided
Screening and other technologies for removing large solids and floatables	US$ 390,000
Maximising in-line storage (including passive and automatic regulators)	US$ 19,500
Removing roof drainage connections from the sewer system	US$ 56,000
Increasing sewer flushing, including evaluating time and location of flushing activities	US$ 998,000
Increasing street sweeping and/or modifying the methods employed for sweeping	US$ 1.06 million

It is evident from the above table that the two most cost effective solutions were i) maximising in-line storage and ii) removing roof drainage connections from the sewer system. Both of these were significantly cheaper than the three remaining options.

2.10.2 Balmforth & Bailey, 1985

As described within Section 2.6.1.7, Balmforth and Bailey (1985) conducted a basic cost/benefit comparison of on-site roof water storage facilities and conventional CSO storage tanks for the management of stormwater runoff. The analysis related to the provision of an 85 m^3 in-sewer storage tank or its on-site equivalent. The comparative costs of these two options were £24,000 for the on-site option and £34,000 (excluding indirect costs) for the traditional approach (Note: these are 1985 prices).

2.10.3 Problems with applying CBA to SUDS

For the majority of previous CBA studies, SUDS have been compared against conventional sewer rehabilitation schemes with respect to their hydraulic performance, economic costs, and in some cases sustainability criteria. Hydraulic performance and economic costs are tangible cost/benefit issues (i.e. those for which an accurate monetary valuation may be readily established). However, the comparative merits of both conventional and SUDS schemes are affected by a number of intangible cost/benefit issues (i.e. for which it may be difficult to assign an accurate monetary value). Examples of intangible costs/benefits include amenity, environmental, social and sustainability issues (e.g. how can a monetary value be ascribed to factors such as environmental quality, or community well being).

It should be noted that given the uncertainty associated with the financial costs for the construction, operation and maintenance of retrofit SUDS (see Section 2.5.11), even the tangible parts of these studies should be viewed with some care.

It is envisaged that only tangible factors (i.e. direct and in-direct costs/benefits) will be directly considered within this any cost-benefit/performance studies conducted as part of this thesis.

2.10.4 Summary

The Literature Review presents a number of cost-benefit studies that have been undertaken to evaluate the merits of applying retrofit SUDS systems for the remediation of urban drainage problems (Icke *et al.*, 1999; Herrmann and Hasse, 1997; Attanasio, Hemphill. and Lee, 1994; Balmforth and Bailey, 1985). These studies have generally compared SUDS against conventional urban water management methodologies using economic, and in some instances sustainability, criteria.

Hypothetical studies conducted by Herrmann and Hasse (1997) and Balmforth and Bailey (1985) indicated that roof-water based retrofit SUDS were economically viable as a sewer rehabilitation methodology.

An American study conducted by Attanasio *et al.* (1994) demonstrated that the use of retrofit SUDS was economically viable in conjunction with conventional techniques as part of an integrated programme of sewer rehabilitation works. Further 'roof-water disconnection schemes', in which roofed areas are effectively disconnected from combined sewer systems, have been shown to be valid, and subsequently adopted for a number of other North American

cities, including Minneapolis, Pittsburgh and Toronto (Norris, 1999). The North American experience runs contrary to the prevailing view within the United Kingdom, which assumes that SUDS are only viable for new development applications. The British perspective would seem to be supported by the results of the catchment X study, which rejected the use of retrofit SUDS in terms of performance. No further UK studies were found within the public domain. This illustrates the need for a detailed analysis of the impacts of retrofit SUDS with respect to UK catchments.

This thesis presents two new retrofit SUDS case studies to address this lack of UK experience. These case studies aim to compare the merits of using retrofit SUDS to address urban drainage problems against those of conventional sewer rehabilitation strategies. These investigations relate to the Meanwood and Gipton urban drainage catchments in Leeds, Yorkshire – these are two catchments, which exhibit two very different sets of drainage problems (Table 2.15).

Table 2.15 Case study catchments

Catchment Name/ Location	Description of primary catchment problems
Meanwood catchment, Leeds, Yorkshire	***Catchment flooding*** – associated with insufficient system capacity
Gipton catchment, Leeds, Yorkshire	***Aesthetics problems*** – associated with excessive CSO discharges

The selection of the Gipton and Meanwood urban drainage catchments for investigation through these studies was influenced by a number of factors:

1. The availability of data and verified models for these catchments
2. The close proximity of these catchments to the University of Sheffield
3. The range of catchment characteristics (e.g. catchment size, geographic location, performance problems, population, topography, etc) and urban drainage problems (Meanwood – Catchment flooding, Gipton – CSO/Aesthetics problems) represented by these two catchments.

These case study investigations were conducted with the intention of developing a decision support tool for the design of retrofit SUDS in a UK context. It was envisaged that this design tool would complement existing design procedures for sewer rehabilitation works, such as the UPM methodology, and incorporate the philosophical concepts and practical guidance that are presented for SUDS in the CIRIA C521, C522 and C523 (2000) guidelines. The proposed design tool should also consider the evaluation of hydraulic performance, and costs, associated with retrofit SUDS. The following Chapters explore these issues, both with respect to the case study catchments and in more generic terms.

3. FEASIBILITY STUDY: GIPTON CATCHMENT

3.1. INTRODUCTION

This Chapter presents investigations that were performed for the Gipton catchment, the first of two UK case studies conducted for this thesis. The Gipton catchment contains four problem CSOs, which contribute to aesthetics problems within a local watercourse. This study aimed to explore the feasibility of retrofitting SUDS to a typical urban environment, and to establish whether such retrofit SUDS options offered a viable means of addressing the catchment's CSO problems. It was hoped that the experiences drawn from these feasibility investigations, and the information assimilated in the literature review (Chapter 2), could be used to develop a more detailed methodology for planning and evaluating retrofit SUDS. It was intended that this detailed methodology would be subsequently developed/improved, in relation to the Meanwood case catchment. Further details of the Meanwood investigations are presented in Chapters 4-7.

This Chapter is the result of a collaborative study undertaken between Leeds City Council, Yorkshire Water and the University of Sheffield. The exact nature of the collaboration is explained here, in order to eliminate any potential for misunderstandings regarding originality and/or ownership of material.

Yorkshire Water commissioned Norman Walker, then of Leeds City Council, to conduct a preliminary study to assess the merits of using retrofit SUDS as a sewer rehabilitation strategy. In January 2000 Norman Walker issued an open invitation to the 'urban-drainage' mailing list for collaborative input, to which the University of Sheffield responded. The collaboration provided the author with an excellent opportunity to work closely with a practising engineer on a local case study.

Over a period of several months, several meetings and e-mail discussions between Walker and the author occurred. These included visits to the catchment, where discussions regarding options for retrofit SUDS took place. The author took all catchment photographs included in this thesis; either during these shared visits, or during subsequent independent site visits. Using Leeds City Council's existing hydraulic model, Walker and the author independently amended the model and undertook hydraulic simulation work. Where similar simulations were undertaken in parallel this provided an excellent opportunity to ensure that the predictions were reasonable and robust. At other times efficiencies were achieved as differing strategies were pursued by Walker and the author. An example of this was some preliminary feasibility work on the use of household water butts. The author undertook the modelling work for this, based on methodologies discussed in Chapter 5 (and also presented by *Swan et al.*, 1999). This component of the study is not presented here, as it was eliminated at an early stage of the collaborative discussions.

Leeds City Council undertook all the costings. Walker's (2000:b) report to Yorkshire Water forms the definitive report on the feasibility study. Walker (2000:a) provided a brief overview

of the project. Consequently, most of the basic data presented in this thesis was presented within these earlier reports. However, it should be noted that the present author is entirely responsible for the catchment maps (Figures 3.1 to 3.5), the GIS-based presentation of the schemes shown in Figures 3.6 to 3.9, the presentation of hydraulic performance comparisons (Figures 3.10 and 3.11) and for the analysis and interpretation of cost versus performance (section 3.4.7; figures 3.12 to 3.14). Further details of this data analysis/ interpretation exercise have been reported previously (Swan *et al.*, 2001).

3.2. GIPTON CATCHMENT

3.2.1. Background

Gipton is a residential district of Leeds, located 5 km to the North of Leeds City Centre. The Gipton urban drainage system (Figure 3.1) serves a 297.8 ha contributory catchment, which is bounded by the A6120 (Leeds Outer Ring Road) in the North and Gledhow Beck/Lake in the South. This system contains four CSO structures (CSO135, CSO136, CSO137 and CSO138) that all discharge into Gledhow Beck. Three of these CSO structures (135, 136 and 138) serve their own separate contributory sub-catchment systems, whilst CSO137 receives pass-forward flows from two upstream CSO structures (CSO135 and CSO136) in addition to runoff from its own small contributory sub-catchment system. Discharges from these CSOs have led to a series of aesthetic problems (i.e. an accumulation of sewer debris) within Gledhow Beck, a local watercourse).

Sections 3.2.2-3.2.5 present a more detailed review of the four CSOs and their contributory sub-catchments.

3.2.2. CSO135

3.2.2.1. CSO135 – Contributory Sub-catchment and Sewerage Network

CSO135 is located at the downstream end of a dendretic sub-section of the Gipton sewerage network. This network receives flow from a predominately flat residential sub-catchment, with a contributory surface area of 79.7 ha. The Moorlands and Sandringham estates, located within the Central and Northern parts of this sub-catchment respectively, are representative of much of the housing found in this locality (Figure 3.2:a and Figure 3.2:b). These estates largely comprise semi-detached housing with garden plots (200-300 m^2). The sub-catchment also contains a number of institutional buildings, including two schools, some offices, and a shopping precinct. The northern part of the sub-catchment is predominately underlain by millstone grit and sandstone, and the southern part by mudstone.

3.2.2.2. CSO 135 – Overflow Structure

CSO135 discharges into the Gledhow Beck; its outfall is located within the front garden of a residential property (Figure 3.2:d). The accessibility of this location means that public complaints are often made in relation to aesthetic pollution events. The high number of public

complaints made in relation to this overflow has served as a trigger for investigating remedial proposals.

The existing storage chamber of CSO135 is located under a busy public highway at the junction of Harrogate Road and Stainbeck Road (Figure 3.2:c). The location of this CSO means that it would be difficult to upgrade this structure, using conventional rehabilitation techniques, without incurring major traffic disruption. This factor obviously increases the financial costs associated with any conventional up-grade options for this structure.

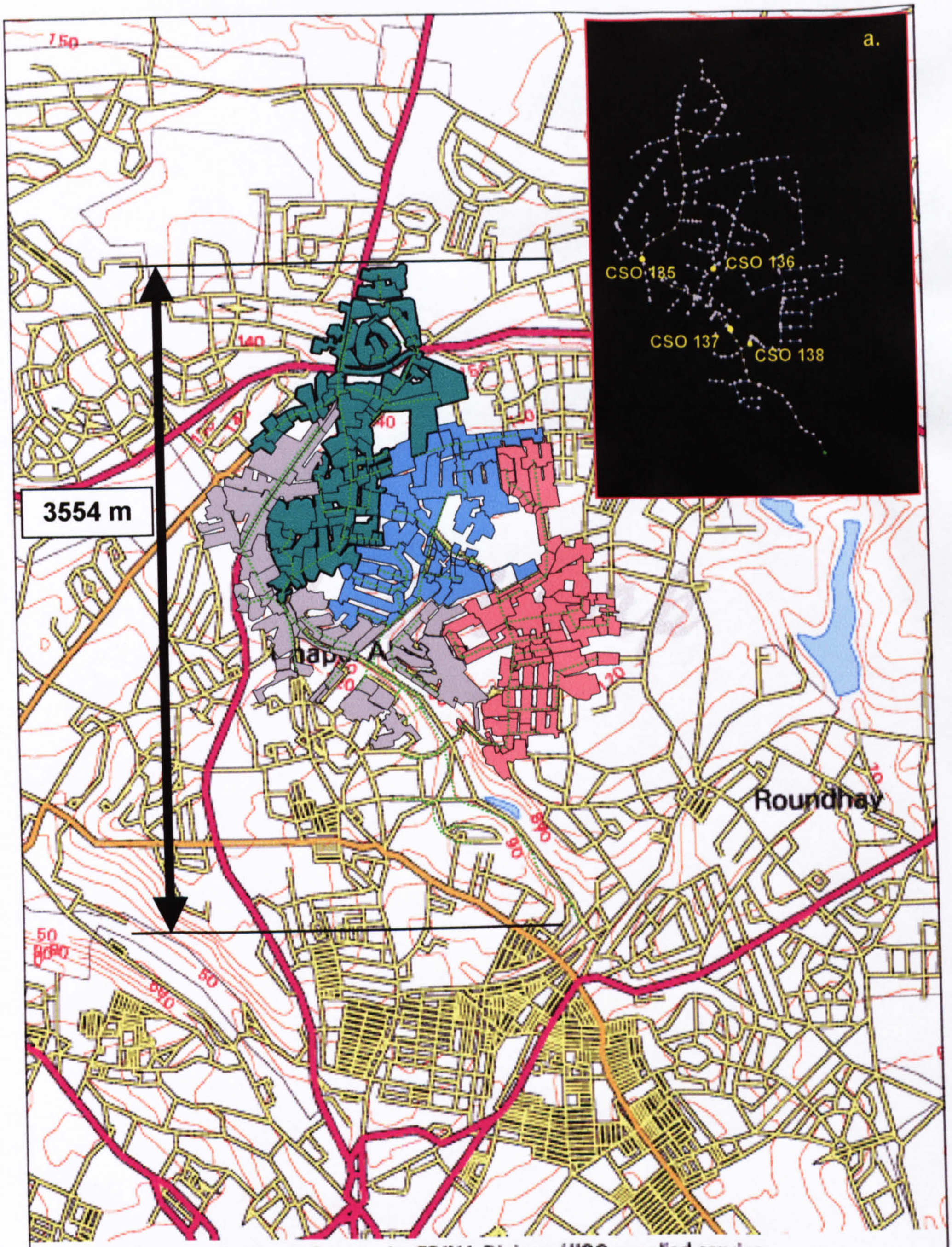


Figure 3.1

Gipton urban drainage system overlaid onto an Ordnance Survey map with the contributory areas of each CSO denoted by different colours:

CSO135 – Green, CSO136 – Red, CSO137 – Grey and CSO138 – Blue

a) Layout of Gipton sewerage system

Notes: The North-South distance of Gipton catchment is 3554 m

North/South axis always corresponds to the page's Top/Bottom axis

Aspect ration is preserved for all ensuing representations of Gipton catchment

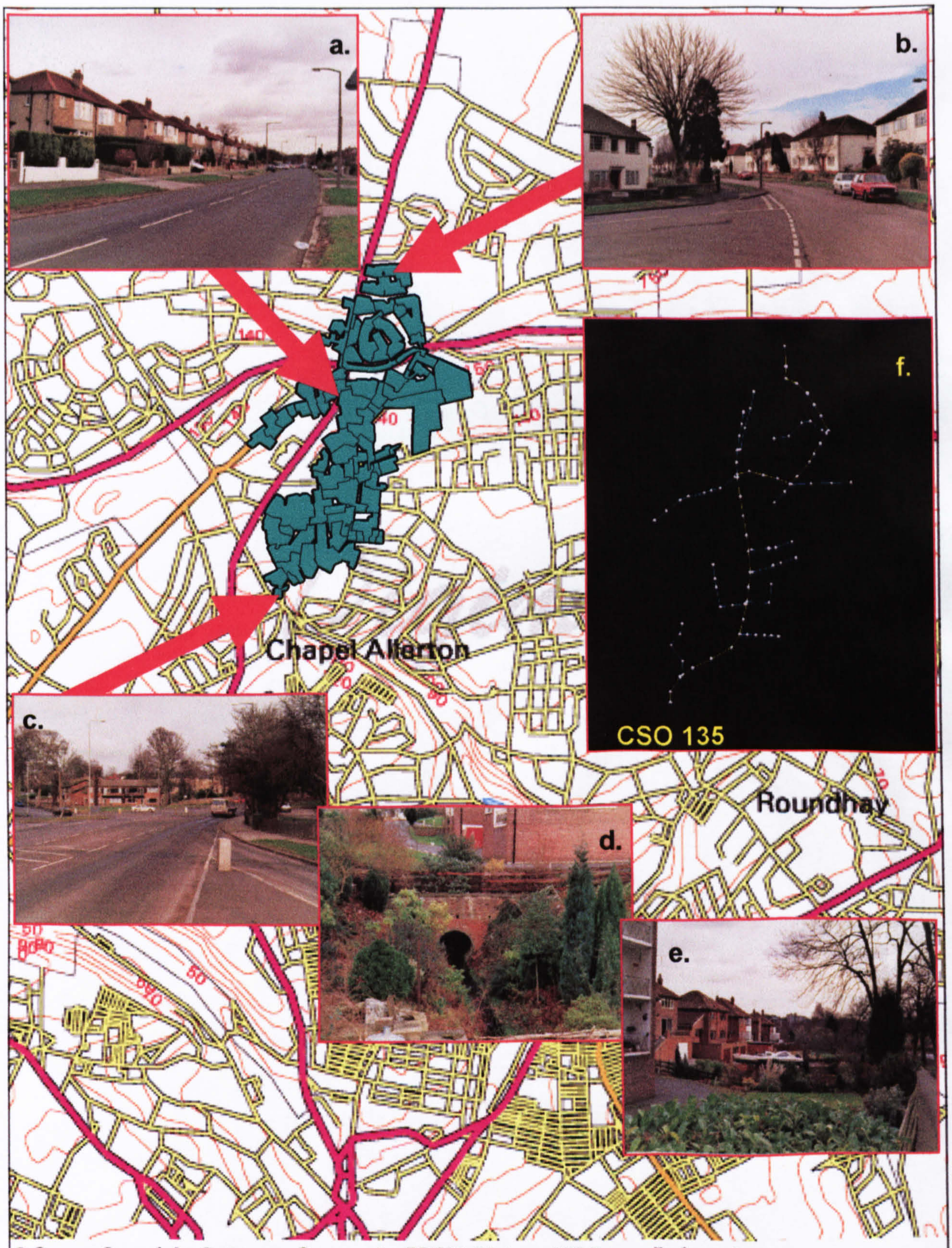


Figure 3.2

CSO135 Sub-catchment:

a) Moorlands Housing Estate (off Sweet Lane) Grid Ref: (30650,38550) (View: W)
b) Sandringham Drive (corner of Sandringham Cres.) Grid Ref: (30850,39500) (View: S)
c) Site of CSO 135 (Junction of Harrogate Road and Stainbeck Road)
Grid Ref: (30450,37800) (View: N)
d) Outfall of CSO 135 (off Harrogate Road) Grid Ref: (30600,37650) (View: NW)
e) Outfall of CSO 135 (off Harrogate Road) Grid Ref: (30600,37650) (View: SE)
f) Layout of CSO135 sewerage sub-system

3.2.3. CSO136

3.2.3.1. CSO136 – Contributory Sub-catchment and Sewerage Network

CSO136 serves a small residential sub-catchment that contains the Allerton Grange and Moor Allerton housing estates. These estates largely comprise semi-detached, and some terraced, properties (Figure 3.3:a and Figure 3.3:b), and are therefore generally more densely housed than those of the CSO135 sub-catchment. The sub-catchment also contains Allerton Grange School. The total contributory surface area of the sub-catchment is 56.1 ha. This is served by a small section of dendretic sewerage, which feeds into CSO136 (Figure 3.3:e). The sub-catchment is generally steeper than the CSO135 sub-catchment, and subsequently this sewerage system contains some steeper Sections of pipe-work. The main trunk sewer slopes moderately from the Northeast to the Southwest of the sub-catchment. The steepest sewers are the branch Sections that feed into the trunk, including those that serve the Allerton housing estate in the west of the sub-catchment. Sandstone underlies much of the northern and southern edges of this sub-catchment, whilst the central area is largely underlain by mudstone.

3.2.3.2. CSO 136 – Overflow Structure

CSO136 discharges into a ditch that is located within a wooded area adjacent to the Allerton housing estate (Figure 3.3:d). This is a relatively inaccessible location, and as a result few public complaints are made about discharges/aesthetic pollution emanating from this structure.

3.2.4. CSO137

CSO137 receives pass forward flows from CSOs 135 and 136, and serves its own small contributory area. The characteristics of its feeder sub-catchment are similar to those of CSO135, particularly in terms of its topography and constituent building or housing types. However, as this structure receives pass-forward flows from two upstream CSOs, in addition to its own contributory sub-catchment, the performance of this structure may not be directly attributed to the flows it receives from its own locality.

Like CSO135, this structure discharges within a publicly accessible area, and is the subject of a number of public complaints.

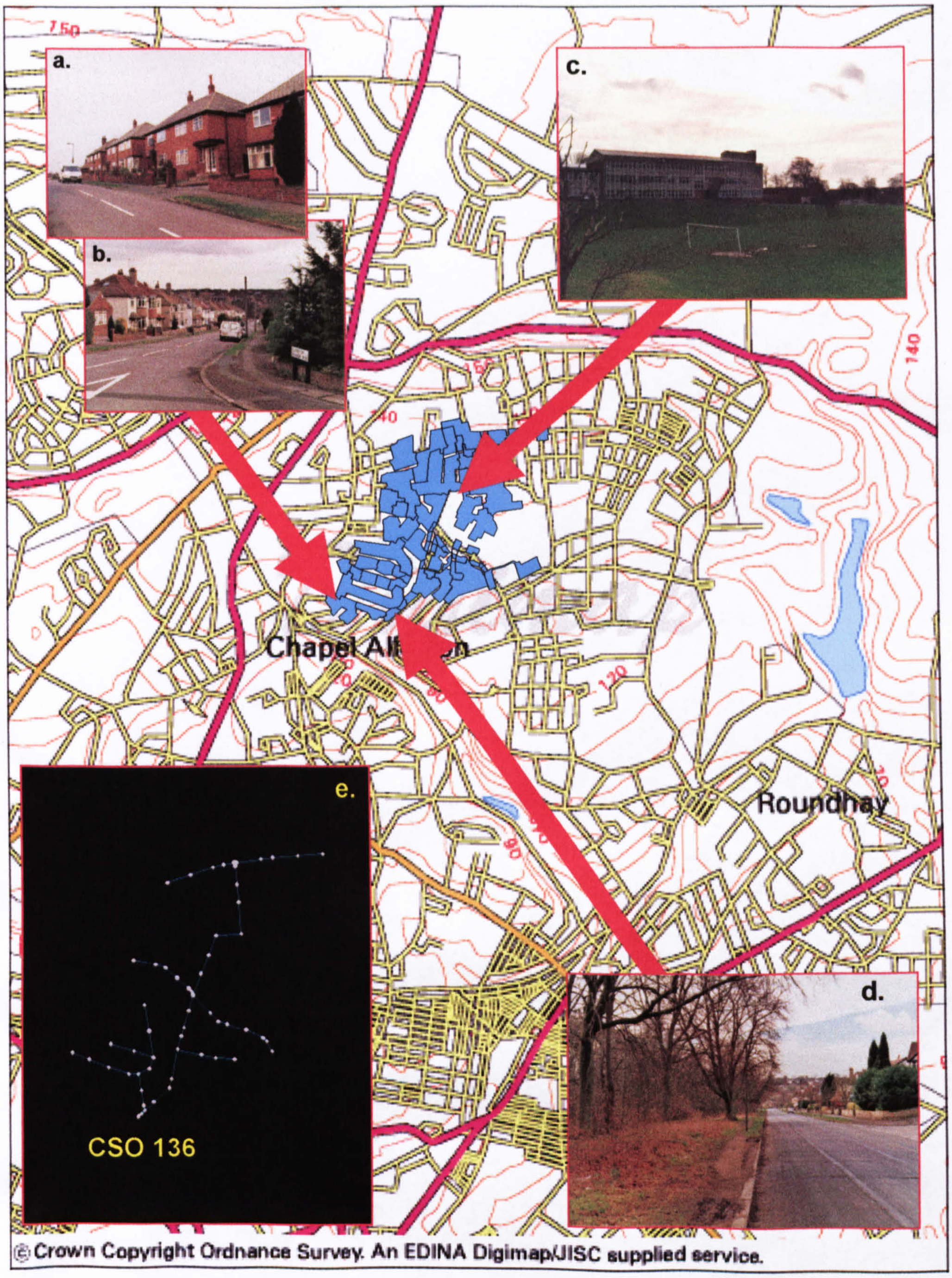


Figure 3.3

CSO136 Sub-catchment:

a) Allerton Grange Rise (corner of Stainburn Tier) Grid Ref: (30700, 37800) (View: NW)
b) Allerton Grange Rise (corner of Allerton Grange Gardens Grid Ref: (View: SE)
c) Allerton Grange School (Talbot Ave) Grid Ref: (31350,38475) (View: SE)
d) Site of CSO 136 (Allerton Grange Way - CSO Outfall on left) Grid Ref: (31036,37839) (View: SW)
e) Layout of CSO136 sewerage sub-system

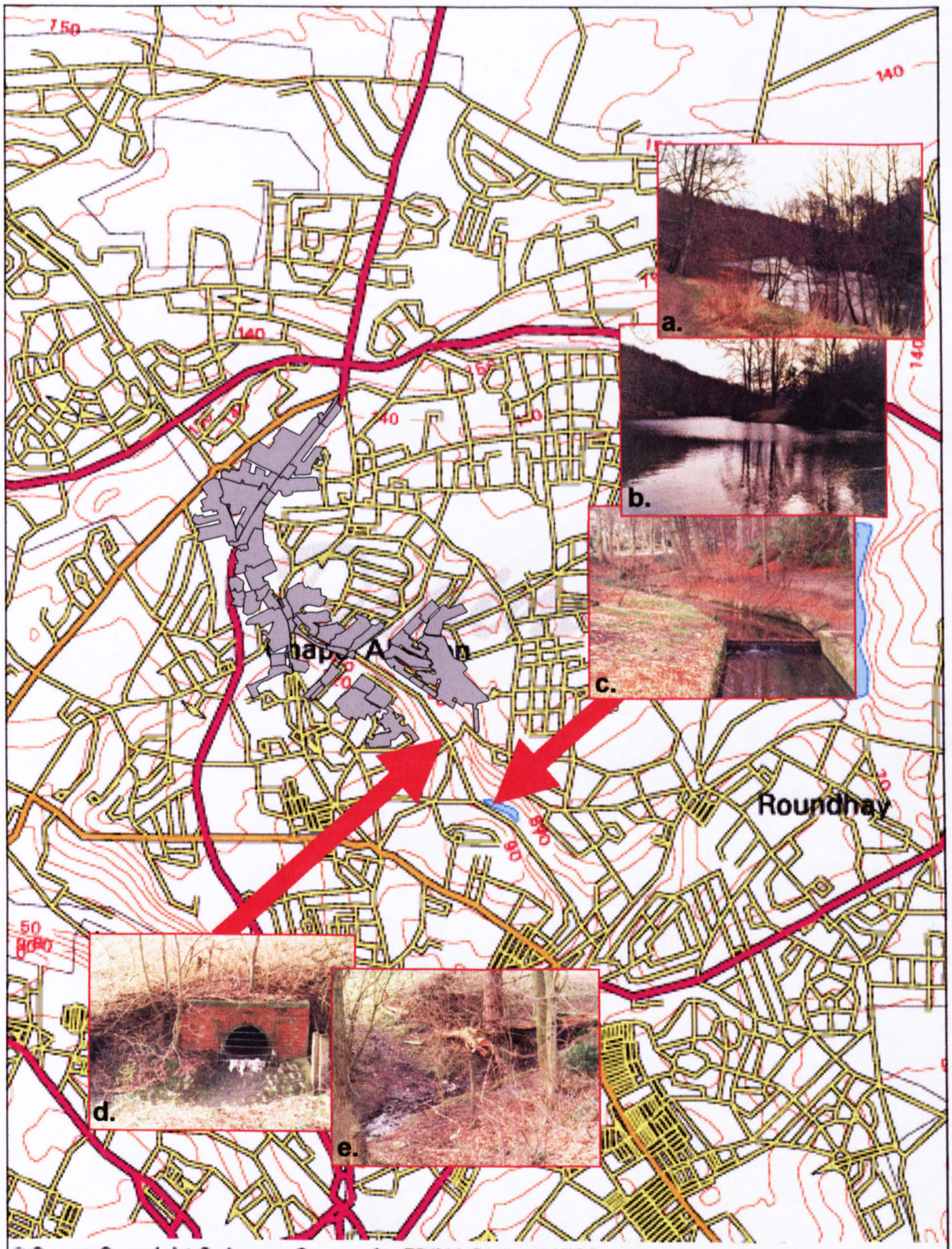


Figure 3.4

CSO137 Subcatchment:

a) Lake (Gledow Park) Grid Ref: (31700,36700) (View: S)
b) Lake (Gledow Park) Grid Ref: (31700,36700) (View: S)
c) Settlement Trap - Inflow to Lake (Gledow Park) Grid Ref: (31500,36700) (View: NW)
d) Site of CSO 137 (Gledow Valley Road) Grid Ref: (31163,37302) (View: SW)
e) Site of CSO 137 (Gledow Valley Road) Grid Ref: (31163,37302) (View: SW)

3.2.5. CSO138

3.2.5.1. CSO138 – Contributory Sub-catchment and Sewerage Network

This CSO serves a residential area that largely consists of terraced and some semi-detached housing. The sub-catchment has two distinct residential areas that are formed by the Gledhow and Lidgett Estates. The Gledhow estate (Figure 3.5:d) contains late 19th century terraced and some detached housing, and contains some large grassed areas (park/sports field). The Lidgett estate largely comprises newer semi-detached housing, and has fewer grassed areas. Both localities are generally more densely housed than those associated with CSO135 and 136. Garden plots within both the Gledhow and Lidgett estates are generally smaller than those within the sub-catchments of CSO135 and 136. Similarly, the roads that run through these two estates are generally narrower than those in these other areas, and are not lined by grassed verges.

The majority of this sub-catchment is founded upon a relatively flat plateau area. This plateau falls steeply down towards the Gledhow Beck, in the southwest of the sub-catchment. This area is underlain by a variety of permeable strata.

3.2.5.2. CSO 138 – Overflow Structure

CSO 138 is located at the base of a dendretic section of sewerage, and receives runoff from 63.3 ha of contributing surface area. The CSO is sited adjacent to the Gledhow Beck, at the foot of a steeply inclined section of sewerage. The CSO storage tank is located beneath Gledhow Lane.

3.2.6. Overview of Gipton's CSO Spill-related Problems

The Gipton catchment contains four CSO structures, all of which discharge into the Gledhow Beck at different locations upstream of Gledhow Lake. These discharges have led to a series of aesthetic problems (i.e. an accumulation of sewer debris) within the Beck. The water quality implications of these CSO discharges into the Gledhow Beck are unclear.

A typical solution to these aesthetic problems would be to retrofit screens within each of the four CSOs. However in this instance, this approach was not considered viable due to spatial limitations within these structures (Walker, 2000:b), and the possible river quality implications of their discharges. Therefore, other strategies to address these aesthetic pollution problems were explored; these included traditional rehabilitation options and the use of retrofit SUDS. Traditional rehabilitation options generally seek to increase the capacity of the sewerage system in order to reduce the frequency of overflow discharges. SUDS-based options generally seek to reduce overflow discharges by attenuating and controlling the peak levels of catchment runoff entering the sewerage system.

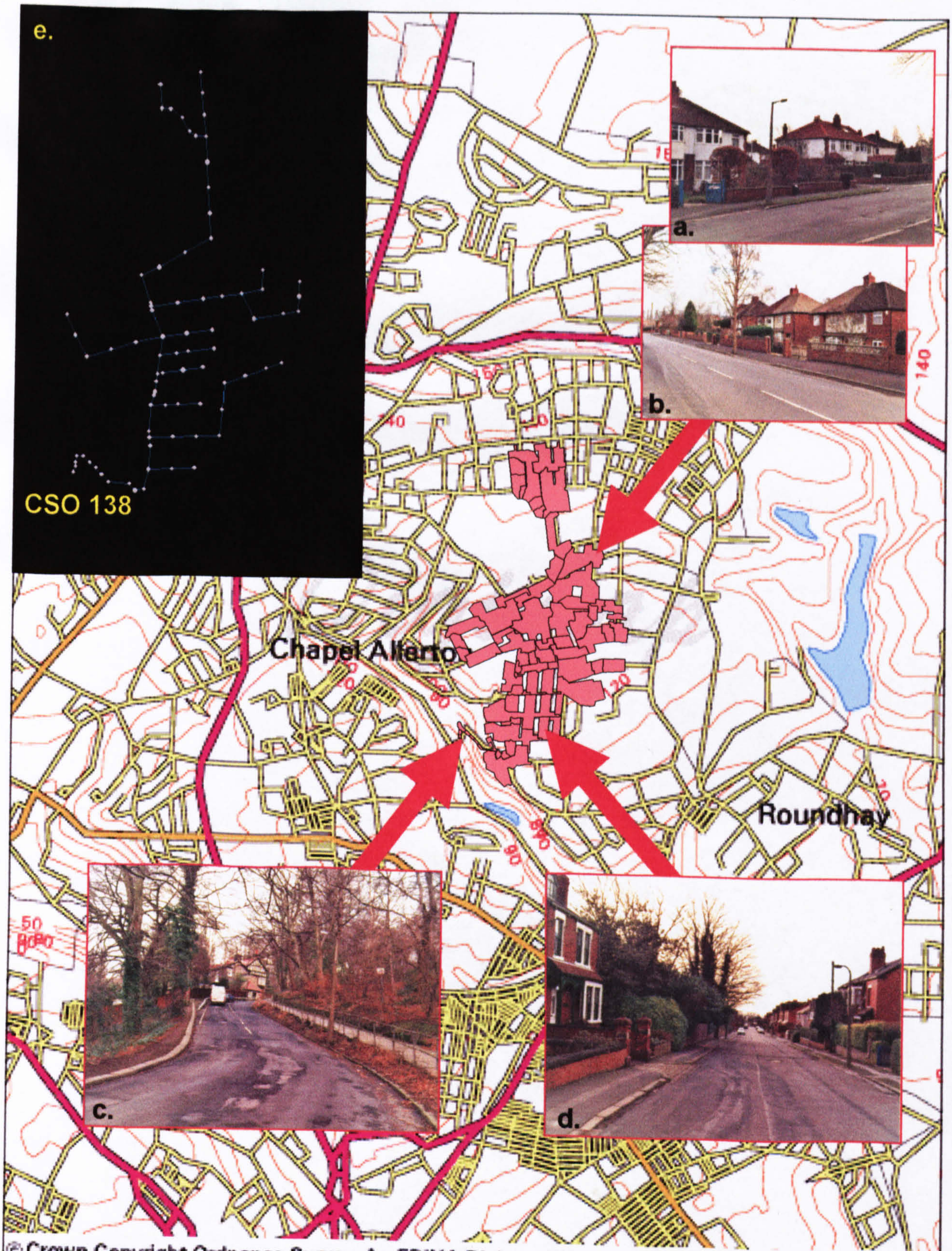


Figure 3.5

CSO138 Subcatchment:

a) Lidgett Place (Corner of North Park Ave) Grid Ref: (31850,38000) (View: S)
b) Lidgett Mount (Lidgett Park Estate) Grid Ref: (31980,38200) (View: S)
c) Site of CSO 138 (Tank under Road: Gledow Park) Grid Ref: (31352,37182) (View: N)
d) Lidgett Grove (Corner of Gledhow Wood Ave) Grid Ref: (31850,37350) (View: E)
e) Layout of CSO138 sewerage sub-system

3.3. GIPTON CATCHMENT - COMPARATIVE STUDY

3.3.1. Background

A comparative design exercise was conducted to evaluate a range of conventional and SUDS-based proposals for reducing aesthetic pollution within the Gipton catchment. This collaborative study was commissioned by Yorkshire Water and jointly undertaken by Leeds City Council (Walker, 2000:b) and the University of Sheffield (Swan *et al.*, 2001).

It is important that the theoretical nature of this study be acknowledge. Some of the procedures adopted in this case study diverge slightly from current regulatory requirements. For example, none of the rehabilitation (i.e. both conventional and SUDS) options presented in this Chapter fully comply with regulatory requirements for aesthetics control as outlined by the UPM methodology (FWR, 1998), which stipulate the removal of aesthetics using screens. Similarly, the use of TSR (as opposed to long rainfall time-series) does not represent current UPM-based modelling practice (FWR, 1998). However, the exercise does provide a basic level of comparison between conventional and SUDS-based rehabilitation options, in terms of their associated costs and hydraulic benefits.

3.3.2. Development of conventional rehabilitation proposals

Conventional proposals were developed for the alleviation of CSO related aesthetic problems within the Gipton catchment. Leeds City Council conducted all detailed design work associated with these solutions (Walker, 2000:b). Each of the four Gipton CSOs was redesigned in accordance with the FR0488 (FWR, 1994) and SDD (SDD, 1977) design guidelines. The FR0488 guidelines are widely used within the UK for the design of sewer overflow structures. As described in Chapter 2, the SDD guidelines are an older methodology that was specifically compiled for the design of sewer overflow structures within Scotland. The SDD methodology generally produces more conservative solutions, and in this instance was used to assess whether further storage might be needed in addition to that included in the FR0488 designed solutions. This more conservative design approach was adopted because these structures were discharging into a high amenity watercourse.

Table 3.1 Conventional Design solutions for Gipton's four CSO structures (Adapted from Swan *et al.*, 2001)

Conventional Design Solution	Proposed Solutions
CSO135	The redesigned CSO135 utilises an extended stilling bay overflow, with combined storage of 500m^3 within the CSO and adjacent pipe-work. This solution incorporates screening and additional storage as calculated by the SDD method.
CSO136	This solution adopts an extended stilling bay overflow, with sufficient storage achieved using the FR0488 design methodology. The provision of a screen was deemed unnecessary due to the public inaccessibility of the CSO's location.
CSO137	This solution, which adopts an extended stilling bay overflow, was designed using the FR0488 approach, with an additional 250 m^3 of storage calculated using the SDD methodology. In this case, screens were incorporated into this design as the overflow was situated within a highly visible location.
CSO138	This structure is located on a steep hill, and surrounded by rock. These factors led to the selection of a hydrodynamic separator design for this location, because it avoided the need for additional storage or screening. The design of this structure was conducted in accordance with FR0488 methodology.

3.3.3. Development of SUDS proposals

3.3.3.1. Preliminary observations

The potential for retrofitting SUDS devices to the Gipton catchment was explored through a collaborative study between Leeds City Council and the University of Sheffield (Swan *et al.*, 2001). This analysis was conducted on a street-by-street basis, and sought to identify all locations where SUDS techniques represented a viable option. This investigation was conducted in accordance with the SUDS Design Manual methodology (CIRIA, 2000), and considered a range of geographic, geological, legislative and social issues. The preliminary findings of this investigation are discussed below, with respect to each of the four Gipton CSOs.

3.3.3.2. CSO135 Sub-catchment

The southern part of this sub-catchment lies predominately upon mudstone soils, which have low percolation rates and are therefore not well suited to the use of infiltration-based SUDS. However the northern part of the catchment is largely underlain by millstone grit and sandstone, both of which are considered to be more appropriate for infiltration-based techniques. House gardens within this part of the catchment are typically large enough to allow soakaways, or other infiltration devices, to be constructed more than 5 m away from any building, in compliance with the UK's Building Regulations (1991).

Most roads within this sub-catchment are lined with 1.5-2 m wide grass verges; these were identified as viable locations for retrofit SUDS conveyance systems (e.g. filter drains or swales). It was considered that such structures might be used to drain surface runoff in conjunction with an existing land drainage network, located within the central swath of the catchment. All ground slopes within this part of the catchment are flat enough to comply with the recommended guidelines for swales contained with the SUDS design manual (CIRIA, 2000). The SUDS design manual (CIRIA, 2000) recommends longitudinal slopes of less than 1 in 17 for effective

infiltration from base of a swale, and longitudinal slopes less than 1 in 50 to prevent erosion of the base of a swale.

There is potential to use source control storage devices, such as water butts or ponds, within most of the region's residential areas. However, there is very little potential to introduce larger scale storage devices due to the limited amount of available space within the region.

3.3.3.3. CSO136 Sub-catchment

The northern and southern parts of this sub-catchment are largely underlain by sandstone, and therefore considered to be well suited to the use of infiltration-based SUDS. The central zone is underlain by mudstones, and therefore deemed less suitable for infiltration devices.

Houses in the northern part of the sub-catchment generally have big enough gardens for the use of source control infiltration devices (i.e. to allow the infiltration device to be placed more than 5 m from property), the southern part of the catchment is more urbanised, and hence less suited to the use of source control infiltration devices. The northern/central part of the sub-catchment also contains the Allerton Grange School, which is surrounded by a large green-field site. This was highlighted as a potential location for larger scale off-site devices – the local geology means that infiltration, as well as detention, facilities are feasible at this site.

Many roads in this sub-catchment are lined with wide grass verges. These were highlighted as potential locations for filter drains or swales. However, it was envisaged that steep slopes would restrict the use of swales within the central swath of this sub-catchment, and limited open spaces would restrict their use within the far south of the sub-catchment. A separate sewer network already served some southern parts of the sub-catchment.

The use of source control storage devices, such as water butts or ponds, is considered to be feasible within most of the region's residential areas.

3.3.3.4. CSO137 Sub-catchment

The southern part of the catchment was largely considered suitable for infiltration, whereas the northern part is predominately underlain by muds and hence considered unsuitable for infiltration devices. The geological conditions and housing types within both the far north and far south of this catchment were considered to be appropriate for the use of source control infiltration devices. Harrogate Road and Gledhow Park Road run through the middle of this sub-catchment. Both roads are lined by grass verges, and therefore considered appropriate locations for the use of conveyance systems. The larger grass areas adjacent to this road were highlighted as potential locations for off-site infiltration devices – the local geology means that infiltration, as well as detention facilities are feasible at this site.

Source control storage devices, such as water butts or ponds, are considered to be feasible within most of the region's residential areas. However, larger scale storage devices there are not considered feasible due to the limited available space within the region.

3.3.3.5. CSO138 Sub-catchment

Most of the region lies upon permeable strata, considered to be well suited for infiltration. However, high housing densities render both source and off-site control devices impracticable within much of this sub-catchment. However, houses in the central/southern part of the sub-catchment generally have big enough gardens for the use of soakaways, and some other source control infiltration devices. Most properties are considered large enough for the use of water butts, but not ponds. Larger scale off-site storage facilities are not considered feasible due to the limited available space within the region.

There are very few roads within this region that contain grassed verges, and most pavements are tarmac sealed. The roads in this locality are generally narrower than those associated with the CSO135 and 136 sub-catchments – the use of swales or filter drains was deemed to be less viable within much of this region.

3.3.3.6. Summary

The preliminary observations described above were collated and used to define suitability maps for retrofitting infiltration SUDS and storage-based SUDS to the Gipton catchment. Figures 3.6-3.7 present suitability maps for retrofitting infiltration SUDS to the Gipton catchment, and Figures 3.8-3.9 present suitability maps for retrofitting storage-based SUDS. These suitability maps graphically highlight areas considered suitable for a range of retrofit SUDS: conveyance systems; source-control infiltration systems; off-site infiltration systems and off-site detention systems. It is evident that source control detention systems, such as water butts, were considered to be appropriate for retrofitting to most of Gipton's domestic properties. Maps were generated for each of the four feeder catchments that are served by the Gipton CSOs. The sub-catchment regions used in these maps correspond to those of a HydroWorks model that was derived for the Gipton catchment by Leeds City Council (Walker, 2000:b).

3.3.4. Integrated retrofit proposal

The preliminary observations described within the previous Section were used to develop an *integrated SUDS-based solution* (Walker, 2000:a) for the alleviation of the Gipton catchment's aesthetic pollution problems. This proposal is presented in Table 3.2 and the ensuing paragraphs. These proposals were developed in accordance with the SUDS design manuals (CIRIA, 2000).

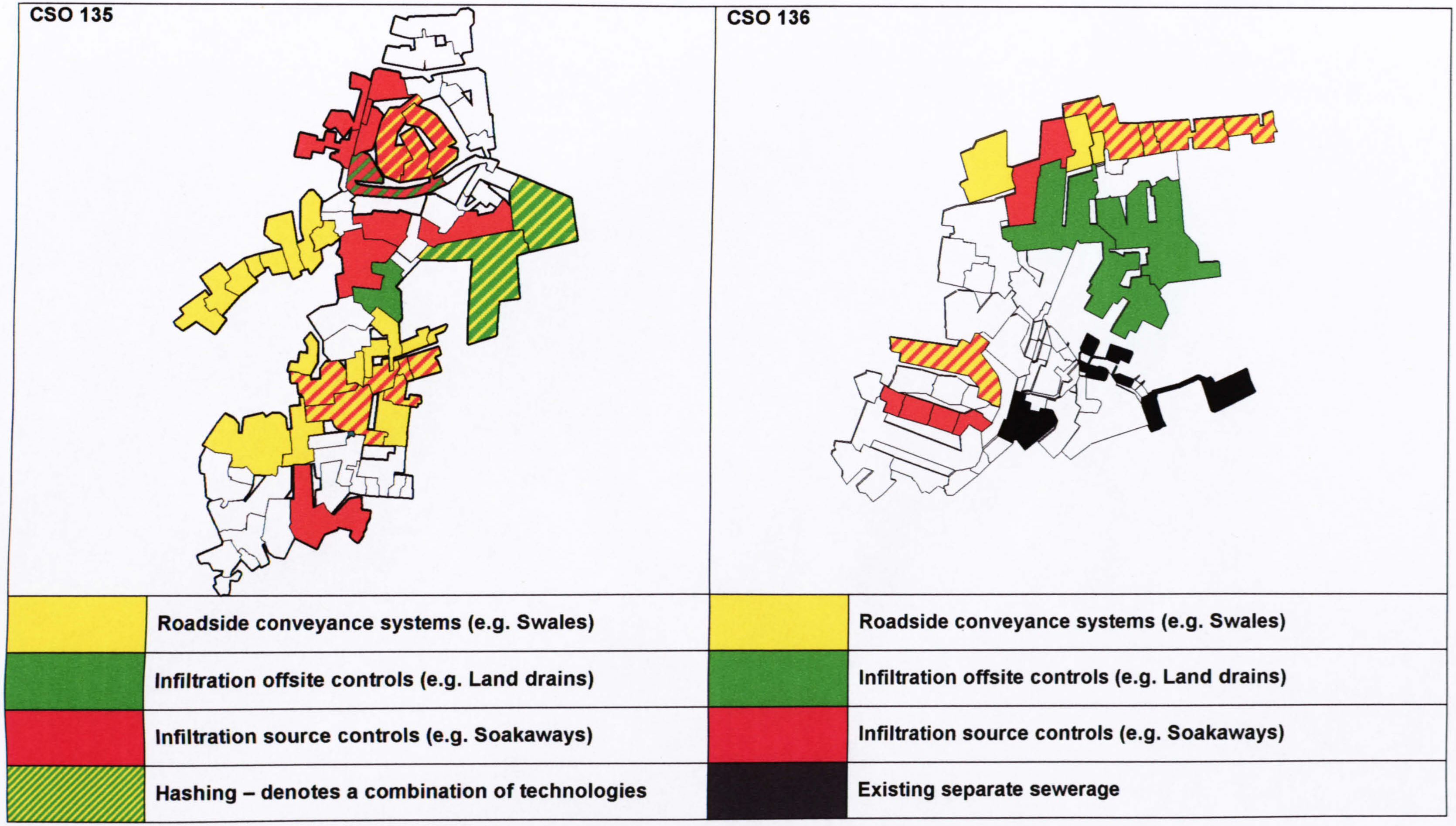


Figure 3.6 Suitability maps for retrofitting Infiltration SUDS to the Gipton catchment

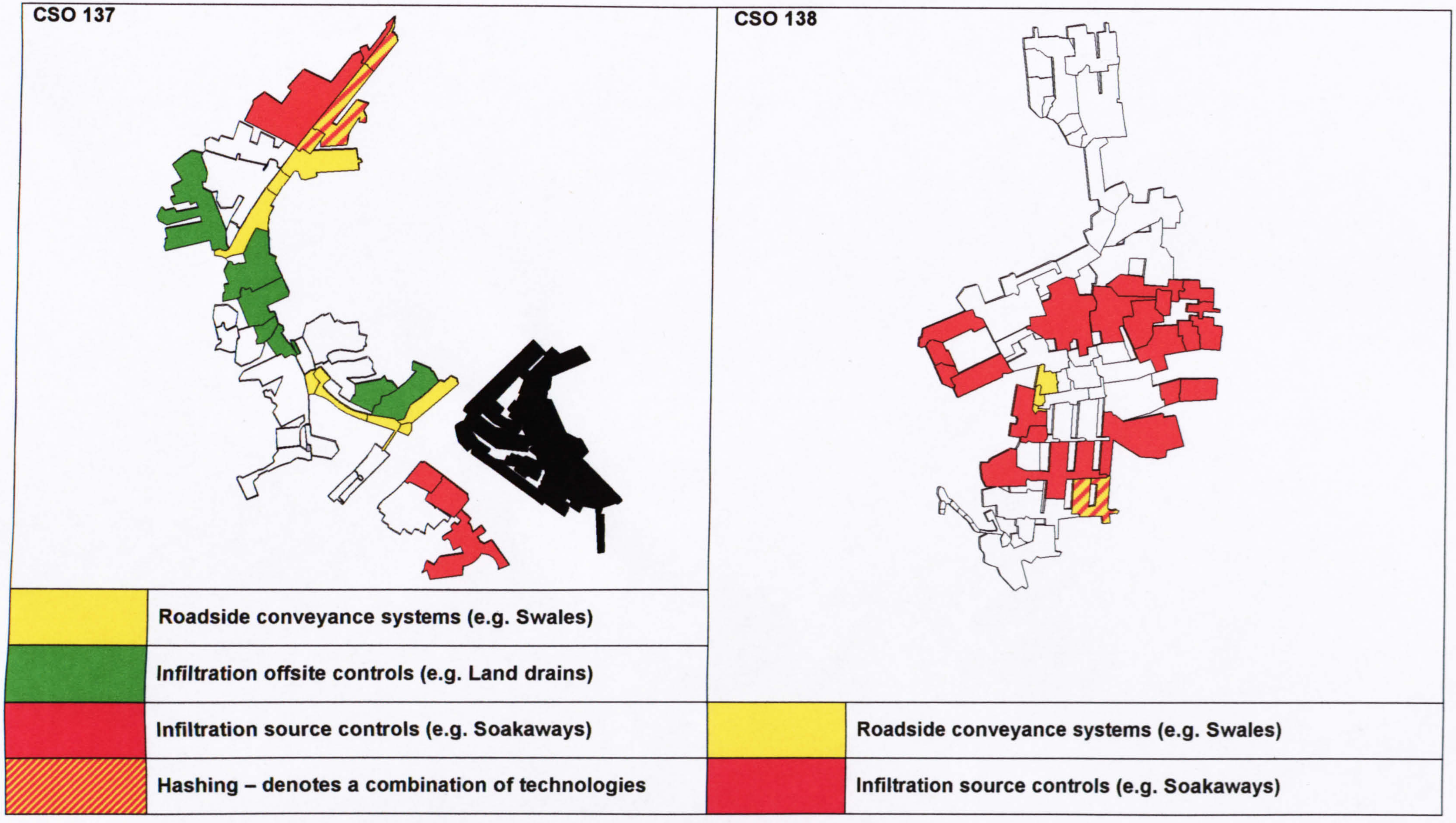


Figure 3.7 Suitability maps for retrofitting Infiltration SUDS to the Gipton catchment

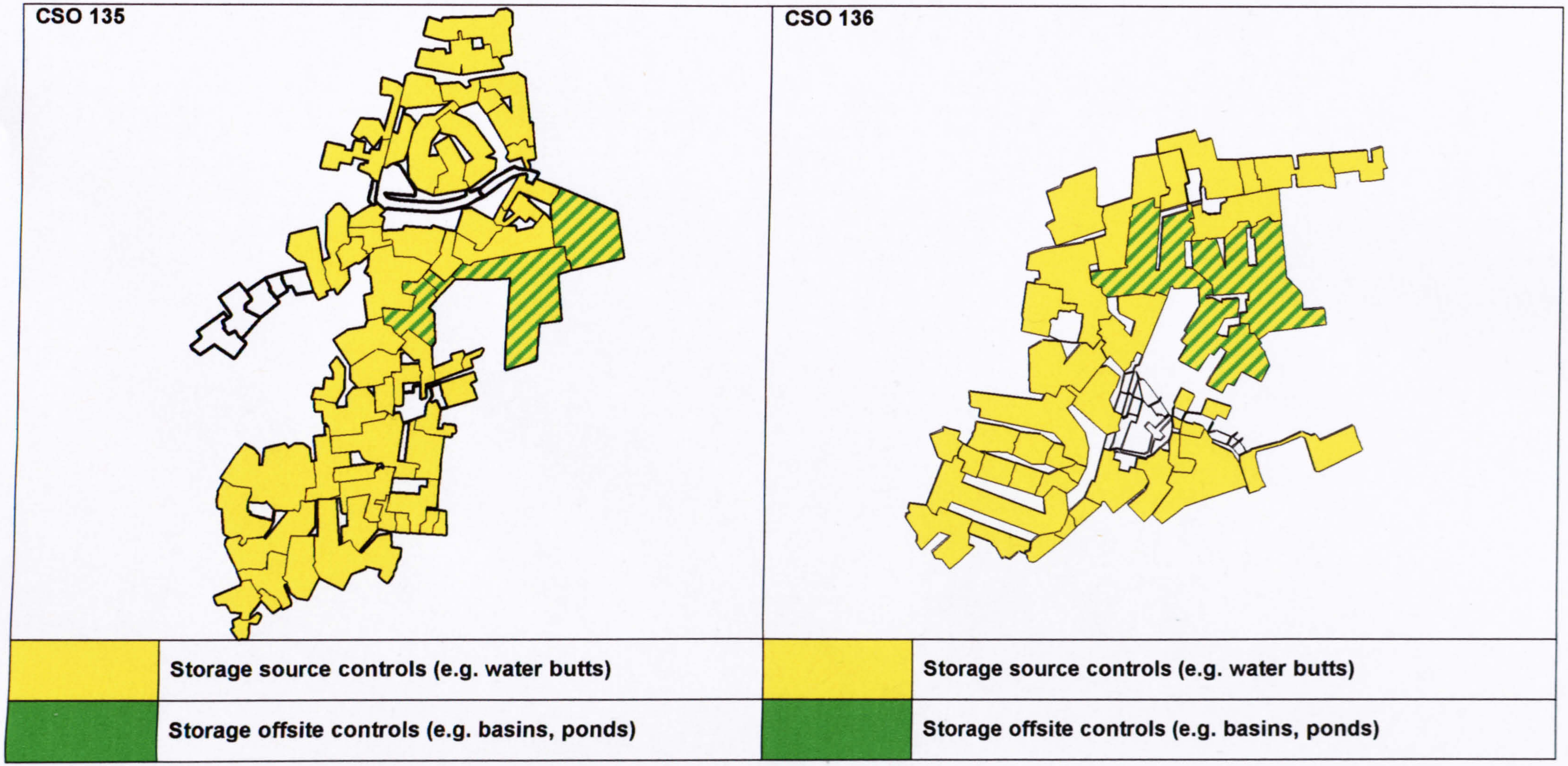


Figure 3.8 Suitability maps for retrofitting storage SUDS to the Gipton catchment

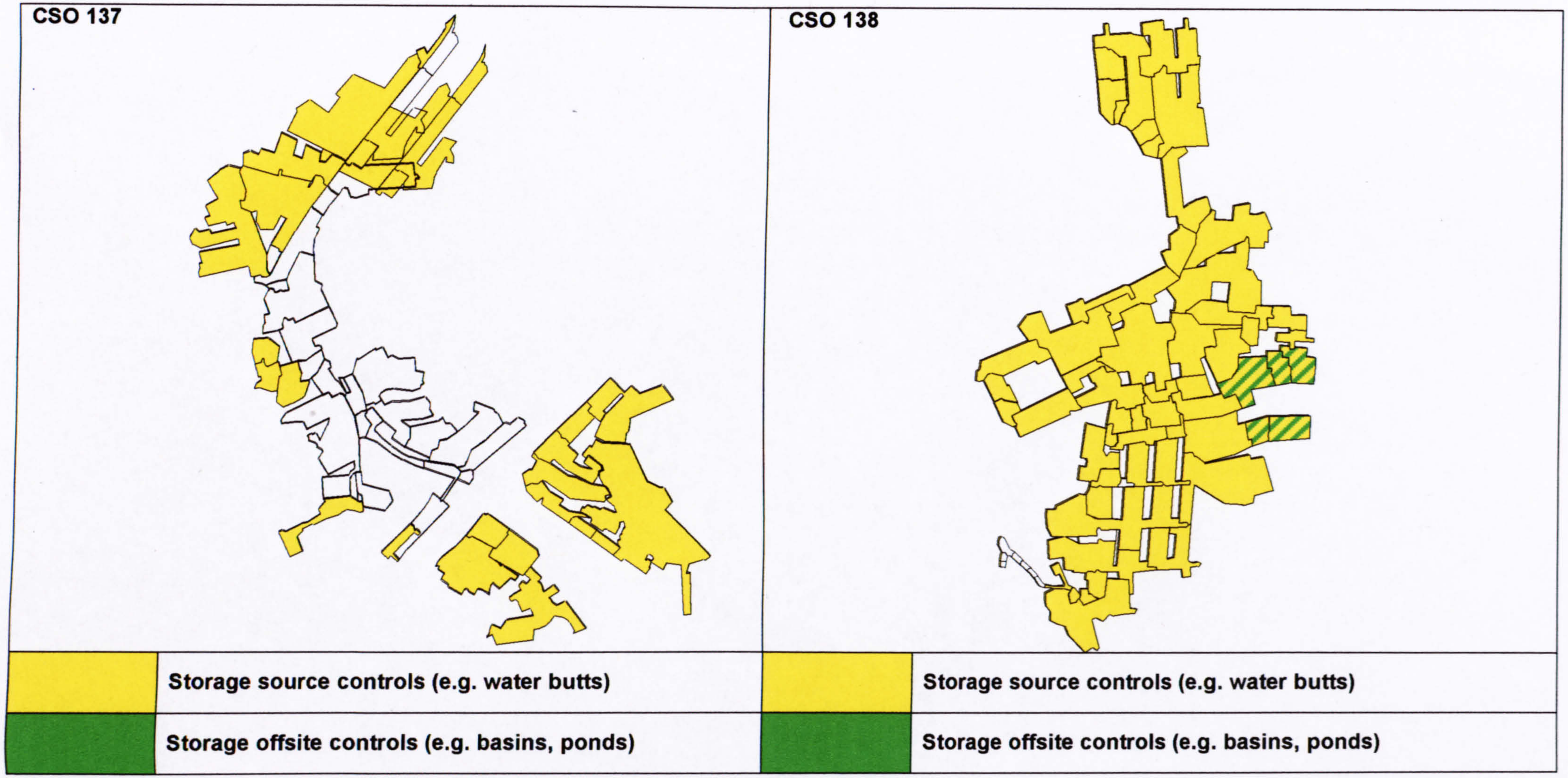


Figure 3.9 Suitability maps for retrofitting storage SUDS to the Gipton catchment

Table 3.2 Summary of Leeds City Council's SUDS-based proposal for Gipton (Swan *et al.*, 2001)

	Proposed Solutions
CSO 135	
Northern region	Use of infiltration techniques and swales in conjunction with existing land drainage
Central region	Use of soakaways/Infiltration techniques and swales
Southern region	Use of swales in conjunction with existing land drainage
CSO 136	
Northern region	Small scale use of swales & infiltration techniques
Southern region	Large land drainage scheme at Allerton Grange School site
CSO 137	
Northern region	None
Southern region	Use of soakaways/Infiltration
CSO 138	
Northern region	None
Southern region	Widespread use of soakaways/Infiltration techniques and small-scale use of swales

This proposal comprises the disconnection of 12.26 ha of roofed area (*31% of the existing total catchment roofed area of 39.52 ha*) and 16.96 ha of paved area (*28% of the existing total catchment paved area*). It is worth noting that this proposal is based upon the assumption that all impervious (i.e. paved and roofed) areas deemed suitable for disconnection, within the feasibility studies, are completely disconnected from the catchment's sewers. However, it is unlikely that this idealised target of 'complete disconnection' for all areas, which were highlighted as being viable for the use of SUDS, would ever be achieved in reality. The actual levels of surface disconnection achieved within these areas would depend upon the take-up rate of individual roof-disconnections by local residents, and road-disconnections by local authority and the Highways Agency. To address this level of uncertainty, the hydraulic performance of a number of alternative SUDS options, which represented a range of disconnection scenarios for both paved and roofed surfaces (Table 3.3), were simulated using the HydroWorks model and compared with the simulated performance of the conventional rehabilitation scheme described in Section 3.3.2. Further details of this comparative modelling exercise are presented with the following Sections.

For all the SUDS-based proposals it was assumed that complete disconnection of all institutional roofs and all dwellings that could be easily connected to the separate system would occur. This accounted for 3.78 ha, or approximately one third, of the roofed area for which disconnection was considered to be viable. The scenarios presented in Table 3.3 assume that between 20 and 100% of the remaining roofed area would be disconnected. Hence the notation 20/x, used in Table 3.3, actually refers to a scenario in which nearly half of the disconnectable roofed area has been removed.

Table 3.3 Summary of Leeds City Council's SUDS-based proposals for Gipton (from Swan *et al.*, 2001)

SUDS Proposal	Description	Roof area connected (ha)	No. of Houses disconnected	Road area connected (ha)	Approx. length of connected Road (km)
-	Existing state	39.52	0	59.65	75
100/100	Complete disconnection of all viable roads and roofs	27.26	743[(1)] + 501[(2)] + 709[(3)]	42.69	56
100/50	Disconnection of all viable roofs and 50% of viable roads	27.26	743 + 501 + 709	50.63	66
80/100	80% disconnection of all viable roofs and 100% of viable roads	28.96	743 + 396 + 575	42.69	56
80/50	80% disconnection of all viable roofs and 50% of viable roads	28.96	743 + 396 + 575	50.63	66
60/100	60% disconnection of all viable roofs and 100% of viable roads	30.65	743 + 298 + 426	42.69	56
60/50	60% disconnection of all viable roofs and 50% of viable roads	30.65	743 + 298 + 426	50.63	66
40/100	40% disconnection of all viable roofs	32.34	743 + 198 + 287	42.69	56
40/50	40% disconnection of all viable roofs and 50% of viable roads	32.34	743 + 198 + 287	50.63	66
20/100	20% disconnection of all viable roofs	34.04	743 + 97 + 144	42.69	56
20/50	20% disconnection of all viable roofs and 50% of viable roads	34.04	743 + 97 + 144	50.63	66

Notes:
[(1)] Number of dwellings that can be easily added to existing separate system (i.e. due to their close proximity, or misconnections into foul sewer)
[(2)] Number of dwellings that can be totally disconnected
[(3)] Number of dwellings that can be partially disconnected
For 'SUDS' proposal names the first figure relates to the roof area disconnected, the second to the road area disconnected

3.4. COMPARATIVE STUDY

3.4.1. Introduction

Leeds City Council (Walker, 2000:b) undertook much of the modelling work for this comparative exercise, with independent validation conducted at the University of Sheffield (See Section 3.5). The results of these simulations were analysed collaboratively (Swan *et al.*, 2001). Leed City Council compiled and validated a HydroWorks model for the Gipton catchment, as part of a drainage area survey that was undertaken in 1994. This model was verified against monitored data collected from around each of Gipton's four CSOs.

This model was used as the basis for these modelling investigations. Amended versions of the HydroWorks Gipton catchment model were used to simulate the hydraulic performance of the Gipton drainage system under each of the eleven rehabilitation proposals (one conventional, and ten SUDS-based) outlined in Table 3.3.

The HydroWorks models used to represent the eleven alternative rehabilitation proposals were each derived by amending the 'existing state' HydroWorks model. For each SUDS proposal, the model's 'contributing surface' input parameters were updated to represent the paved, roofed and impervious area associated with each option – this required model parameters to be changed at the sub-catchment level. Further details on the SUDS modelling techniques that were developed for HydroWorks are presented in Chapter 5. The conventional rehabilitation proposal featured in Section 3.3.2 was represented by amending the catchment model's manhole parameters to increase the available in-sewer storage.

The accuracy of the catchment model is obviously an important issue in relation to this form of analysis. Catchment models that have been verified against monitored flow data are likely to be more accurate than those that have not. The model was verified against monitored data collected from around each of Gipton's four CSOs. However, amended catchment models were used to represent the performance of each of the design proposals considered within this paper. It was therefore inevitable that, since these models represented proposals for future schemes, they were not, and could not have been, verified.

The hydraulic performance of each of these options was compared with that simulated for the existing state catchment. These simulations were generated using HydroWorks' time series analysis for a 99 storm-event Time Series Rainfall (TSR) set. The 'Henderson' TSR (WRc, 1986) for the North East region of the UK was adopted for this study. However, this data set was not specifically localised for the Gipton site. This decision related to the fact that this exercise was intended as a comparative study of alternative proposals, not as an accurate representation of the catchment system's existing-state performance.

A more detailed review of modelling retrofit SUDS is presented with respect to the Meanwood catchment within Chapter 5.

3.4.2. Hydraulic performance criteria

For the purpose of this study, hydraulic performance was defined using two model output parameters:

i) Total annual CSO spill volume,

ii) Total annual number of CSO spills.

These parameters were adopted because they were considered to be key factors influencing the severity of the aesthetic pollution within Gipton Beck. This rationale is based upon the assumption that a reduction in both the annual number and volume of CSO spills into the Beck will produce a corresponding reduction in terms of the severity of aesthetic pollution – the effects of which will in turn be manifest through a reduction of public complaints received by the sewer operator. These criteria were used to assess the performance of Gipton's four CSOs, both individually, and corporately as a complete system.

3.4.3. Results – Hydraulic Performance

A time series analysis was conducted for the 'existing-state' HydroWorks model of the Gipton catchment that sought to simulate the hydraulic performance of the current Gipton catchment system in terms of the two performance parameters highlighted in Section 3.4.2. These 'existing-state' results were used as a benchmark against which the simulated performances of alternative proposals could be compared.

The performance of the one conventional and ten SUDS-based rehabilitation proposals was then simulated using HydroWorks, and compared with that of the 'existing-state' model using these criteria. The results of this exercise are presented in Table 3.4 and Table 3.5 (located after Section 3.4.6), and graphically illustrated in Figure 3.10 and Figure 3.11.

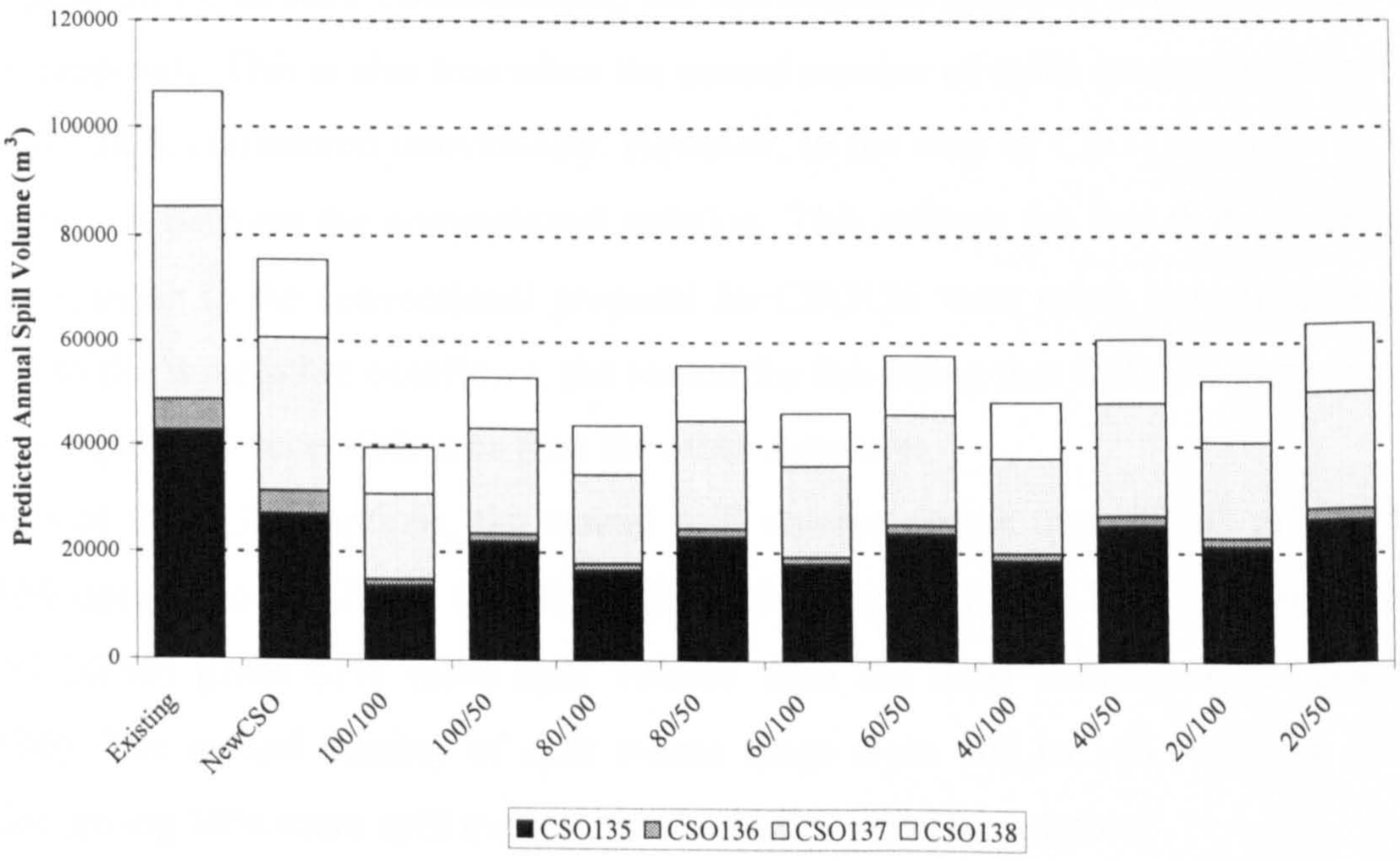


Figure 3.10 Annual CSO Spill Volumes (m^3) from Gipton CSOs 135, 6, 7 & 8 For 'existing-state' conditions and alternative remedial proposals (Swan *et al.*, 2001)

(Refer to Table 3.3 for further details of the notation used in Figures 3.10-11)

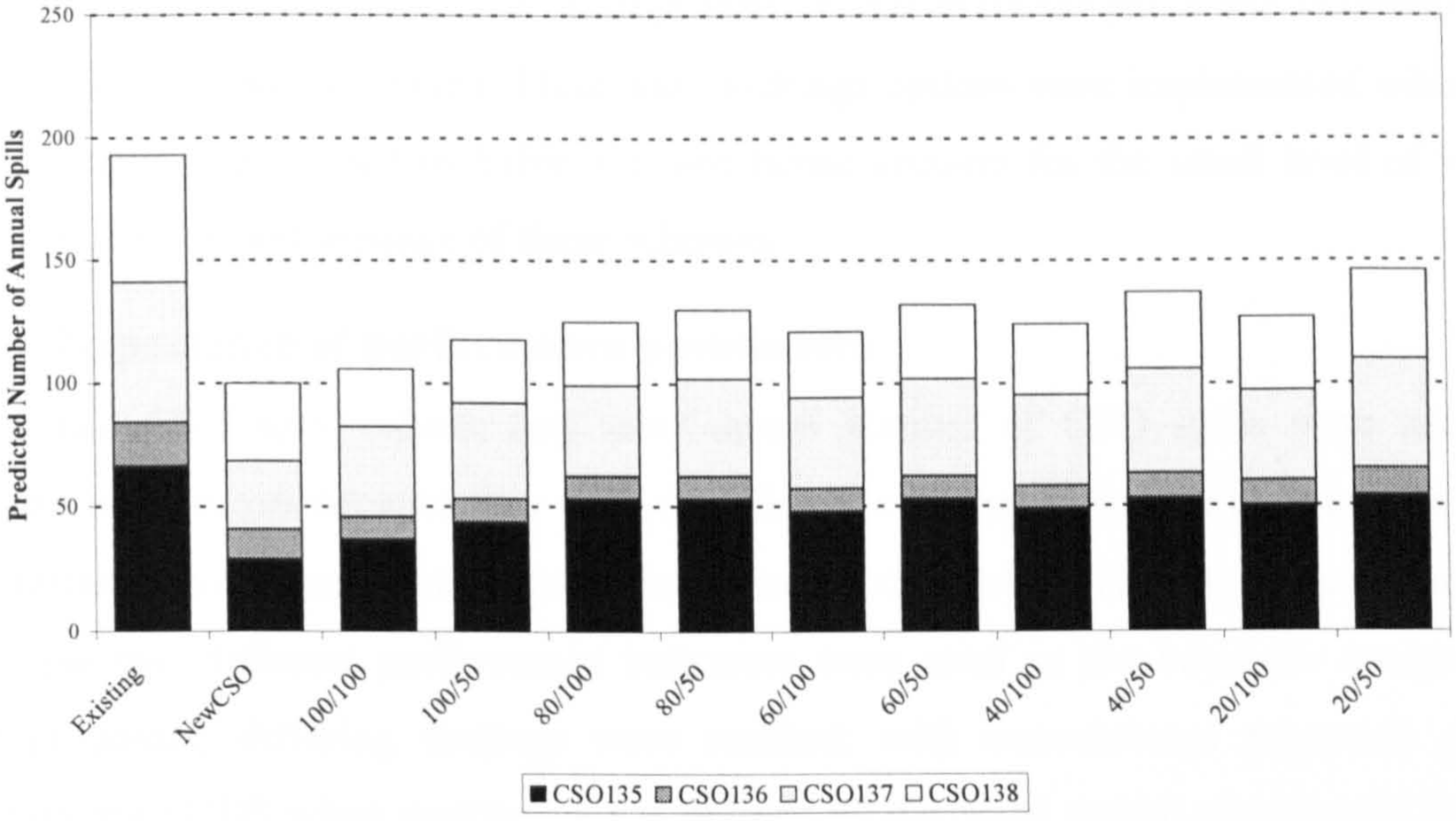


Figure 3.11 Annual number of CSO Spill from Gipton CSOs 135, 6, 7& 8 For 'existing-state' conditions and alternative remedial proposals (Swan *et al.*, 2001)

3.4.4. Discussion of Results

Inspection of Table 3.4 and Figure 3.10 reveals that, where system performance is defined by the cumulative annual spill volume from all four of Gipton's CSOs, then the SUDS proposals produce much better results than the conventional option. This is demonstrated by the fact that all ten of the SUDS proposals outperform the NewCSO option. The SUDS options also outperform the conventional solution when the annual spill volume emanating from each of the CSOs is considered individually. However, this is reversed when system performance is defined as the combined number of annual spills emanating from the catchment's four CSOs (Table 3.5 and Figure 3.11). In such circumstances, the conventional proposal outperforms all ten of the SUDS proposals. This is also true when the annual number of spills emanating from CSOs 135, 137 and 138 is considered individually. However, in the case of CSO136 all ten of the SUDS proposals out perform the conventional solution. This reflects the fact that the design criteria used in relation to the conventional proposal for CSO136 were much less stringent than those applied to the three other overflows; the reason for this being that CSO136 discharges within a much less publicly accessible area than the other structures.

In terms of the SUDS options, the annual spill volume ranges from 39563 m^3 (for the SUDS 100/100 option) to 63679 m^3 (for the SUDS 20/50 option). The least comprehensive option (SUDS 20/50) gives 61% more spill volume than the most comprehensive option (SUDS 100/100). The annual number of spill events range from 106 to 146, with the SUDS 20/50 solution giving 38% more spill events than the SUDS 100/100 solution.

These results indicate that even the minimum SUDS option (SUDS 20/50) achieves significant gains in system performance, and that the incremental benefits associated with implementing the more comprehensive SUDS options are comparatively small. This reflects the fact that there are only a limited number of easy opportunities for SUDS within this catchment, which if implemented would lead to significantly improvements in system performance. These 'easy

pickings' include the disconnection of large institutional roofs/car-parks and redirecting roof-water to separate sewer sewerage. These easy pickings options were implemented within all of the SUDS options presented in Table 3.3, and hence account for the small level of variation associated with the performance of these schemes.

3.4.5. Importance of performance parameters

Total annual CSO spill volume and total annual number of CSO spills were adopted as performance indicators because they were considered to be key factors influencing the severity of the aesthetic pollution within Gipton Beck (See Section 3.4.2). However, it is apparent that when these two different performance indicators were used as the basis for comparing the eleven proposals, differing findings were reached; with conventional proposals generally outperforming SUDS when performance is defined by the 'total annual number of CSO spills' parameter, and SUDS outperforming conventional proposals when the 'total annual CSO spill volume' parameter is used. This demonstrates that although SUDS are more effective at reducing spill volumes, they do not deal with small frequent spill events as well as the conventional proposals.

In terms of this analysis it might be argued that the number, not size, of annual CSO spill events is of greater importance – because every spill event, no matter how small, carries the potential for aesthetic pollution, and conssequently for public compliant. In fact a large single spill event might receive the same amount of public complaint as a smaller event. However, the annual CSO spill volume parameter is still a useful indication of system perform – especially when issues of water quality pollution are being considered.

3.4.6. Summary

This exercise identified the main factors considered to affect the viability of retrofitting SUDS to a typical urban catchment, and highlighted the potential benefits of using such devices rather than conventional approaches, particularly in terms of improving the hydraulic performance of the urban drainage system. However, an investigation into the comparative costs of both methodologies was required to establish the economic viability of SUDS.

Section 3.4.7 presents corresponding construction cost estimates that were generated for each of these conventional and SUDS proposals. These costings are used as the basis for a set of scatterplots that compare the cost/performance of each of the rehabilitation proposals.

Table 3.4 CSO ANNUAL SPILL VOLUMES (m^3) (Swan *et al.*, 2001)

Note: For 'SUDS' solutions the first figure represents the percentage of roof area disconnected, the second the percentage of road area, compared to the maximum that could be disconnected

	Existing	NewCSO	20/50	20/100	40/50	40/100	60/50	60/100	80/50	80/100	100/50	100/100
CSO135	42704	27091	26300	21330	25141	18815	23595	17991	22989	16831	22112	13862
CSO136	5970	4219	1936	1449	1766	1311	1663	1212	1553	1124	1424	1044
CSO137	36700	29344	22222	18093	21486	17553	20744	16975	20337	16550	19691	15908
CSO138	21181	14891	13131	11769	12277	10969	11451	10239	10760	9554	9912	8749

Table 3.5 CSO ANNUAL NUMBER OF SPILLS (No.) (Swan *et al.*, 2001)

	Existing	NewCSO	20/50	20/100	40/50	40/100	60/50	60/100	80/50	80/100	100/50	100/100
CSO135	66(64)	29(28)	54(53)	50(46)	53(53)	49(41)	53(49)	48(40)	53(49)	53(50)	44(37)	37(34)
CSO136	18(17)	12	11(9)	10(9)	10(9)	9	9	9	9	9	9	9
CSO137	57(57)	27	45(39)	37(35)	43(39)	37(36)	40(38)	37(35)	40(37)	37(33)	39(37)	36(33)
CSO138	52(48)	32(28)	36(31)	30(28)	31(29)	29(27)	30(25)	27(24)	28(26)	26(24)	26(24)	24(23)

COSTS

Table 3.6 Construction costs (£,000's) of Gipton Stormwater management proposals (Walker, 2000:a)

	CSO135	CSO136	CSO137	CSO138	Total
New	880	194	593	384	2051
100/100	966	576	496	515	2526
100/50	760	520	382	496	2158
80/100	871	503	411	438	2223
80/50	664	446	324	419	1853
60/100	744	426	349	361	1880
60/50	537	369	262	342	1510
40/100	617	352	294	282	1545
40/50	411	295	207	263	1176
20/100	495	277	232	205	1209
20/50	289	220	145	186	840

3.4.7. Costs

Walker (2000:a) generated cost estimates for each of these eleven proposals. The results of this analysis are presented within Table 3.6, and graphically illustrated within Figure 3.12.

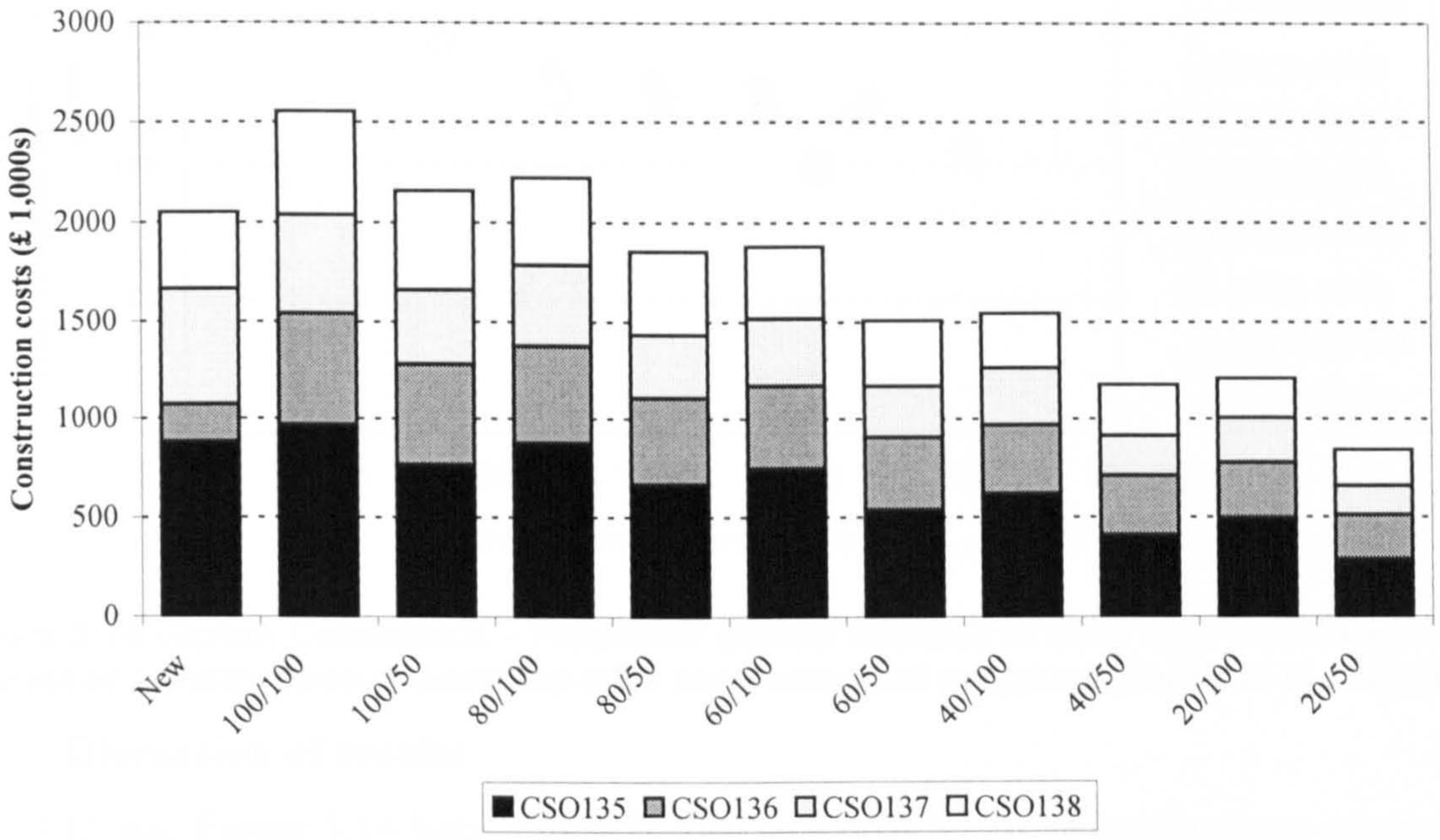


Figure 3.12 Construction costs (£ ,000's) of Gipton proposals (Walker, 2000:a)

It may be observed from Figure 3.12, that only three of the ten SUDS proposals were estimated as more expensive to construct than Walker's conventional solution. These were the three most comprehensive SUDS solutions (100/100, 100/50 and 80/100). The most costly SUDS proposal (100/100) was 10% more expensive, and the least costly proposal (20/50) was 67% cheaper, than the conventional solution. Figure 3.13 and Figure 3.14 display the construction costs for each Gipton proposal together with associated CSO performance, in terms of annual CSO spill volume and number of CSO spill-events respectively.

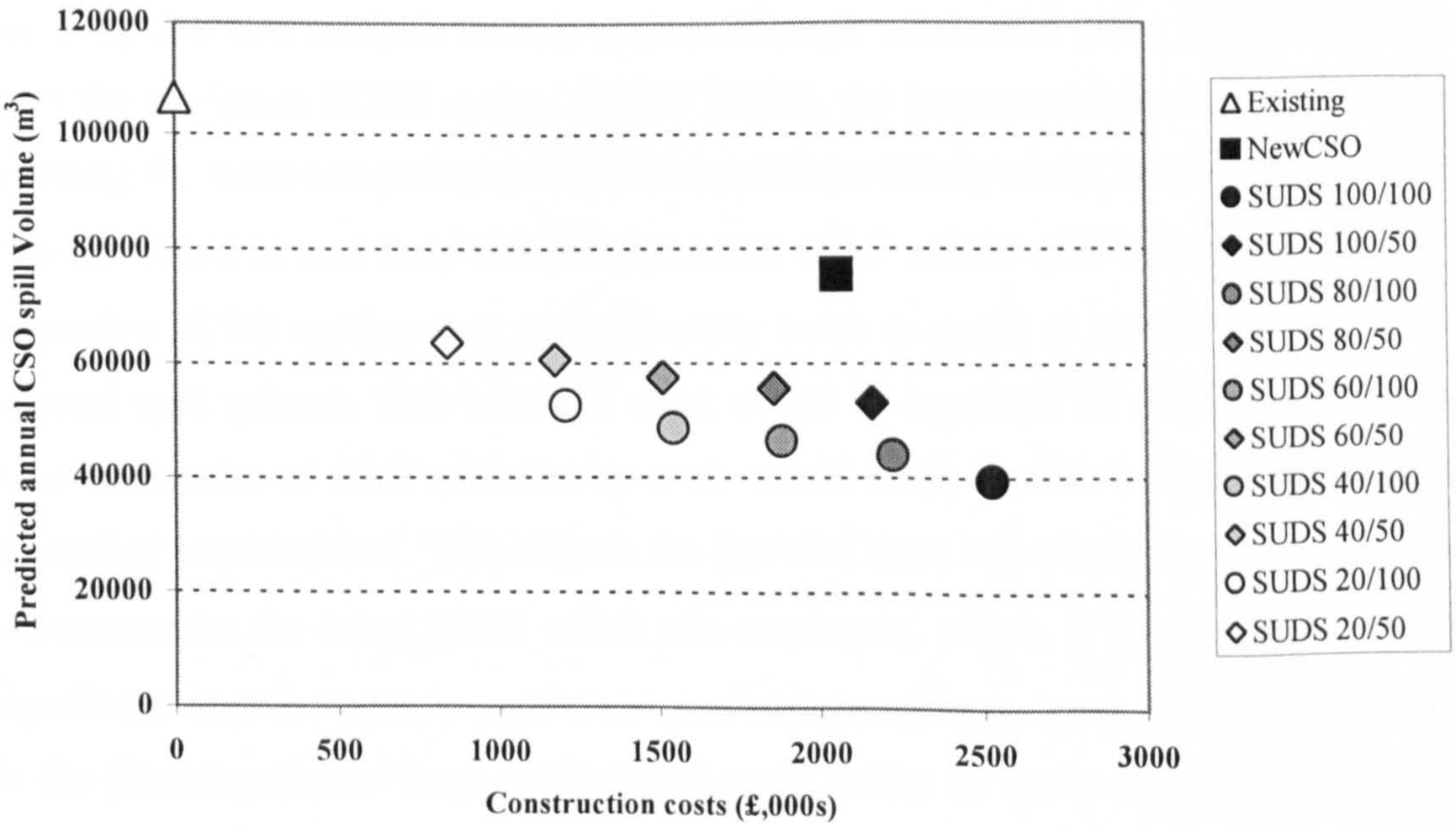


Figure 3.13 Gipton Catchment – Predicted annual CSO spill volume against cost of construction associated with each remedial proposal (Swan *et al.*, 2001)

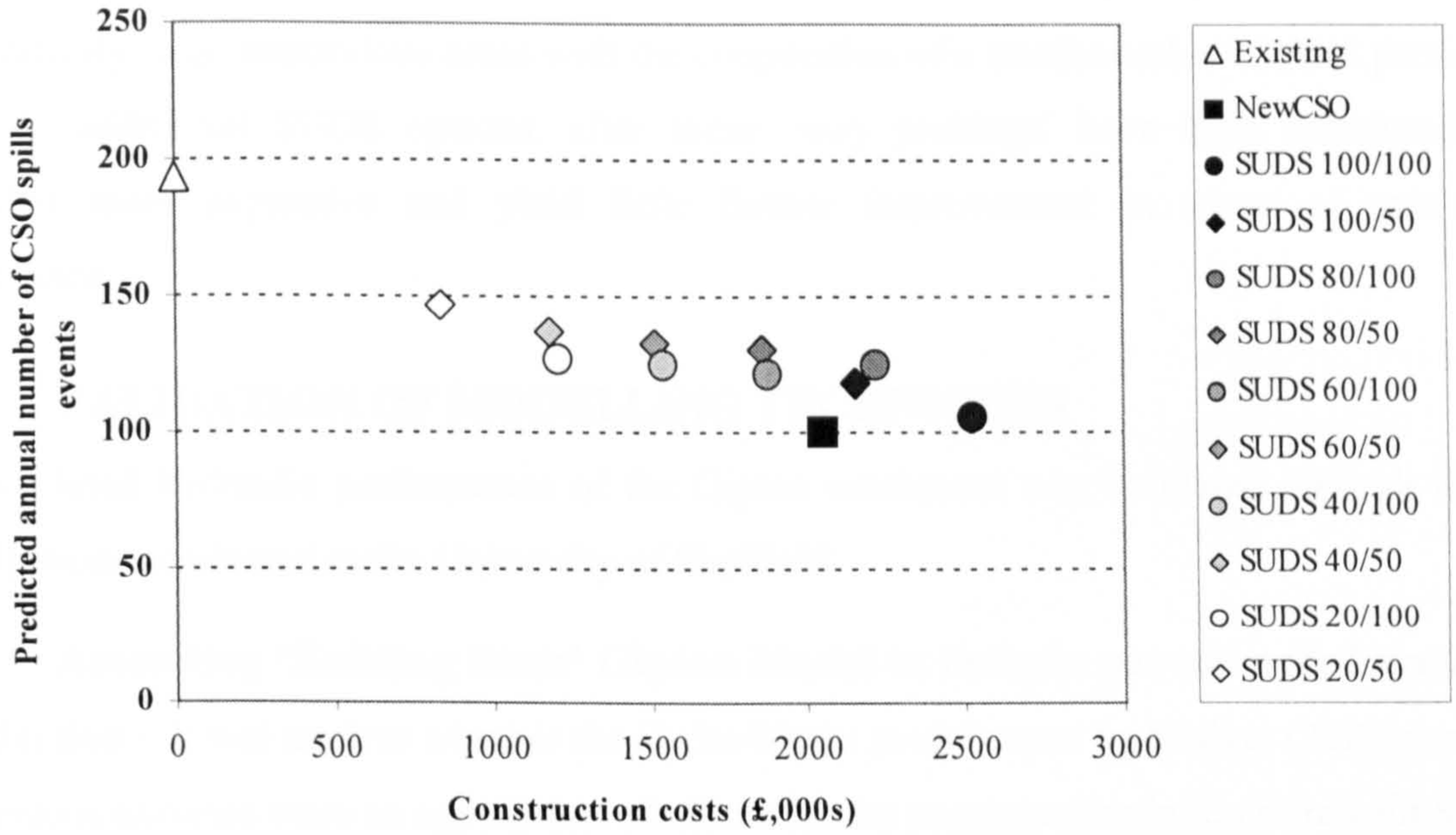


Figure 3.14 Gipton Catchment – Predicted annual number of CSO spill events against cost of construction associated with each remedial proposal (Swan *et al.*, 2001)

3.4.8. Discussion of results

Figure 3.13 and Figure 3.14 both highlight that improved levels of performance amongst the SUDS proposals correspond to increased levels of expenditure and surface disconnection. The SUDS options that utilise the larger disconnection components (as denoted on the scatter plot by the darker data points) achieve the best levels of performance amongst the SUDS, but unsurprisingly have the highest associated construction costs.

The cheapest SUDS option betters the performance of the more than twice as expensive conventional solution in terms of spill volume, whilst the SUDS solution that achieves comparable performance to the conventional solution in terms of number of spill events is only 23.1% more costly than the conventional approach. This evidence strongly supports the economic viability of the SUDS approaches.

Another thing that this analysis reveals is that although substantial gains in performance arise with even the minimum SUDS option (SUDS 20/50), the incremental benefits associated with implementing the more comprehensive SUDS are comparatively small. Indeed, the 20/50 SUDS option is calculated to cost only £20 per prevented m^3 of annual spill volume, whilst the most comprehensive SUDS options cost approximately twice as much at around £40 per prevented m^3 of annual spill volume. This contrasts what would be expected for a conventional solution where the economies of scale and start up costs would make smaller schemes more expensive per unit cost of improvement. This reflects the fact that there are a limited number of relatively cheap opportunities for using SUDS within this catchment, which, if implemented, would lead to a significant improvement in catchment performance. These 'easy pickings' opportunities include the disconnection of large institutional roofs and/or car parks and the division of some roof-water to separate sewerage. These types of approach are likely to be both cheaper, and

logistically simpler to implement because they would achieve the disconnection of comparatively large impervious areas with the cooperation of a small number of third parties. However, additional SUDS options, after these 'easy pickings' have been exhausted, are somewhat more expensive and yield little further improvement in terms of catchment performance.

3.5. VALIDATION OF MODELLING TECHNIQUES

The simulated hydraulic performance of the Gipton catchment was validated through further investigations conducted at the University of Sheffield.

3.5.1. Amending 'Existing State' Gipton Model to include paved/roofed areas

Introduction – It was unclear whether the HydroWorks models used by Walker (2000:a) within the previous exercise were an appropriate platform for the accurate simulation of retrofit SUDS. This uncertainty relates to the fact that these models had been compiled using two HydroWorks surface types (i.e. one for impervious, and the other for pervious areas), rather than three (i.e. one for paved areas, the second for roofed areas and the third for pervious areas). The HydroWorks's default paved surface type is represented as having a much slower response time than the default roofed surface type, with the default paved surfaces (*Surface No. 10*) generally having four times the initial depression storage associated with corresponding default roof surfaces (*Surface No. 20*). Therefore, in order to verify the accuracy of Walker's (2000) results, an independent modelling exercise was conducted at the University of Sheffield. This work involved modifying the existing-state HydroWorks model of the Gipton catchment so that it could be used to accurately represent retrofit SUDS schemes that involved the disconnection of paved or roofed areas. This modification called for the redefinition of all impervious area values into separate paved and roofed area values. However, it was not necessary to amend the model's pervious area values. The modification of this catchment model is described in the ensuing Section.

Methodology – Digitised maps (1:10,000) were used in conjunction with the MapInfo GIS software package (MapInfo Corporation, 1995) to calculate the cumulative paved areas contained within each sub-catchment of the Gipton HydroWork model. Cumulative roofed areas were calculated by subtracting these paved areas away from the impervious areas as defined in the existing-state HydroWorks model for each sub-catchment. See Appendix 5D for further details of this methodology as applied to the Meanwood catchment.

3.5.2. Comparison of results generated by 'IMP/PERV' model and 'PAVED/ROOFED/PERV' model for existing state catchment

3.5.2.1. Introduction

The amended model of the Gipton catchment (i.e. with impervious areas redefined as separate paved and roofed areas) (Section 3.5.1) was analysed using HydroWorks time series

simulations. These simulations adopted the same TSR input data and output performance parameters as the Walker (2000:b) study (Section 3.4). However, the results of this investigation were generated using a sampling strategy that analysed the first five storm events, and every fifth of the remaining 94 storm events. Results were extracted as normal for the first five events, but the results from the remaining events are multiplied by a factor of five to allow for the missing events. Such sampling techniques are commonly used for time-series analysis, but require that the input TSR events are correctly ranked (Wallingford Software, 1999).

3.5.2.2. Results

HydroWorks time-series simulations were conducted for the redefined (PAVED/ROOFED/PERV) model of the Gipton catchment. The results of this analysis were compared with Walker's results for corresponding simulations conducted using the IMP/PERV model (Section 3.4). Table 3.7 and Table 3.8 compare the predicted hydraulic performance of these models; this data is also represented graphically in Figure 3.15 and Figure 3.16. System performance is defined as annual CSO spill volume (m^3) for Table 3.7 and Figure 3.15, and as the annual number of CSO spills for Table 3.8 and Figure 3.16.

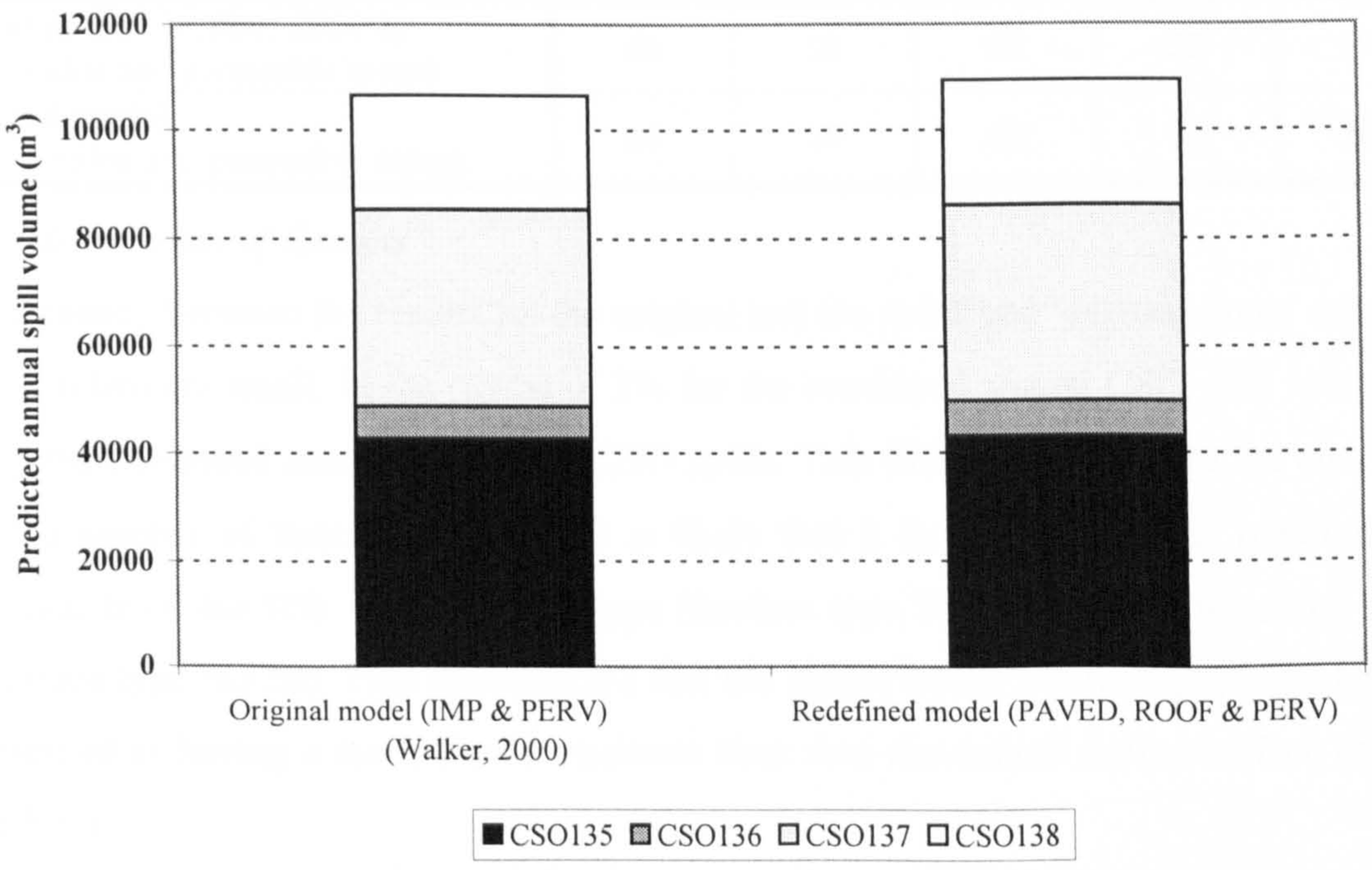


Figure 3.15 Comparison of Gipton 'existing state' catchment model results for original (Walker, 2000:b) and redefined models: Predicted Annual Spill Volumes (m^3)

Table 3.7 Comparison of Gipton 'existing state' catchment model results for original (Walker, 2000:b) and redefined models: Predicted Annual Spill Volumes (m^3)

Existing state catchment model	CSO135	CSO136	CSO137	CSO138	All
Original model *(Walker, 2000:b)* (Impermeable and permeable areas)	42704	5970	36700	21181	106555
Redefined model (Paved, Roofed and permeable areas)	43123	6553	36449	23381	109506

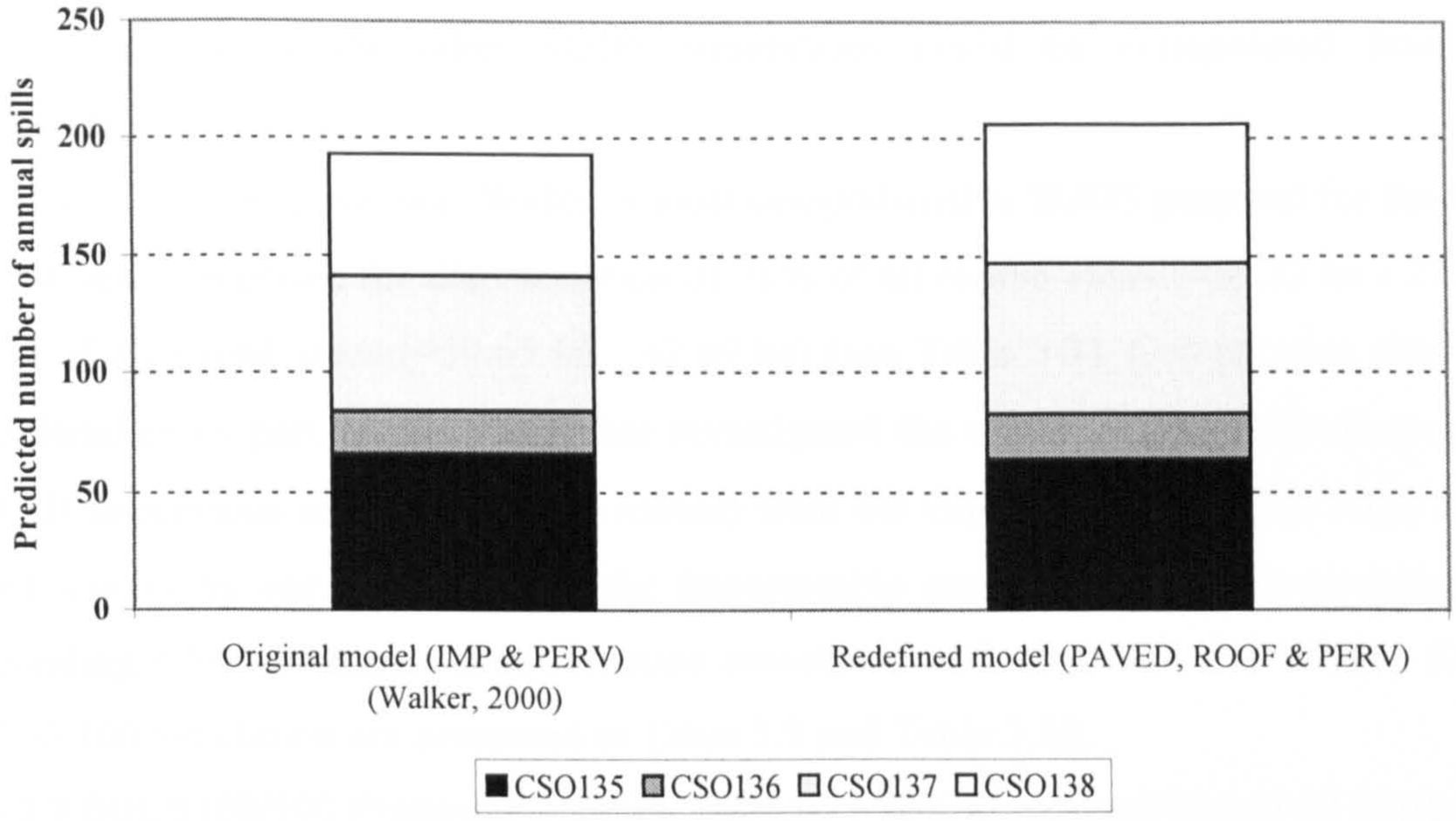


Figure 3.16 Comparison of Gipton 'existing state' catchment model results for original (Walker, 2000:b) and redefined models: Predicted Number of Annual Spills

Table 3.8 Comparison of Gipton 'existing state' catchment model results for original (Walker, 2000:b) and redefined models: Predicted Number of Annual Spills

Existing state catchment model	CSO135	CSO136	CSO137	CSO138	All
Original model *(Walker, 2000:b)* (Impermeable and permeable areas)	66	18	57	52	193
Redefined model (Paved, Roofed and permeable areas)	64	19	64	59	206

3.5.2.3. Discussion of Results

The discrepancy between the results for the original and the redefined 'existing-state' catchment models is relatively small, in the region of 3% for the combined annual CSO spill volume and 6.5% for the combined annual number of CSO spills. This discrepancy may be the cumulative result of a number of factors. However, it is likely that it largely reflects the redefinition of roofed areas from the HW paved surface type (Surface type No 10) to the HW roofed surface type (Surface type No 20). This relates to the fact the HydroWorks's default paved surface type is represented as having a much slower response time than the default roofed surface type (see Section 3.5.1.

This highlights the sensitivity of the HydroWorks models, and reinforces the importance of verifying such models against monitored flow data.

However, the scale of these discrepancies would not seem to be overly significant, particularly when the nature of this modelling exercise is considered – i.e. because the study is of a comparative nature, and the margin of discrepancy will be consistent for all simulations conducted using this model.

3.5.3. Verification of SUDS SIMULATIONS

Additional simulations were undertaken to check the accuracy of Walker's simulations (2000) for the Gipton catchment. Given the limitations of this project it was decided that only the

results from one of the SUDS proposals (SUDS 100/100) should be investigated – it was hoped that the reliability of the other SUDS simulations could be extrapolated from these investigations.

The SUDS100/100 proposal was Walker's most comprehensive SUDS proposal for the Gipton catchment, and comprised the disconnection of 31% of all roofed areas (=39.52 ha - 27.26 ha) and 28% of all paved areas (=59.65 ha - 42.69 ha) (see Table 3.3). Comparative simulations were undertaken as part of this thesis that investigated the affect of uniformly disconnecting 30% of all impervious areas (paved and roofed) from the Gipton model. At this stage this was achieved simply by removing 30% of the impermeable area from each sub-catchment. The corresponding CSO discharge characteristics associated with this, and the Walker (2000:b) SUDS100/100 simulation are presented in Table 3.9 and Table 3.10.

Table 3.9 SUDS100/100 Proposal (Walker, 2000:b) v 30% disconnection of all impervious areas – Predicted annual spill volumes (m^3)

	CSO135	CSO136	CSO137	CSO138	All
SUDS 100/100 simulation (Walker, 2000:b)	13862	1044	15908	8749	39563
30% of Impervious areas disconnected (*Thesis investigations*)	17342	2006	15283	8128	42759

Table 3.10 SUDS100/100 Proposal (Walker, 2000:b) v 30% disconnection of all impermeable areas – Predicted number of annual spill events

	CSO135	CSO136	CSO137	CSO138	All
SUDS 100/100 simulation (Walker, 2000:b)	37	9	36	24	106
30% of Impervious areas disconnected (*Thesis investigations*)	44	9	39	24	116

The discrepancy between the results for Walker's SUDS 100/100 simulation and the 30% of disconnection of impermeable areas is relatively small, in the region of 7.5% for the combined annual CSO spill volume and 9% for the combined annual number of CSO spills. It is likely that this discrepancy relates to the fact that Walker (2000:b) modelled the disconnection of paved and roofed surfaces only in the specific areas where SUDS were considered viable, whereas the 30% disconnection of impermeable area was performed uniformly across the whole catchment. However, the general level of conformity demonstrated by these results supports the validity of both of these the modelling investigations.

3.6. OVERVIEW

The Gipton investigations highlighted three key issues associated with retrofitting SUDS to UK catchments: i) These investigations illustrated that retrofit SUDS-based solutions can be economically viable; ii) These investigations highlighted that it was feasible to assess the performance of retrofit SUDS using HydroWorks; iii) These investigations indicated which site information was required to evaluate potential SUDS.

The lessons learnt from these feasibility investigations for the Gipton catchment were assimilated with the information presented within Chapter 2 (Literature Review) and used to develop more detailed methodologies for planning, modelling and evaluating retrofit SUDS schemes. These methodologies were subsequently applied to a second case study catchment (Meanwood, Leeds).

It should be noted that simplistic costing data, design work, and modelling techniques were employed for the Gipton study. This level of analysis was considered to be appropriate for such a preliminary design exercise. More sophisticated methodologies were developed and employed for the Meanwood catchment. Further details of these methodologies, and their application to the Meanwood catchment are presented within the following Chapters.

4. RETROFIT SUDS EVALUATION – DESIGN ISSUES

4.1. INTRODUCTION

This Chapter builds upon the Gipton study, and other existing SUDS studies highlighted in Chapter 2, to comprehensively explore the design issues associated with retrofitting SUDS to a range of different urban applications and surface types. The main aim of this Chapter was to establish a list of the factors that most affect the viability of different retrofit SUDS, with respect to a range of urban settings. The first part of the Chapter reviews a number of SUDS applications and aims to define basic guidelines for their design, based upon observations made from the preceding SUDS studies. The latter part of the Chapter (from Section 4.3 onwards) attempts to apply these design guidelines to a second case study catchment, in order to establish individual best-case catchment coverage scenarios for a range of different SUDS technologies.

4.2. USE OF SUDS TECHNIQUES IN RETROFIT CONTEXT

This Section explores the use of retrofit SUDS in relation to 3 different SUDS applications:

1. Source controls (Section 4.2.1)
2. Conveyance systems (Section 4.2.2)
3. Off-site (e.g. site and regional controls) (Section 4.2.3)

The order in which these SUDS grouping are considered reflects the CIRIA treatment train concept (CIRIA, 2000) highlighted in Chapter 2.

4.2.1. Retrofit Source controls

Two types of retrofit source control were considered in this analysis; these were storage-based schemes (Section 4.2.1.1), and infiltration-based schemes (Section 4.2.1.2). The following Sections explore the design issues associated with retrofitting both forms of source control SUDS to a range of different contributory surface types.

4.2.1.1. Storage-based retrofit source controls

This Section reviews the main issues considered to influence the design, implementation and cost of storage-based retrofit source controls. It should be noted that financial issues are only briefly discussed within this Chapter; a more detailed review of the costs associated with retrofit SUDS is presented within Chapters 6 and 7. The importance of other issues, such as the operation, ownership and maintenance of retrofit technologies is acknowledged. The next three subsections present the main design issues associated with retrofitting storage-based source controls to three different urban applications:

1. Residential applications
2. Institutional applications
3. Other paved surfaces

Residential applications – It is considered that water butts and garden ponds are the most viable storage-based source controls that may be retrofit to a typical residential (property) roof. The overflows from such devices may be directed back into the sewer system, onto the garden, or disposed of by some other means. Sewer rehabilitation proposals involving the widespread use of such technologies would generally require the voluntary cooperation of local residents (i.e. to voluntary install water butts or ponds to properties). It is felt that a large proportion of the general public would be willing to support such voluntary schemes. This premise is supported by two observations. Firstly, by the large number of retrofit garden ponds and water butts already in use within the UK; and secondly, by the growing number of roof-water disconnection schemes initiated by local water companies (Yorkshire Water, 2000) – such schemes are often accompanied by a financial incentive (e.g. reduced water rates for customers who disconnect their roofs from the local sewer system).

A number of other retrofit options were considered for application to domestic properties, including 'above surface tanks' and 'underground storage' facilities (e.g. underground tanks and porous pavements). However, it was felt that these options were much less feasible retrofit applications than ponds and water butts because of the level of disruption associated with the construction of underground technologies, and the excessive size of surface storage tanks. It is likely that this would mean low adoption rates for such technologies, unless compulsory schemes were pursued. However, introducing a compulsory element to these schemes would cause a range of problems, such as the need for compensation arrangements, additional legalisation and potential loss of public support/good will. Therefore, only water butts and garden ponds were considered within this analysis.

The main design issues considered to affect the use of water butts and garden ponds for retrofit source control applications to residential properties are presented in Table 4.1.

Table 4.1 Storage-based retrofit source controls for residential applications

Technology	Appropriate Uses	Main design issues
Water butt *Typical size: 0.3 m^3*	Residential roofs	1. Size of roof/capacity of tanks 2. Available space 3. Direction of overflow 4. Maintenance 5. Social issues/take-up rates
Garden Pond	Residential roofs or Residential paved areas	As above plus: 6. Soil permeability (e.g. risk of infiltration into a SPZ) 7. Water table level (should never reach bottom of pond) 8. Safety 9. Amenity value

Notes on Table 4.1: Design issues

Size of roof/capacity of roof – This constraint relates to whether the capacity of the storage device (e.g. pond, water butt, etc.) is adequate for the collection of peak runoff from the contributory impermeable surface. The key factors that influence the magnitude of peak runoff are the characteristics of the rainfall event and the size of the contributory surface (e.g. roof). The key factors that limit the capacity of storage devices are available space and cost.
Available space – One of the key factors that limit the capacity of retrofit storage devices is having sufficient available space in which to construct them. In the case of storage-based retrofit source controls for residential applications this will typically relate to having an enough space within a garden to install either a pond or a water butt.
Overflow – Another important issue that relates to the design of retrofit source controls relates to how the overflow from the pond/water butt is to be disposed of. The main alternatives are to discharge the overflow back into the local sewer system or to dispose of it via other methods of disposal, such as via infiltration devices, or to directly discharge it to a local watercourse.
Maintenance – The continued maintenance of storage-based SUDS devices, and other components of integrated SUDS schemes, is essential for the effective long-term performance of such a scheme. The maintenance issues that typically relate to storage-based retrofit source controls for residential applications are those that relate to responsibility (i.e. who will be responsible for monitoring the performance and maintenance of the ponds/water butts).
Social issues/take-up rates – Social issues are important to the design of storage-based retrofit source controls for residential applications, since these techniques require the cooperation of individual homeowners. It is therefore important that the local community have favourable views towards the introduction of ponds/water butts. For retrofit source control schemes that require the voluntary purchase of SUDS devices by property-owners (i.e. as opposed to subsidised schemes) it is essential that the price of the technology is not prohibitively expensive.
Soil permeability – The prevailing ground conditions should be considered as they will determine whether a pond needs to be lined to prevent unwanted infiltration – this may be the case within a designated Source Protection Zone (SPZ) I area, in which infiltration of runoff is not permitted.
Water Table level – The water table should not reach the bottom of any infiltration device or pond – so as to minimise the risk of pollution to the water table.
Safety – Safety is an issue that may have to be considered by some inhabitants, particular those with young children considering retrofitting a pond.
Amenity value – Ponds may be considered to improve the amenity value of a residential property, whereas large water butts might detract from the amenity value of a residential property.

The application of retrofit source controls to contributory surfaces other than roofs was not extensively explored because most residential properties contain negligible amounts of paved area that are directly connected to the local sewer system.

Note: It is considered that there are negligible benefits, in terms of controlling or reducing extreme storm flows, to be attained through the use of storage schemes that return overflow volumes back into the local sewer. This relates to the limited storage capacity of retrofit source control facilities, and the high frequency of rainfall events within most parts of the UK – which means that such devices are often completely or partially full.

Institutional applications – One benefit of retrofitting source controls to institutional rather than residential properties is that large contributory areas can be disconnected from the sewer system with the involvement of fewer third parties. This means that institutional proposals for SUDS are likely to be easier and cheaper to promote, monitor and maintain than those for residential proposals. For example, if a typical residential property has a roofed area of 50 m^2 and a typical institutional property 200 m^2, then the disconnection of 1000 m^2 of roofed area could be achieved through the removal of 20 typical residential properties or 5 typical institutional properties. It is therefore likely that the institutional scenario would be the easier of the two options to coordinate, promote and manage.

Many of the technologies discussed previously in relation to residential properties may also be applied to institutional properties (e.g. schools, hospitals and offices). However, the inherent differences between typical institutional and residential properties affect the design techniques that should be applied to retrofit source controls within either context. The major differences between institutional and residential properties relate to issues of scale and land usage. Institutional buildings tend to have larger roofs than domestic properties, and as a result would generally require larger retrofit roof-water storage facilities than appropriate for residential properties (e.g. water butts). However, institutional buildings generally have larger plots of land than residential properties, and can therefore accommodate larger storage facilities with few problems. For example, institutional properties would generally have available space that could be utilised for accommodating large above ground tanks, or for the construction of sub-surface storage facilities. It is felt, that given this additional available space, sub-surface storage facilities might be constructed without incurring the same degree of disruption (and consequently opposition from property owner/local residents) that would accompany their introduction to residential properties.

Institutional properties are also likely to have large paved areas (e.g. car-parks and school playgrounds) and these represent further opportunities for the use of retrofit storage source controls. However, if the overflows from such storage facilities are intended to be disposed of by infiltration – then some form of treatment may be required in order to comply with the Environment Agency's policy and practice for the protection of groundwater (1998). See Chapter 2 for further details on the level of pre-infiltration treatment required for different SPZs. It was concluded that the four most viable storage-based retrofit source controls for institutional applications were: 1) Above ground storage; 2) Below ground storage; 3) Porous pavements; and 4) Ponds. The main design issues that should be considered with respect to the use of these retrofit technologies are presented within Table 4.2.

Table 4.2 Storage-based retrofit source controls for institutional applications

Technology	Appropriate Uses	Main design issues
Above ground storage tank	Institutional roofs	1. Size of roof/capacity of tanks 2. Available space 3. Direction of overflow 4. Maintenance 5. Take-up rates
Below ground storage tank	Institutional roofs and paved areas	As for above ground storage tank, plus 6. Local geology
Porous pavements	Institutional roofs and paved areas	As above plus 7. Soil permeability (e.g. possible infiltration into a SPZ) 8. Water table level (should never reach bottom of device) *For further details relating to the design of porous pavements for infiltration purposes* – See Table 4.4
Detention Pond	Institutional roofs and paved areas	As above plus 9. Safety 10. Amenity value *For further details relating to the design of ponds for infiltration purposes* – See Table 4.3

Notes on Table 4.2: Design issues

Size of roof/capacity of roof – See corresponding Notes on Table 4.1
Available space – See corresponding Notes on Table 4.1.
Overflow – See corresponding Notes on Table 4.1.
Maintenance – The continued maintenance of storage-based SUDS devices, and other components of integrated SUDS schemes, is essential for the effective long-term performance of such a scheme. The maintenance issues that typically relate to storage-based retrofit source controls for institutional applications are those that relate to responsibility (i.e. who will be responsible for monitoring the performance and maintenance of the ponds/storage devices).
Institutional attitudes/take-up rates – It is important that the local institutions have favourable views towards the introduction of storage SUDS devices. For retrofit source control schemes that require Institutions to voluntarily purchase SUDS devices (i.e. opposed to subsidised schemes) it is essential that the price of the technology is not prohibitively expensive.
Local geology – It is worth noting that it will generally be cheaper and therefore more feasible to apply underground tanks, porous pavements and ponds within loose soils than to rock.
Soil permeability – See corresponding Notes on Table 4.1.
Water Table level – See corresponding Notes on Table 4.1.
Safety – The safety implications of using ponds will have to be considered in some locations (e.g. schools)
Amenity value – See corresponding Notes on Table 4.1.

Paved surfaces – Permeable or porous pavements were the only storage-based source control technologies considered appropriate for retrofitting directly to existing roads and other paved areas. There are other technologies that can be used to store runoff from paved areas, but these generally require conveyance away from the source (e.g. using pipes or swales). Retrofit conveyance systems are discussed in more detail within Section 4.2.2.

Runoff may be stored within the sub-base component of permeable/porous surfaces, and the overflow directed back into the local sewer or disposed of by other means. Pre-treatment would generally be required when the overflow is intended for infiltration (Environment Agency, 1998). The other design issues associated with retrofit porous pavements for storage-based source controls were discussed within the previous Section (Table 4.2).

4.2.1.2. Infiltration-based retrofit source controls

This Section reviews the main issues considered to affect the design, implementation and cost of infiltration-based retrofit source control technologies, with respect to residential applications, institutional applications and paved areas.

Residential applications – Infiltration ponds and soakaways are considered to be the most viable infiltration-based source control technologies for retrofit applications to residential properties. Infiltration trenches and French drains are other feasible approaches. However, it is assumed that most homeowners would generally prefer to have a soakaway constructed at the bottom of their garden, rather than an infiltration trench running down the length of their garden, because excavations associated with a soakaway would be much more concentrated than those associated with an infiltration trench.

It is worth noting that the Environment Agency's Policy and Practice for the Protection of Groundwater (1998) does not require runoff from residential roofs to undergo any form of treatment prior to infiltration, and states that runoff from residential paved surfaces only requires pre-infiltration treatment if located within a Zone I SPZ.

The main design issues that should be considered in relation to the use of retrofit soakaways or infiltration ponds are presented within Table 4.3.

Table 4.3 Summary of design issues relating to infiltration-based retrofit source controls for residential applications

Technology	Appropriate Uses	Main design issues
Soakaway	Residential roofs and paved areas	1. Soil permeability 2. Soil protection zones 3. Storage/Infiltration capacity 4. Building Regulations 5. Social acceptability 6. Maintenance
Infiltration ponds	Residential roofs and paved areas	As above plus: 7. Safety

Notes on Tables 4.3:

Building regulations – The use of infiltration devices would generally not be feasible within densely urbanised catchments (i.e. with tightly packed buildings and narrow roads), as the UK's Building regulations (1991) prohibit their use within 5 m of any building.
See the Notes on Tables 4.1 and 4.2 for further details of all other design issues

Institutional applications – Many of the technologies presented for residential application may also be applied within an institutional context. However, as described previously, inherent differences between typical institutional and residential properties may affect the design process for retrofit source controls. Institutional buildings tend to have larger roofs than domestic properties, and as a result require larger infiltration facilities. However within an institutional context these larger facilities might be accommodated as a landscaping feature (e.g. basin or pond), or as porous car park. Most of these technologies may be used to infiltrate runoff both from paved surfaces and adjacent roofs. Once again, pre-infiltration treatment may be required

in some areas to comply with the Environment Agency's policy and practice for the protection of groundwater (1998).

Paved areas – Permeable or porous pavements can also be used as an infiltration device. Runoff may be stored within the sub-base component of porous pavements, and the excess infiltrated into the local soil. Pre-infiltration treatment of runoff is generally required to comply with the Environment Agency's SPZ guidelines (1998). However, this relates to the level of traffic associated with the porous pavement.

The main design issues that should be considered in relation to infiltration-based retrofit source controls for paved are presented within Table 4.4.

Table 4.4 Summary of design issues relating to infiltration-based retrofit source controls for paved areas

Technology	Appropriate Uses	Main design issues
Porous pavements	Residential roofs and paved areas	1. Permeability 2. Source Protection Zones (SPZs) 3. Type of permeable surface 4. Usage 5. Location 6. Maintenance

Notes on Table 4.4: Design issues

Permeability – The permeability of the prevailing soils obviously affects the viability of infiltration devices. It considered that suitable percolation rates for most infiltration drainage systems are those that exceed 0.001mm/hr = 4.63×10^{-06} m/s (BRE 365, 1991)
Source Protection Zones (SPZs) – Another key factor that may determine the viability of infiltration drainage systems are the Environment Agency's '*Source Protection Zones' (SPZs)*. These prohibit the infiltration of all paved runoff within a Zone I designated area, and require varying degrees of treatment for runoff from institutional paved surfaces (e.g. car-parks) depending upon the designated SPZ.
Type of permeable surface – An important consideration that relates that design of porous surfaces is the type of surface that should be adopted - this will be influenced by the type of usage the surface will be subjected to, cost and aesthetic considerations.
Construction issues associated with location – The location in which it is intended to retrofit a porous surface will obviously influence the design process and the type of technology that may be appropriate. For example, the level of disruption that may be associated with construction will strongly influence the type of technologies that are appropriate within different areas.

4.2.2. Retrofit conveyance systems

It should be noted that retrofit SUDS conveyance systems are only worth exploring if feasible opportunities for off-site site controls exist downstream. It is considered that the most feasible retrofit SUDS conveyance systems are swales and French drains. Retrofit pipe-based systems are regarded as a conventional technology and hence not discussed within this Chapter. The main design issues associated with conveyance systems are presented below:

Table 4.5 Summary of design issues relating to retrofit conveyance systems

Technology	Appropriate Uses	Main design issues
French Drains	Roofs and paved areas	1. Available space 2. Permeability 3. Construction issues relating to location 4. Level of water table 5. Maintenance
Swales	Roofs and paved areas	As above plus: 6. Slope

Notes on Table 4.5: Design issues

Available space – See notes on Table 4.2. Retrofit French drains and swales are considered to be most viable on existing green urban areas, such as roadside grassed verges and fields. This largely relates to the additional costs associated with excavating paved surfaces. The minimum width requirements for these devices will depend upon their contributing surface area, and can be calculated using existing design guidelines (CIRIA, 2000).
Permeability – See notes on Table 4.1
Construction issues relating to location – See notes on Table 4.4
Level of water table – See notes on Table 4.1
Maintenance – See notes on Table 4.2
Slope – Design manuals recommend that swales should not be used on slopes greater than 1:50, and filter strips on cross-slopes greater than 1:20; in both instances these restriction are to avoid surface erosion (UWTC, 2000)

4.2.3. Retrofit Site and Regional controls

For the purpose of this report the term 'retrofit off-site control' is used to describe both retrofit site controls and regional controls. The two main groups of retrofit off-site controls are: i.) Storage-based controls and ii.) Infiltration-based controls. Storage-based approaches are discussed within Section 4.2.3.1, and infiltration-based retrofit source controls within Section 4.2.3.2. Retrofit off-site (e.g. site and regional) controls are only considered to be feasible in catchments where it is possible to retrofit conveyance systems for the transfer of runoff away from its initial point of contact, or 'source', to the off-site controls.

4.2.3.1. Storage-based retrofit offsite controls

The most common forms of large-scale storage-based off-site controls are basins and ponds. Basins are surface features that store runoff under storm conditions, but which are completely free of water under dry weather conditions. Examples of this approach include flood plains, detention and extended detention basins. Ponds contain water in dry weather conditions and are generally designed to receive more water under storm conditions.

The main technical issues that affect the design of retrofit basins or ponds are presented within Table 4.6:

Table 4.6 Summary of design issues relating to storage-based offsite controls

Technology	Appropriate Uses	Main design issues
Basins or Ponds	Roofs and paved areas	1. Available space 2. Overflow 3. Soil permeability 4. Level of water table

Other examples of storage-based offsite controls are conventional storage tanks. However, these techniques are not SUDS-based solutions, and hence not discussed in detail within this thesis.

4.2.3.2. Infiltration-based retrofit offsite controls

Retrofit SUDS devices that primarily utilise infiltration mechanisms are considered to be more effective for application to hydraulically overloaded urban catchments than those SUDS devices that rely on storage. This relates to the fact that infiltration options effectively remove runoff from the surface water/urban drainage system, rather than attenuating it within the surface water system.

Many of the infiltration devices described within Section 4.2.1.2 as source control technologies may also be applied as off-site controls. The issues that affect the design of such devices are similar within both contexts; however, off-site technologies are generally of a much larger scale.

Table 4.7 Summary of design issues relating to infiltration-based retrofit SUDS for off-site controls

Technology	Appropriate Uses	Main design issues
Porous pavements	Roofs and paved areas	1. Soil permeability 2. Soil protection zones 3. Available space 4. Storage/Infiltration capacity 5. Building Regulations 6. Maintenance 7. Level of water table
Infiltration trenches	Roofs and paved areas	As above
Infiltration ponds	Roofs and paved areas	As above plus 8. Safety

4.2.4. Review

It has been demonstrated that many catchment features, such as geology, geography or topography, can act as constraints in terms of the extent to which retrofit SUDS may be implementation within a catchment. Many of these catchment constraints are technology specific, whilst others apply to all forms of retrofit SUDS.

The rest of this Chapter relates to the Meanwood catchment, and the main constraints/factors considered to limit/influence the implementation of retrofit SUDS to this catchment. The Meanwood catchment represents the second of the two case studies that were undertaken for this thesis.

4.3. CASE STUDY: MEANWOOD CATCHMENT

4.3.1. Background

4.3.1.1. Introduction

Meanwood is a peri-urban district of Leeds, situated 4 km to the North West of the City Centre. The Meanwood urban drainage catchment (Table 4.1) covers an area of 55.8 ha, bounded by the A6120 (Leeds Outer Ring Road) in the North and Grove Lane/Stainbeck Road in the South. The catchment is concentrated along Meanwood Road, Parkside Lane and Tongue Road.

4.3.1.2. Meanwood Catchment Flooding Problems

The Meanwood sewer system consists of a main trunk sewer, with a single split-ended branch section. The main trunk sewer receives foul and surface water from three small residential estates (Parklands, King Alfred's and West Lea) and a number of other properties clustered along Stonegate Road. The branched section serves contributory areas along both Parkside Lane and Tongue Road.

During extreme storm events the Stonegate Road trunk sewer surcharges and produces flooding problems at four sites along Stonegate Road. The most severe of these flooding incidents occurs at the junction of Meanwood Road and Stonegate Road (Figure 4.2). This location corresponds

to a point on the main Stonegate Road trunk sewer where a steep section is immediately followed by a much flatter section of pipe-work (Figure 4.2:a). Under extreme flow conditions, flows backup from the flatter D/S section of pipe due to insufficient D/S capacity (i.e. due to a combination of inadequate gradient and pipe diameter). These flooding incidents occur at an approximate frequency of one per year.

A number of retail outlets and public buildings (e.g. Church, Health Centre and Public House) are concentrated around the junction of Meanwood Road and Stonegate Road, where the system's worst flooding incidents occur. In addition to general 'area' flooding problems, four of these properties experience internal flooding under severe storm conditions.

4.3.1.3. Contributory catchment

The Meanwood catchment largely consists of 20th Century housing, retail premises and a small number of institutional buildings (schools, library and churches). The catchment also contains significant amounts of grassed and wooded areas. However, on the whole, these do not contribute large amounts of runoff to the local sewer system.

Residential Areas – The largest contributory areas of the Meanwood catchment are three housing estates (Parklands, King Alfred's and West Lea) located adjacent to Stonegate Road, in the northern part of the catchment. A number of other smaller contributory surface areas are spread along Stonegate Road, Tongue Road and Parkside Lane. The Parklands, King Alfred's and West Lea estates contain mostly semi-detached housing, with a small number of detached and terraced properties, whilst the residential properties scattered along Stonegate Road, Tongue Road and Parkside Lane are generally detached or semi detached.

A new housing development has recently been constructed upon the Meanwood Park Hospital site at the junction of Parkside Lane and Tongue Road. This development has its own surface drainage, and hence does not contribute storm-water to the Meanwood sewer system.

Institutional Buildings – A number of shops and other institutional buildings (churches and schools) are scattered around the Meanwood catchment; these include a new retail park on Stonegate Road (located between Monk Bridge Road and Tongue Road). However, none of these institutional buildings are connected to Meanwood's combined sewerage system (Walker, 2000:b).

Geological Summary – The Meanwood catchment lies upon clay and mudstone deposits, sandstone and Stanningley rock. The use of infiltration devices was considered to be viable within the northern sections of the Meanwood catchment, since much of this region is founded upon sandstone deposits. However, the soil conditions of the remainder of the Meanwood catchment are less suitable for infiltration.

The Meanwood catchment is not part of a Groundwater Protection Zone I, II or III, as defined by the Environment Agency (Policy and Practice for the protection of groundwater, 1998), and therefore the infiltration of surface waters is permissible within this locality.

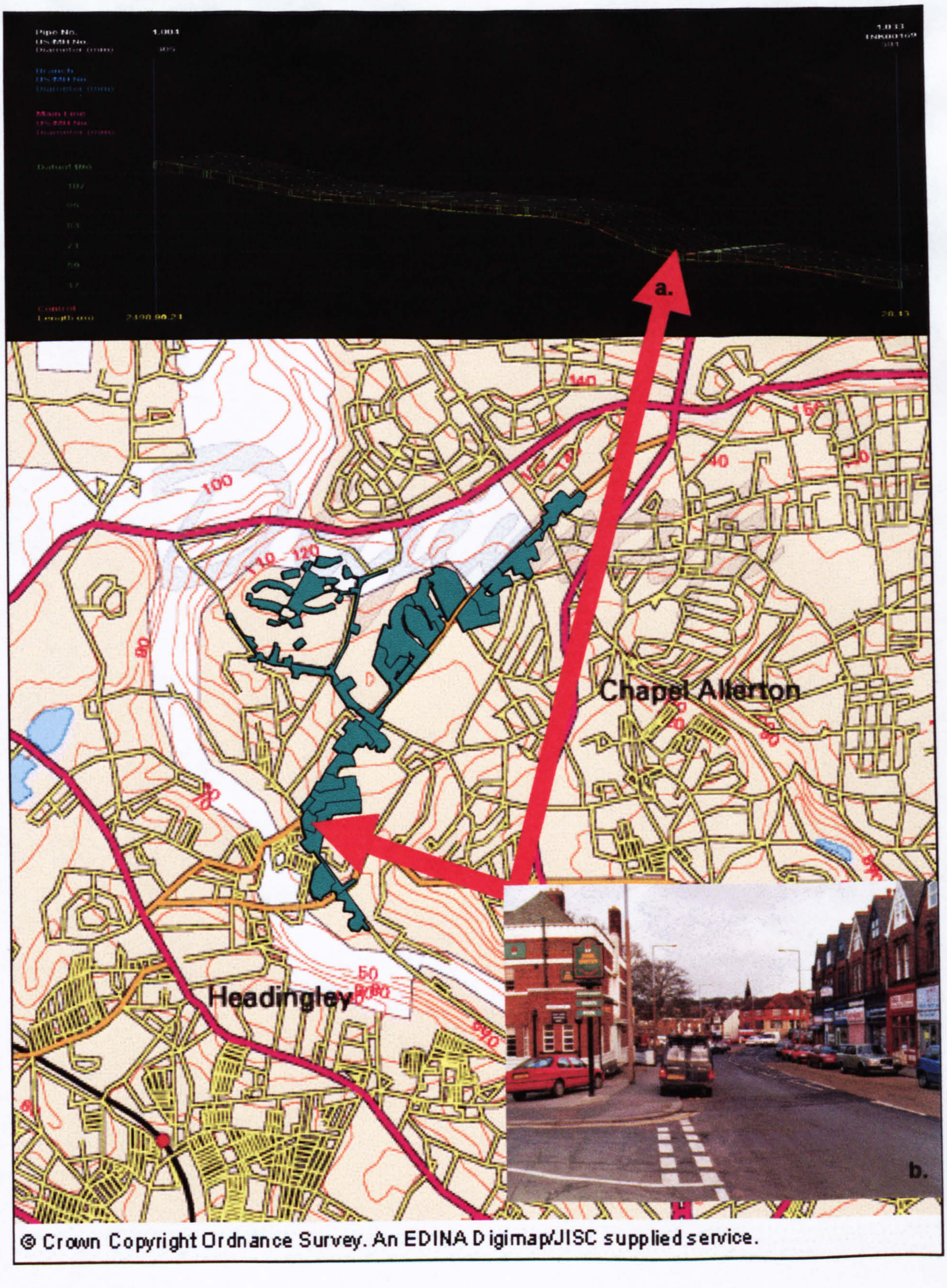


Figure 4.2

Meanwood urban drainage system:

a. Point of main flooding indicated on longitudinal section of Stonegate Road
b. Point of main flooding: Junction of Meanwood Road and Stonegate Road (B6157) – Grid Ref: (28625,36925) (View: N)

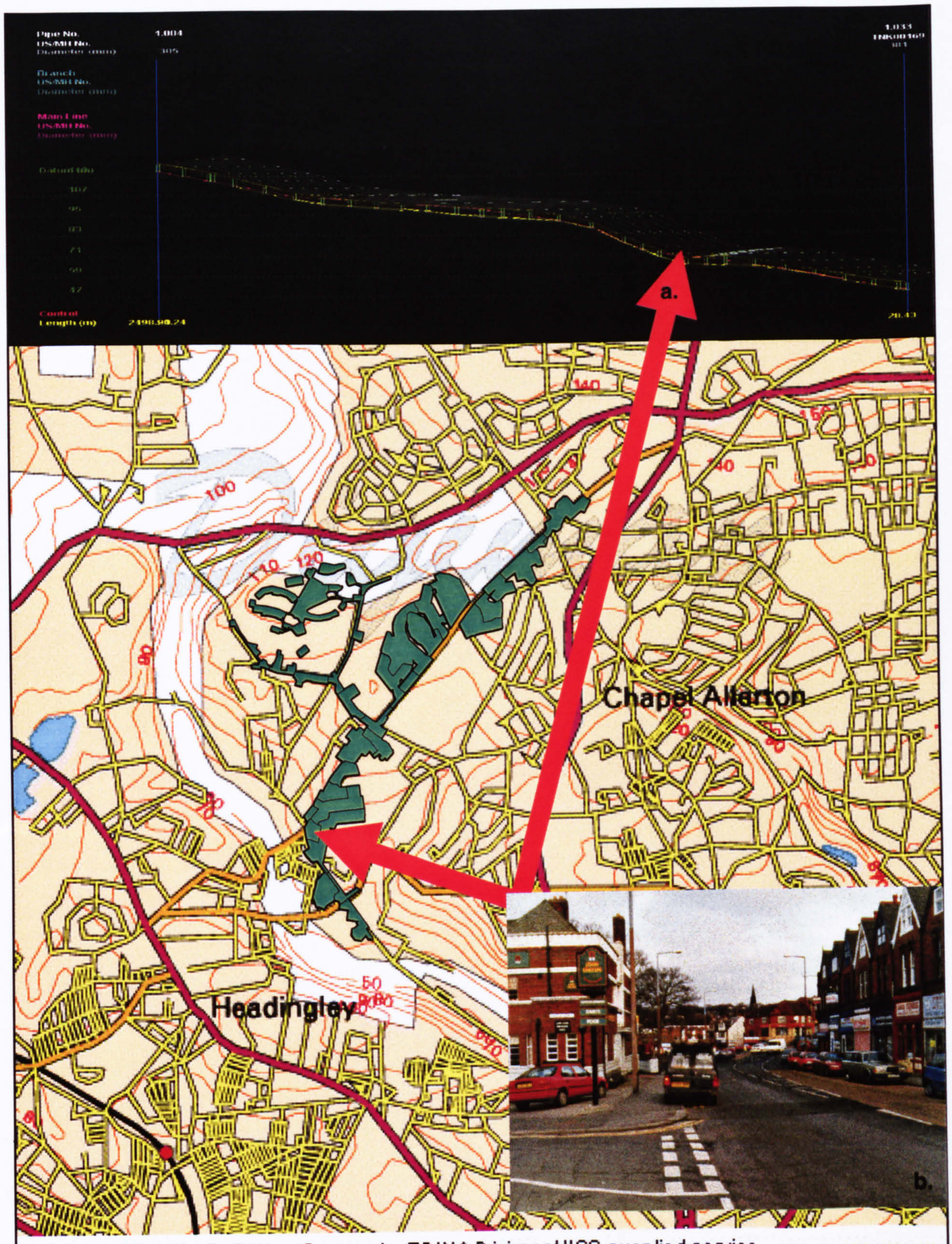


Figure 4.2

Meanwood urban drainage system:

a. Point of main flooding indicated on longitudinal section of Stonegate Road
b. Point of main flooding: Junction of Meanwood Road and Stonegate Road (B6157) – Grid Ref: (28625,36925) (View: N)

4.3.2. Retrofitting SUDS to Meanwood catchment: Catchment constraints

This Section investigates the potential for applying retrofit SUDS to the Meanwood catchment. This analysis sought to identify the main constraints to the application of retrofit SUDS within the catchment. The main factors considered as affecting the viability of SUDS approaches within the Meanwood catchment were: Geology, Urban Landscape, Topography, Source Protection Zones (SPZ), and Building regulations, each of these are summarised within Table 4.8 in terms of the constraints discussed in the previous Section. The impacts of these factors in relation to the Meanwood catchment are discussed within the ensuing sub-sections. The implications of these constraints upon different SUDS technologies are outlined within Section 4.4.

Table 4.8 Summary of factors that are considered to affect the viability of SUDS in Meanwood catchment

Factors considered to affect the viability of SUDS with respect to Meanwood catchment	Constraints highlighted within Section 4.2
Geology	Soil permeability
	Water Table level
Urban landscape	Available space
	Size of roof/capacity of roof
	Building regulations
	Construction issues relating to location
	Overflow
Topography	Slope
Source Protection Zones (SPZs)	Source Protection Zones (SPZs)
Other (non physical) constraints	Amenity value
	Maintenance
	Social issues/Institutional attitudes/take-up rates
	Safety

4.3.2.1. Catchment constraints: Geology

Background – Catchment geology is considered to be one of the major factors that can limit the extent to which retrofit SUDS may be implemented within a catchment. It has been reported that the use of infiltration devices (e.g. soakaways and infiltration trenches) is unfeasible within soils that have a percolation rate lower than 0.001 mm/h (= 4.63×10^{-6} m/s) (BRE 365, 1991). Argue (2001) reports that infiltration trenches and soakaways have been used in Australian soils with percolation rates as low as 1×10^{-8} m/s. However, within a British context, it is likely that the time taken to empty soakaways within soils with such low percolation rates (1×10^{-8} m/s) would be prohibitive – given the high frequency of rainfall within the UK.

The point is reinforced by the worked example presented in Appendix 4A, which uses the BRE 365 guidelines (1991) to design a soakaway for use within a soil with a percolation rate of 1×10^{-8} m/s. These example calculations produce an emptying time from full to ½ storage volume of 4452.8 hours for a 2.5 x 2.4 x 1.93 m soakaway.

Another geological factor that is considered to affect the viability of infiltration devices is whether the local water table ever reaches the base of the device, as this constitutes a pollution risk to the water table.

Application to Meanwood Catchment – The Meanwood catchment contains three broad soil/rock types: Sandstone; Mudstone; and Stanningley rock (Walker, 2000:b). Figure 4.3 shows the three predominant soil/rock types associated with each sub-catchment of the Meanwood model – this diagram was generated by overlaying the Meanwood catchment model (i.e. sub-catchment boundaries) and local geological maps.

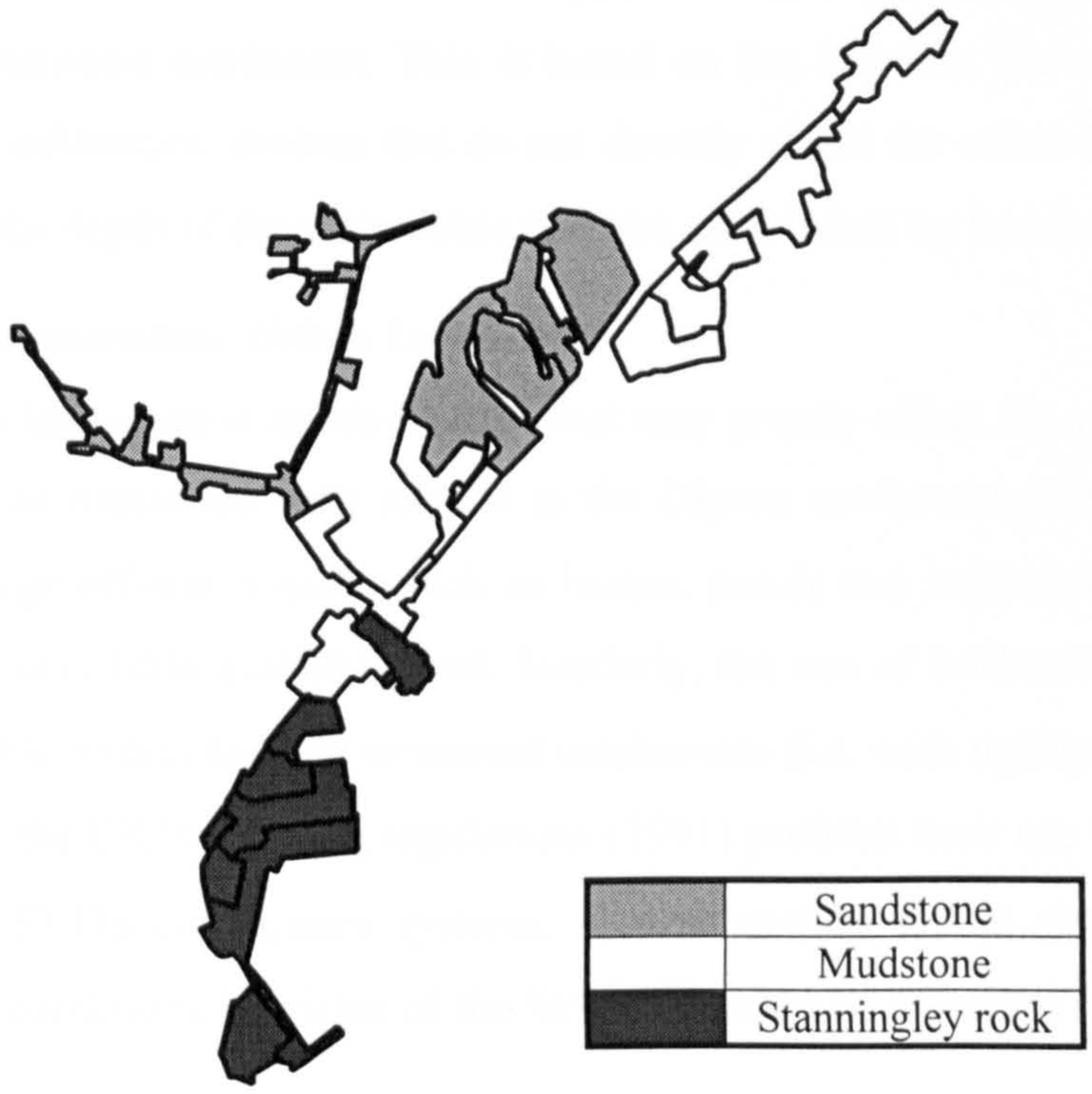


Figure 4.3 Predominate soil/ rock types underlying each sub-catchment of the Meanwood model

Standard percolation rates were assigned to each of the Meanwood soils/rocks (Table 4.9). These values were obtained from CIRIA Report 156 (1996) for comparative soil/rock types. This approach was adopted because it was not feasible to physically establish percolation rates using site-based investigations due to the financial and time constraints of this project.

Note: Existing guidelines (CIRIA 156, 1996; BRE Digest 365, 1991) recommend that site-based investigations be undertaken in order to establish the infiltration characteristics of local soils/rocks. For example, the design methodology for soakaways described within BRE Digest 365, involves digging a trial pit and filling it on several successive occasions, in order to measure the flow rate of water to keep it topped up. This gives a basis for estimating the local infiltration rate (e.g. outflow from the soakaway) and hence the size of soakaway required.

Table 4.9 Summary of Meanwood soil types

Zone No.	Zone Col.	Soil Type	Typical Soil percolation rate, f		Assumptions
			(mm/hr)	(m/s)	
1.		Sandstone	0.001	4.63E-06	$f_{sandstone} \approx f_{chalk}$
2.		Mudstone	0.0001	4.63E-07	$f_{mudstone} \approx f_{clay}$
3.		Stanningley rock	0.00001	4.63E-08	$f_{stanningley} \approx f_{rock}$

The only Meanwood soil/rock type considered appropriate for the use of infiltration devices is sandstone (See Table 4.9).

It was not envisaged that infiltration devices would pose a credible threat to the local water table in relation to the Meanwood catchment. This is based on the fact that the catchment already contains a number of infiltration devices that do not directly affect the water table. However, it is still advisable that the depth of the water table level be established by borehole investigations.

4.3.2.2. Catchment constraints: Urban Landscape

Background – Urban landscape is another factor that may greatly affect the viability of retrofit SUDS. For example, as illustrated with respect to the Gipton catchment (Chapter 3), it is not viable to construct large off-site controls such as basins, ponds and infiltration devices within catchments that have very little available land. Similarly, the use of infiltration devices would generally not be feasible within densely urbanised catchments (i.e. with tightly packed buildings and narrow roads), as the UK's Building regulations (1991) prohibit their use within 5 m of any building. The use of SUDS conveyance systems, such as swales, would also be significantly restricted under such conditions by virtue of the limited number of locations in which they may be used.

The location in which a retrofit device is to be applied will obviously influence its construction costs and the type of technology that may be appropriate. For example, the introduction of swales to densely urbanised areas (i.e. with narrow roads) would generally mean the loss of existing pavements, or the significant narrowing of existing roads – both approaches would result in high construction costs, and would be likely to be highly disruptive. However it is possible that such measures (e.g. street narrowing) might be cost effective if introduced in conjunction with traffic calming or pedestrianisation schemes.

The urban landscape will also influence the adopted method of disposal for overflows from swales and SUDS storage devices. The conventional approach would be to direct flow into the local sewer, however alternative methods of disposal (e.g. infiltration and discharge into local watercourses) may be adopted if viable means of disposal exist near the technology.

Application to Meanwood Catchment – For the purpose of this analysis SUDS conveyance systems were only considered viable for introduction to existing grassed areas (e.g. fields and grassed roadside verges) – since retrofitting swales, or filter drains, to paved locations would involve comparable construction costs and disruption as conventional pipe-based conveyance

systems. Figure 4.4 displays all roads within the Meanwood catchment that are lined with grassed verges, and hence considered to be appropriate for the use of SUDS conveyance systems. Figure 4.5 shows all large-scale grassed or undeveloped areas adjacent to the Meanwood catchment that were considered to be appropriate for the construction of retrofit SUDS off-site controls, such as infiltration trenches, ponds or porous car parks. It should be noted that most of these areas are located downstream of the grass verged roads (highlighted within Figure 4.4). It is worth noting that no appropriate locations for offsite controls could be identified immediately within the catchment boundaries.

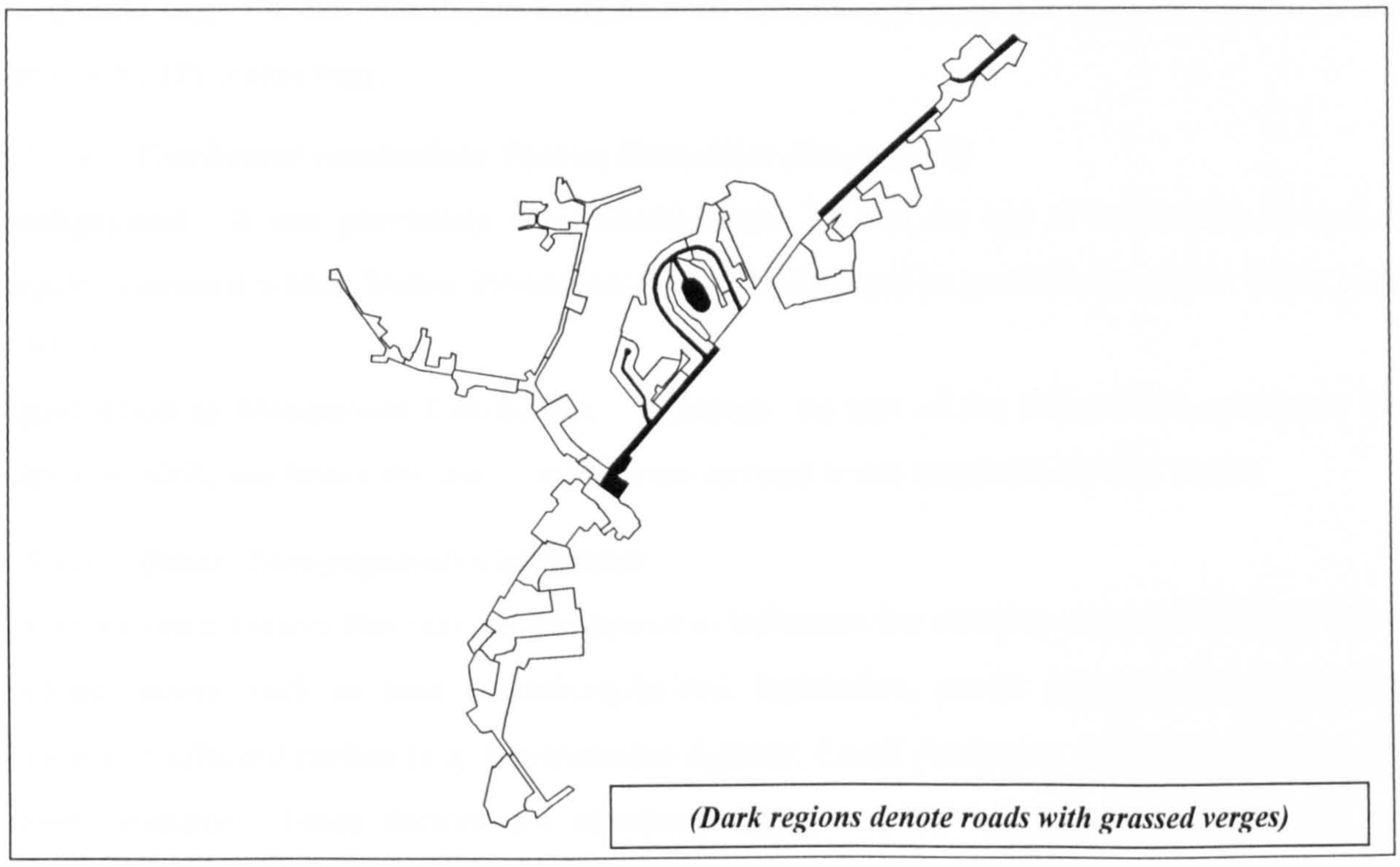
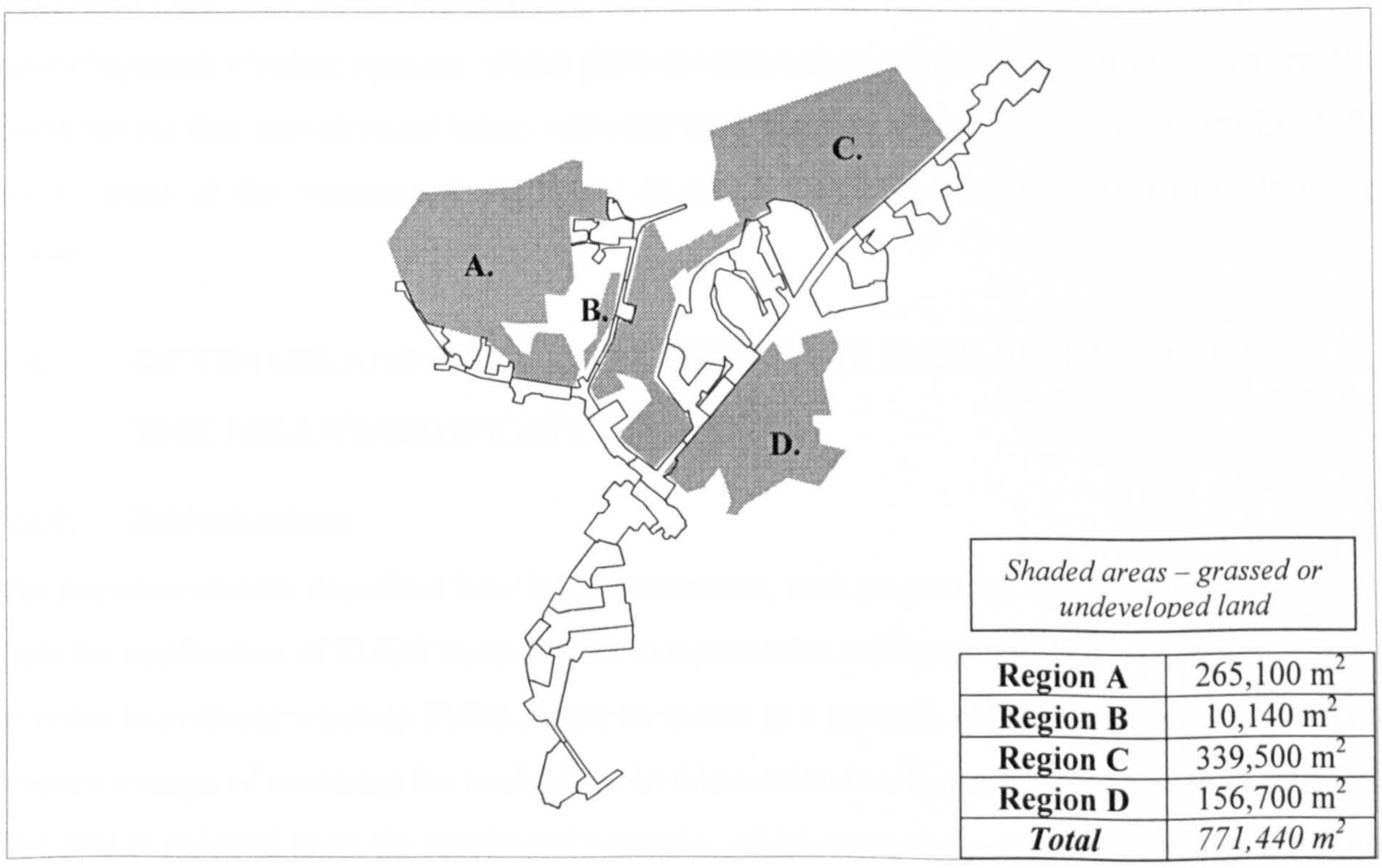


Figure 4.4 Meanwood sub-catchment breakdown showing roads with grassed verges



Region A	265,100 m^2
Region B	10,140 m^2
Region C	339,500 m^2
Region D	156,700 m^2
Total	*771,440 m^2*

Figure 4.5 Meanwood: sub-catchment breakdown showing grassed land available for off-site controls

4.3.2.3. Catchment constraints: Topography

Background – Topography is another factor that can influence the extent to which retrofit SUDS may be used within a catchment. It is recommended that swales should not be used on slopes greater than 1:50, and filter strips on cross-slopes greater than 1:20; in both instances these restrictions are to avoid surface erosion (UWTC, 2000). In regions containing much higher gradients it may become impracticable to operate other retrofit SUDS, such as porous pavements and other infiltration technologies.

Application to Meanwood Catchment – It is evident from maps of the local area that none of the ground slopes in the Meanwood catchment are sufficiently steep to hinder the retrofit of any form of SUDS technology.

4.3.2.4. Catchment constraints: Source Protection Zones (SPZ)

Background – It was previously described (Chapter 2), that the use of infiltration devices is largely restricted within Source Protection Zones (SPZs), and in particularly within Class I and II SPZs.

Application to Meanwood Catchment – However, no part of the Meanwood catchment lies within an SPZ, and hence the use of infiltration devices is not restricted by this factor.

4.3.2.5. Other (Non-physical) Constraints

There are other factors that may be considered to influence the viability of retrofit SUDS. These include factors such as land availability/prices, legislation, social issues and the planning policies of affected parties (e.g. Environment Agency, Local Authority, Highways Agency and Sewer operator). These factors are obviously important, but on the whole these are not considered to be as rigid as the issues presented in Sections 4.3.2.1-4.3.2.4. This primarily relates to the fact that non-physical constraints may be eliminated by a change in policy/legislation/public opinion, whilst physical constraints are generally harder to change. It is worth noting that non-physical issues were not considered to constrain the use of retrofit SUDS within areas of the Meanwood catchment in which they had been deemed to be physically viable.

4.4. OPTIMUM AND BEST-CASE RETROFIT SUDS PROPOSALS FOR THE MEANWOOD CATCHMENT

4.4.1. Introduction

The previous section described how local constraints, such as geology and urban landscape, can limit the application of SUDS technologies in a particular catchment.

In order to evaluate whether SUDS might be viable in a specific context, the engineer needs to prepare a range of scenarios for evaluation. In this section two types of scenario are described. The first is referred to as the 'optimum' scenario, which essentially considers the application of SUDS to all paved and roofed areas in a catchment (and the subsequent disconnection of their

contributory surface areas from the local sewer). Clearly, if this scenario does not produce a significant improvement in hydraulic performance, then there will be little value in pursuing more detailed design options. Disconnection of contributory surfaces may be achieved via either infiltration-based or storage-based SUDS, each of which exhibit different hydraulic behaviour. Storage-based SUDS generally have a much smaller capacity than infiltration devices, and as such may fill and overflow back into the combined sewer system during times of excessive rainfall. It is therefore important, even at this preliminary stage, to identify which parts of the optimum solution are based on infiltration and which depend upon storage. Due to the smaller capacity of storage devices, infiltration technologies are considered to be the more preferable option. The optimum SUDS scenario should therefore utilise infiltration devices wherever possible, with storage facilities used for the remainder of roofed/paved catchment. At this stage the only criterion for determining whether infiltration is feasible is geology (i.e. soil permeability); technical constraints affecting the construction of specific SUDS devices are discussed later. It is worth noting that the SUDS scenarios that utilise conveyance and offsite infiltration facilities may achieve greater coverage (in terms of the paved/roofed areas served) than those that only adopt source control devices. The only criteria considered to restrict the use of storage options are the assumptions that source-control storage facilities would practicably be limited to a capacity of between 0 to 6 litres per m^2 for roofed areas, and 0 to 10 litres per m^2 for paved areas (the rationale for these assumptions is presented in Section 5.3.4.1).

Section 4.4.2 outlines five optimum SUDS scenarios that were investigated in relation to the Meanwood catchment – the first two consider infiltration alone, whilst the next two consider the use of storage facilities to supplement the use of infiltration devices, and the final option considers the use of storage facilities on their own (Table 4.10).

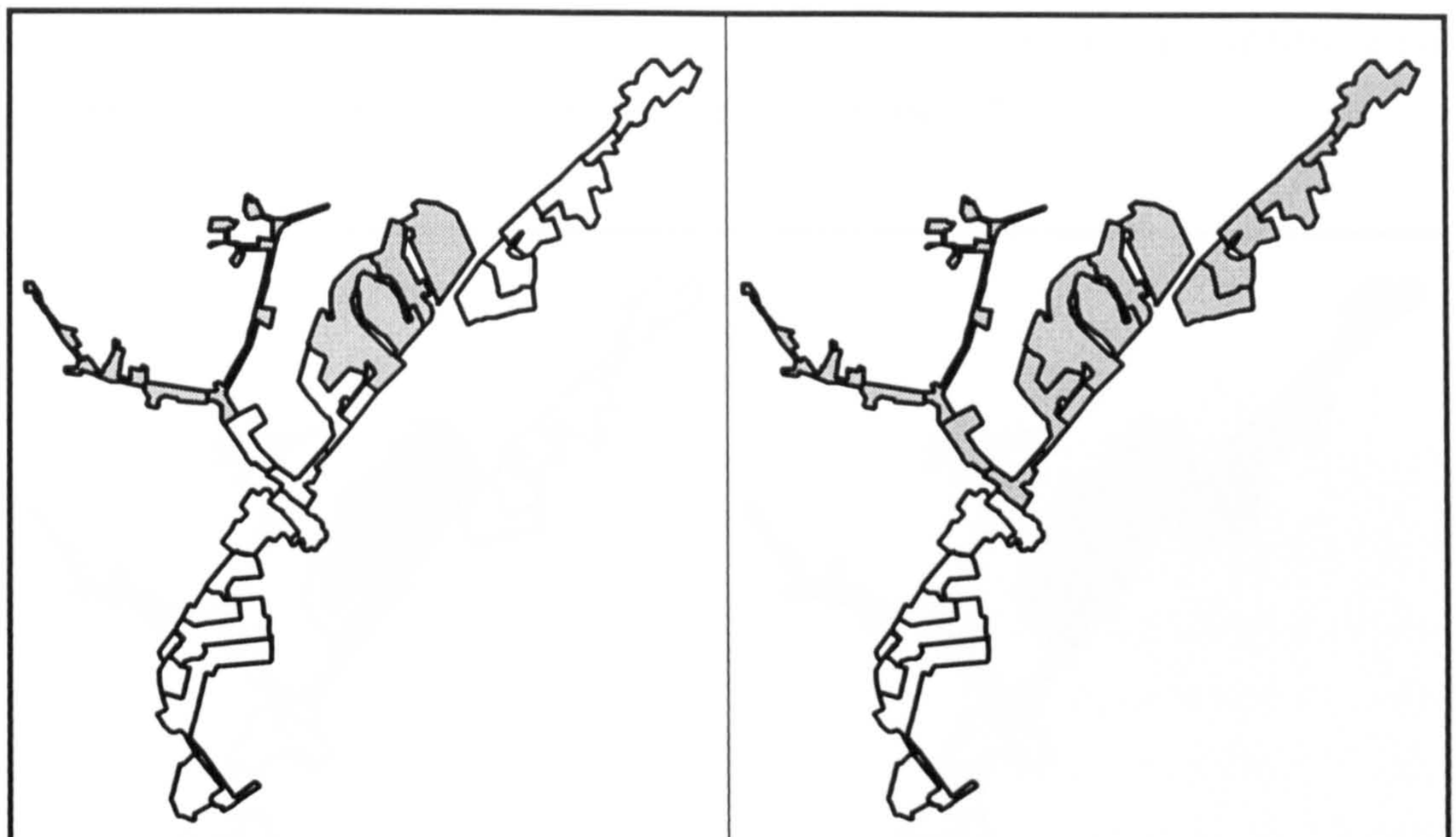
Table 4.10 Summary of Optimum SUDS Scenarios for the Meanwood catchment

Scenario	Description
Optimum Proposal 1	Considers the use of Infiltration-based source-control technologies
Optimum Proposal 2	Considers the use of Infiltration-based source-control technologies, with Conveyance and Infiltration-based off-site control technologies
Optimum Proposal 3	As **Optimum Proposal 1,** but with source-control storage facilities adopted in the remainder of the catchment
Optimum Proposal 4	As **Optimum Proposal 2,** but with source-control storage facilities adopted in the remainder of the catchment
Optimum Proposal 5	Source-control storage facilities adopted throughout catchment

4.4.2. Optimum SUDS scenarios

4.4.2.1. Optimum infiltration SUDS scenarios

Two optimum scenarios were developed for infiltration-based SUDS, the first option explored the sole use of infiltration-based source-control devices, and the second explored the combined use of infiltration-based source and off-site control devices. These scenarios are illustrated in Figure 4.6 and described in detail below:



Optimum proposal 1: Disconnection of all impervious surfaces contained within Meanwood's sandstone region using infiltration-based source control SUDS *Roofed area disconnected: 3.022 ha, or 41% of all roofs* *Paved area disconnected: 3.423 ha, or 37.2% of all paved area*	Optimum proposal 2: Disconnection of all 'infiltratable' impervious surfaces using infiltration-based source and offsite control SUDS *Roofed area disconnected: 5.583 ha, or 75.8% of all roofs* *Paved area disconnected:6.369 ha, or 69.2% of all paved area*

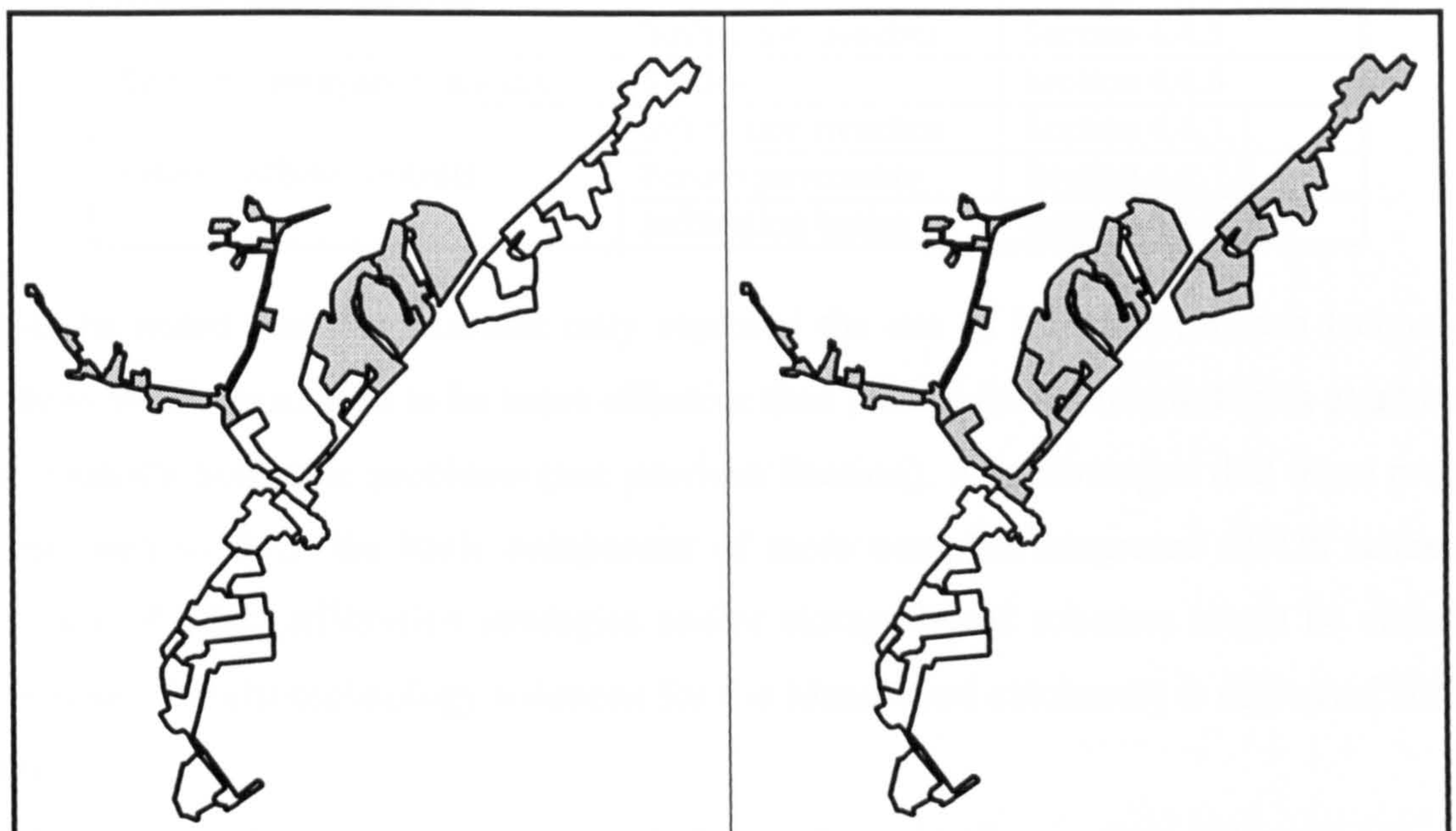
Figure 4.6 Optimum Source and Offsite control options using infiltration SUDS for the Meanwood catchment

Optimum proposal 1 (the optimum infiltration-based source-control scenario) involves the disconnection of all impervious (paved and roofed) areas contained within Meanwood's sandstone region (i.e. suitable for infiltration). **Optimum proposal 2 (t**he optimum infiltration-based source and off-site control scenario) would involve the disconnection of all 'infiltratable' impervious areas. These were defined as being upstream of what was considered to be the most down-stream viable location for an off-site infiltration-based control facility within the Meanwood catchment. Those parts of the catchment located down-stream of this point were not considered viable for infiltration SUDS due to the fact that they were highly urbanised, coupled with unfavourable ground conditions.

4.4.2.2. Optimum storage-based scenarios

Three further optimum scenarios were developed in relation to use of storage-based source controls: the first option **(Optimum proposal 3)** related to the use of storage-based source control devices as a supplement to the optimum infiltration-based source control scenario; the second **(Optimum proposal 4)** related to the use of storage-based source control devices as a supplement to the optimum infiltration-based source and off-site control scenario; and the last option **(Optimum proposal 5)** related to the use of storage-based source controls in conjunction

with all impermeable surfaces contained within the Meanwood catchment. The first two of these storage-based source control options are presented in Figure 4.7.



Optimum Proposal 3: **Combined infiltration/storage** Optimum source control (infiltration) proposal in addition to: Storage to all impervious surfaces not contained within Meanwood's sandstone region ***(S/C storage to all impervious areas contain within un-shaded region)***	**Optimum Proposal 4:** **Combined infiltration/storage** Optimum off-site control (infiltration) proposal in addition to: Storage to all impervious surfaces not considered to be 'infiltratable' ***(S/C storage to all impervious areas contain within un-shaded region)***

Figure 4.7 Optimum storage SUDS scenarios

Further details of these optimum storage-based scenarios are presented in Chapter 5.

No further analysis was undertaken to develop optimum scenarios for the application of storage-based off-site controls to the Meanwood catchment. This related to the fact that all viable locations for such facilities had already been earmarked for off-site infiltration-based facilities. It was considered that infiltration-based proposals were more appropriate for reducing/eliminating catchment flooding than storage-based options (see Section 4.2.3.2).

4.4.3. Best case scenarios

This Section explores the specific design issues associated with a range of SUDS technologies (see Table 4.11). Best-case scenarios (i.e. in terms of achievable coverage of the Meanwood catchment) were generated for each investigated technology – in order to establish which design factors influenced their use in a retrofit context. These scenarios represent the best-case implementation proposals that were considered practicable for each individual retrofit technology with respect to the Meanwood Catchment, given the constraints outlined previously (Section 4.3).

Table 4.11 Summary of following Sections

SUDS Category	SUDS Technology	Relevant Section
Retrofit source controls	Soakaways	Section 4.4.4
	Infiltration trenches	Section 4.4.5
Retrofit conveyance devices	Swales	Section 4.4.6
Retrofit offsite controls	Infiltration trenches	Section 4.4.7.1
	Porous pavements	Section 4.4.7.2
	Infiltration basins	Section 4.4.7.3

It should be noted that this exercise only explored the use of infiltration-based technologies, since these were considered to be more effective than storage-based technologies at addressing the catchment's hydraulic problems (see previous Section). It is envisaged that these proposals could be used to form the basic component of more complex/integrated SUDS schemes, to which parts of other infiltration strategies and/or storage-based schemes might be added. The development of multi-technology solutions for the Meanwood catchment is discussed further in Chapter 7.

Final design calculations were generated for each technology using relevant UK design guidelines. Further details of this design work is presented in Appendices 4A to 4F. The hydraulic performance associated with each of these schemes was simulated using HydroWorks catchment models; the results of this analysis are presented in Chapter 5. Corresponding scheme costings were derived, and are discussed in Chapter 6.

It should be noted that source control devices were investigated as standalone technologies, whereas off-site controls were investigated in conjunction with conveyance devices.

Section 4.4.8 compares each of these implementation scenarios with the optimum source and offsite control options (Figure 4.6).

4.4.4. Source control proposal 1: Retrofit Soakaways

The most extensive use of soakaways considered feasible given the constraints of the existing-state Meanwood catchment was the proposed connection of individual soakaways to every roof within the sandstone region. Table 4.12 presents a summary of this proposal.

Table 4.12 Source control proposal 1: Soakaway

	Roofed area and No. of properties served by soakaways	Roofed area connected to combined sewer system (ha)	Roofed area connected to combined sewer system (%)
Soakaways to every roof within **sandstone** region	3.0221 ha (426 properties)	4.346 ha	59.0%

It was assumed that each of the 426 properties roofs contained within the Meanwood sandstone region was connected to its own individual 1.5 x 1.8 x 1.8 m soakaway by a 6 m length of gulley. The design calculations used to generate these soakaway dimensions were based upon the BRE 365 methodology, and assumed that $f_{sandstone} = 4.63 \times 10^{-6}$ m/s and that a typical contributory property had a roofed area of 50 m^2.

This proposal was considered to be viable because: i) sandstone soils are sufficiently permeable to allow the use of infiltration devices; ii) local gardens within this region are large enough to allow the use of soakaways without contravening Building Regulations (5 m rule); and iii) no part of the catchment lies within a ground water protection zone. See Appendix 4A for further details.

The simulated hydraulic performance of this proposal is presented in Chapter 5, and corresponding costings are presented in Chapter 6.

4.4.5. Source control proposal 2: Retrofit Infiltration trenches

It was not considered practical to explore schemes that involved the construction of infiltration trenches within individual properties due to the high levels of disruption that would be associated with their construction (Section 4.2.1.2). However, the use of infiltration trenches in open land immediately adjacent to domestic properties was considered to be more feasible, and was therefore explored. It is considered that this proposal may be classified as a source control, as conveyance devices are only required to transfer runoff to the boundary of the receiving properties.

The most extensive use of infiltration trenches that was considered feasible within Meanwood involved the construction of 1065 m of infiltration trenches to serve 86 properties within the sandstone region (see Figure 4.8). This proposal adopted infiltration trenches to serve all properties within the sandstone region that bordered open grassland. These locations were selected due to favourable geological conditions, ease of construction, and the fact that infiltration technologies did not contravene any SPZs (E.A., 1998) or Building Regulations (5 m rule).

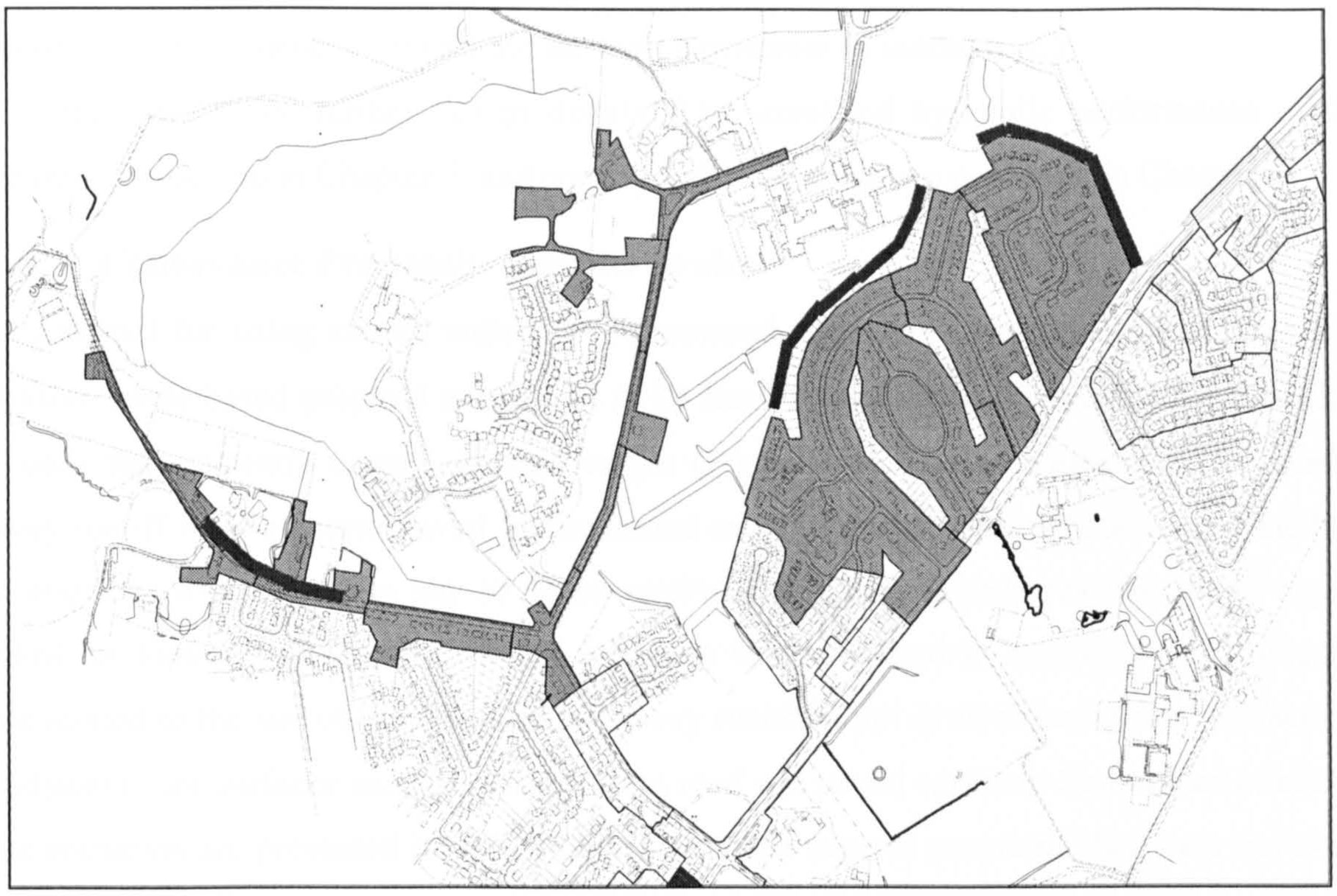


Figure 4.8 Maximum infiltration trench proposal for existing Meanwood catchment

Solid black lines indicate feasible locations for infiltration trenches; Solid grey areas indicate sub-catchments that are predominately underlain by sandstone

A summary of this proposal is presented in Table 4.13.

Table 4.13 Source control proposal 2: Infiltration trenches

Proposal	Roofed area and No. of properties served by infiltration trenches	Roofed area connected to combined sewer system (ha)	Roofed area connected to combined sewer system (%)
Construction of 1065 m of infiltration trenches to serve 86 properties within **sandstone** region	0.4728 ha (86 properties)	6.896	93.6

It was assumed that each of the 86 roofs to be served by this proposed scheme would be connected to the infiltration trench by individual lengths of gulley. The CIRIA 156 (1996) methodology was used to design these infiltration trenches. These calculations were used to investigate the performance of a 0.6 x 1 x 1065 m infiltration trench assuming an $f_{sandstone}$ value of 0.001 mm/h (4.63 x 10^{-6} m/s) and a total contributory roofed area of 0.4728 ha. This configuration produced an emptying time (i.e. for emptying from full to half full conditions) of 76.57 hrs. This represents a significant amount of time, especially since it is recommended within BRE 365 (1991) that all infiltration devices should be designed to empty critical storm runoffs from full to half full conditions within 24 hrs. To produce a viable infiltration trench in relation to this criterion the length of the trench would need to be extended from 1065 m to 8000 m, or the $f_{sandstone}$ value increased from 0.001 mm/h to 0.0031 mm/hr. (Note: as the soil

percolation rates of sandstone can range from 0.001 to 100 mm/hr (BRE 365, 1991) this proposal would be viable within all but the least permeable of sandstones.)

See Appendix 4B for further design details. The simulated hydraulic performance of this proposal is presented in Chapter 5, and corresponding costings are presented in Chapter 6.

4.4.6. Conveyance Proposal: Retrofit swales

The potential for using swales within the Meanwood catchment was investigated. The most extensive swale-based proposal considered to be feasible was the construction of swales along all roads that currently contain grassed verges (Figure 4.4). These swales could be used to convey runoff from adjacent paved and/or roofed areas to downstream offsite control facilities that could be located within any of Meanwood's large undeveloped area (see green regions marked on Figure 4.5). Three different scenarios were explored in relation to this proposal, these related to the use of these swales to convey runoff from: i) all adjacent road surfaces; ii) all adjacent roof surfaces and iii) both adjacent roof and paved surfaces. Summaries of each of these scenarios are presented in Table 4.14. The offsite control proposals that were developed for use in conjunction with these conveyance schemes are presented in the next Section.

Table 4.14 Disconnection options of impermeable area associated with the proposed introduction of Swales to all grassed verges within Meanwood catchment (Proposed Swale length: 4930 m)

Proposal	Roofed or (Paved) area and No. of properties served by proposal	Roofed or (Paved) area connected to combined sewer system (ha)	Roofed or (Paved) area connected to combined sewer system (%)
Swale Option A: Disconnection of all ROOFS adjacent to swales	1.8998 246 properties	5.469	74.2
Swale Option B: Disconnection of all PAVED areas adjacent to swales	(2.8860)	(6.316)	(68.6)
Swale Option C: Disconnection of both ROOFED and PAVED areas adjacent to swales	1.8998 (2.8860) Total: 4.7858 ha	5.469 (6.316)	74.2 (68.6)

It should be noted that the typical length of connection required between the house and swale was defined as 10 m. See Appendix 4C for further details.

4.4.7. Off site controls

Three infiltration-based off-site technologies (i.e. Infiltration trenches, Porous pavements and Infiltration basins) were investigated as potential offsite controls for use in conjunction with each of the conveyance proposals highlighted within the previous Section (see Table 4.14). The following Sections present design dimensions that were defined for: infiltration trenches (Section 4.4.7.1); Porous pavements (Section 4.4.7.2) and Infiltration basins (Section 4.4.7.3). These design dimensions were generated using CIRIA 156 design methodologies corresponding to each of these technologies. It should be noted that these calculations were performed using

appropriate input parameter values to represent the physical characteristics of the catchment and of each of the three disconnection scenarios presented for the swale proposal in Table 4.14 of the previous Section.

4.4.7.1. Offsite control proposal 1: Infiltration trenches

The potential for using infiltration trenches as an off-site control within the Meanwood catchment was investigated.

The following tables present design dimensions that were generated for three separate infiltration trench proposals, to drain contributory areas of 1.8998 ha, 2.8860 ha and 5.469 ha respectively. These contributory areas correspond to the three disconnection options that were considered for the swale proposal presented within the previous Section (see Table 4.14).

The design dimensions associated with these proposals were generated using the CIRIA 156 design methodology for infiltration trenches. These calculations assumed a fixed trench width of 1 m and a fixed depth of 3 m, and were conducted with respect to two different soil percolation rates (0.01 and 0.001 mm/hr). Different percolation rates were considered in order to represent a wide range of permeability characteristics that may be associated with different sandstone types.

Table 4.15 Required Infiltration trench dimensions to adequately drain 1.8998 ha (Disconnected roofed area associated with Swale Option A)

All Design work conducted in accordance with CIRIA 156 methodology

Soil Infiltration coefficient, **f** (mm/hr)	Trench base width, **Wb** (m)	Trench base length, **Lb** (m)	Trench base area, **Ab** (m^2)	Calculated minimum trench depth required, **D** (m)	Calculated time of emptying from full to half full, **t** (hrs)
0.01	1	720	720	2.98	14.65
0.001	1	885	885	2.99	146.67

Table 4.16 Required Infiltration trench dimensions to adequately drain 2.886 ha (Disconnected paved area associated with Swale Option B)

All Design work conducted in accordance with CIRIA 156 methodology

Soil Infiltration coefficient, **f** (mm/hr)	Trench base width, **Wb** (m)	Trench base length, **Lb** (m)	Trench base area, **Ab** (m^2)	Calculated minimum trench depth required, **D** (m)	Calculated time of emptying from full to half full, **t** (hrs)
0.01	1	1090	1090	2.96	14.67
0.001	1	1350	1350	2.99	146.60

Table 4.17 Required Infiltration trench dimensions to adequately drain 4.7858 ha (Disconnected paved & roofed area associated with Swale Option C)

All Design work conducted in accordance with CIRIA 156 methodology

Soil Infiltration coefficient, **f** (mm/hr)	Trench base width, **Wb** (m)	Trench base length, **Lb** (m)	Trench base area, **Ab** (m^2)	Calculated minimum trench depth required, **D** (m)	Calculated time of emptying from full to half full, **T** (hrs)
0.01	1	1800	1800	3.00	14.68
0.001	1	865	2250	3.00	98.60

For further details of these design calculations see Appendix 4B.

It is worth noting that in relation to the less permeable of the two investigated sandstone types (i.e. with a soil infiltration coefficient = 0.001mm/hr) none of these infiltration trench proposals was considered to be viable. The emptying times (i.e. from full to half full conditions) calculated for each of these proposals were far larger than the 24 hour period recommended within the BRE 365 (1991) guidelines.

4.4.7.2. Offsite control proposal 2: Porous pavement

This Section explores porous pavements proposals to drain runoff from each of the conveyance options presented within Section 4.4.6. Porous pavements are only considered feasible as an off-site technique where there is an existing conventional car-park/paved area, or a need for a new car-parking facility and available land. There are no existing car parks, or any foreseeable need for car parks within the Meanwood catchment – therefore in practical terms this option was not worth exploring. However, as porous pavements would be feasible to construction in other catchments – the economical and technical merits of this option were investigated.

The following tables present design dimensions for three proposals that were intended to drain their own surface areas in addition to the runoff conveyed from each of the three alternative impervious area disconnection scenarios presented in Table 4.14. The dimensions of the off-site facilities presented within this Section were calculated using the CIRIA 156 methodology.

Table 4.18 Required dimensions of porous pavement to adequately drain its own surface and an additional 1.8998 ha of contributing area (i.e. Disconnected roofed area associated with Swale Option A)

All Design work conducted in accordance with CIRIA 156 methodology

Soil Infiltration coefficient, **f** (mm/hr)	Contributory Area, **C**, (m^2)	Width of paved strip, **W**, (m)	Required length of paved strip **L**, (m)	Required area of paved strip, **A** (m^2)
0.01	18998	77	77.54	5970.46
0.001	18998	120	121.55	14586.03

Table 4.19 Required dimensions of porous pavement to adequately drain its own surface and an additional 2.886 ha of contributing area (i.e. Disconnected roofed area associated with Swale Option B)

All Design work conducted in accordance with CIRIA 156 methodology

Soil Infiltration coefficient, **f** (mm/hr)	Contributory Area, **C**, (m^2)	Width of paved strip, **W**, (m)	Required length of paved strip **L**, (m)	Required area of paved strip, **A** (m^2)
0.01	28860	95	196.27	18645.49
0.001	28860	150	196.27	29440.25

Table 4.20 Required dimensions of porous pavement to adequately drain its own surface and an additional 4.7858 ha of contributing area (i.e. Disconnected Roof & Paved areas associated with Swale Option C)

All Design work conducted in accordance with CIRIA 156 methodology

Soil Infiltration coefficient, **f** (mm/hr)	Contributory Area, **C**, (m^2)	Width of paved strip, **W**, (m)	Required length of paved strip **L**, (m)	Required area of paved strip, **A** (m^2)
0.01	47858	123	122.65	15086.51
0.001	47858	185	193.78	35848.42

It is worth noting that the porous pavement proposals generated with respect to the less permeable sandstone (i.e. with a soil infiltration coefficient = 0.001 mm/hr) were significantly

larger than those generated for the more permeable sandstone types. However, none of the required base areas of these porous pavements exceed the amount of undeveloped land available in the Meanwood catchment (see Figure 4.5).

For further details of these design calculations see Appendix 4D.

4.4.7.3. Offsite control proposal 3: Infiltration basin

This Section investigates the use of infiltration basins as a potential off-site control technology. Infiltration ponds could be introduced as a landscaping feature to existing green areas. The following tables present design dimensions for three proposals that were intended to drain runoff from each of the three alternative impervious area disconnection scenarios presented within Table 4.14. These design dimensions were generated using the CIRIA 156 design methodology for infiltration basins. Calculations were conducted with respect to two different soil percolation rates (0.01 and 0.001 mm/hr), and assumed that the basin had a square base. Different percolation rates were considered in order to represent the wide range of permeability characteristics that may be associated with different sandstone types.

Table 4.21 Infiltration basin dimensions required to adequately drain 1.8998 ha of contributing area (i.e. Disconnected roofed area associated with Swale Option A)

All Design work conducted in accordance with CIRIA 156 methodology

Soil Infiltration coefficient, f (mm/hr)	Width of basin base, Wb (m)	Length of basin base, Lb (m)	Area of basin base, Ab (m^2)	Minimum basin depth required, D (m)	Time of emptying from full to half full, t (hrs)
0.01	50	50	2500	0.31	23.00
0.001	160	160	25600	0.03	22.81

Table 4.22 Infiltration basin dimensions required to adequately drain 2.886 ha of contributing area (i.e. Disconnected roofed area associated with Swale Option B)

All Design work conducted in accordance with CIRIA 156 methodology

Soil Infiltration coefficient, f (mm/hr)	Width of basin base, Wb (m)	Length of basin base, Lb (m)	Area of basin base, Ab (m^2)	Minimum basin depth required, D (m)	Time of emptying from full to half full, t (hrs)
0.01	65	65	4225	0.27	20.32
0.001	200	200	40000	0.03	22.04

Table 4.23 Infiltration basin dimensions required to adequately drain 4.7858 ha of contributing area (i.e. Disconnected roofed area associated with Swale Option C)

All Design work conducted in accordance with CIRIA 156 methodology

Soil Infiltration coefficient, f (mm/hr)	Width of basin base, Wb (m)	Length of basin base, Lb (m)	Area of basin base, Ab (m^2)	Minimum basin depth required, D (m)	Time of emptying from full to half full, t (hrs)
0.01	80	80	6400	0.31	22.74
0.001	250	250	62500	0.03	23.70

It is worth noting that the emptying times (i.e. from full to half full conditions) calculated for each of these proposals were all less than the 24 hour period stipulated within the BRE 365 (1991) guidelines. However, the design solutions associated with the less permeable of these sandstones (percolation rate = 0.001 mm/hr) produced basins with base areas around ten times

larger than corresponding design solutions for permeable sandstones (percolation rate = 0.01 mm/hr). For further details of these design calculations see Appendix 4E.

4.4.8. Comparison of Proposals

Table 4.24 summaries the amount of impervious area (in terms of paved and roofed areas) considered to be disconnected by each of these proposals, and contrasts these against those of the optimum proposals highlighted in Section 4.4.2. All the scenarios presented below are based entirely on infiltration.

Table 4.24: Comparison of technology specific and optimum disconnection scenarios

Proposal	*Roofed*, *(Paved)* or **Total Imp.** area served by proposal (ha)	*Roofed*, *(Paved)* or **Total Imp.** area connected to combined sewer system (ha)	*Roofed*, *(Paved)* or **Total Imp.** area connected to combined sewer system (%)
Optimum Proposal 1: **(Source control)** Disconnection of all impervious areas in sandstone sub-catchments of Meanwood catchment	*3.022 ha* *(3.423 ha)* **6.445 ha**	*4.346 ha* *(5.779 ha)* **10.125 ha**	*59.0 %* *(62.8 %)* **61.1 %**
Source control proposal 1: Soakaways* to every roof *(426 properties)* in **sandstone** region	*3.022 ha* *(0 ha)* **3.022 ha**	*4.346 ha* *(9.202 ha)* **13.548 ha**	*59.0 %* *(100 %)* **81.8 %**
Source control proposal 2: Construction of 1065 m of infiltration trenches to serve *86 properties* in **sandstone** region	*0.473 ha* *(0 ha)* **0.473 ha**	*6.896 ha* *(9.202 ha)* **16.098 ha**	*93.6 %* *(100 %)* **97.2%**
Optimum Proposal 2 **(Off-site control)** Disconnection of all impervious areas in Meanwood subcatchments u/s of Node 450_150 (i.e. the most d/s location that is considered appropriate for an off-site control facility within the Meanwood catchment)	*5.583 ha* *(6.369 ha)* **11.952 ha**	*1.786 ha* *(2.833 ha)* **4.619 ha**	*24.2 %* *(30.8 %)* **27.9 %**
Swales Option A: ***Offsite control proposals 1,2&3:*** Disconnection of all ROOFS adjacent to swales *(246 properties)*	*1.900 ha* *(0 ha)* **1.900 ha**	*5.469 ha* *(9.202 ha)* **14.671 ha**	*74.2 %* *(100 %)* **88.5 %**
Swales Option B: ***Offsite control proposals 1,2&3:*** Disconnection of all PAVED areas adjacent to swales	*0 ha* *(2.886 ha)* **2.886 ha**	*7.368 ha* *(6.316 ha)* **13.684 ha**	*100 %* *(68.6 %)* **82.6 %**
Swales Option C: ***Offsite control proposals 1,2&3:*** Disconnection of both ROOFED and PAVED areas adjacent to swales *(246 properties)*	1.900 ha *(2.886 ha)* **4.786 ha**	5.469 ha *(6.316 ha)* **11.785 ha**	74.2 % *(68.6 %)* **71.1 %**

Note:
Off-site control proposal 1, 2 and 3 relate to the use of infiltration trenches, porous pavements and infiltration basins respectively.

It is clear that neither of the two technology specific source control proposals achieve anywhere near the same level of disconnection of impervious area (from the Meanwood combined sewer system) as **Optimum proposal 1** (optimum source control proposal). This is illustrated by the fact that 61.1% of all impervious areas would remain connected to the Meanwood combined sewer under **Optimum proposal 1,** whilst it is considered that 81.8% and 97.2% of all impervious areas would remain connected under source control proposals 1 and 2 respectively. The shortfalls between **Optimum proposal 1** and the two technology specific proposals may largely be attributed to the fact that it was not considered to be practicable to retrofit source controls to any of the paved areas contained within Meanwood's sandstone region. The low disconnection rate attributed to source control proposal 2 relates to the very limited opportunities for retrofitting infiltration trenches to roofs within the sandstone region.

Similarly, none of the three technology specific offsite control proposals achieve anywhere near the same level of disconnection of impervious area (from the Meanwood combined sewer) as the **Optimum Proposal 2**. The main factor behind these shortfalls is the fact that not all roads within this region are considered appropriate for retrofitting SUDS conveyance systems (e.g. swales). Consequently, these proposals do not achieve the full coverage levels assumed within the optimum off-site infiltration option. It is possible that this problem could be addressed by the use of supplementary storage-based source-control technologies – i.e. to serve areas not covered by the off-site technologies.

The scenarios developed in this Chapter have highlighted the fact that single technology SUDS schemes are unlikely to be able to deliver the full potential disconnection that might initially appear to exist within a catchment. It has been suggested here that combinations of device types (including both infiltration-based and storage-based technologies) would probably enable better coverage to be achieved.

However, given that some areas might practically be served by more than one technology type, it is clear that the generation of multiple-technology SUDS schemes is not straightforward. Indeed, before an approach to this problem can be developed, it is necessary to incorporate information concerning the hydraulic performance and costs associated with each type of SUDS technology.

Chapter 5 outlines how urban drainage modelling techniques were used to simulate the hydraulic performance associated with each of these scenarios, and Chapter 6 describes how corresponding costs were calculated.

5. RETROFIT SUDS EVALUATION: MODELLING ISSUES

5.1. INTRODUCTION

This Chapter aims to investigate the hydraulic performance of retrofit SUDS through the use of urban drainage catchment modelling tools, such as HydroWorks (Wallingford Software, 1999). HydroWorks v.5.0 is a detailed deterministic model that utilises the Wallingford set of rainfall/runoff equations (National Water Council, 1981) and derivatives of the St Venant conservation equations for in-sewer flow routing. At the time these investigations were conducted, neither this model, nor any of its main competitors, contained direct procedures for modelling SUDS devices*. This Chapter reviews the HydroWorks model, and explores a number of different modelling options for representing retrofit SUDS. The best of these techniques were adopted for simulating the performance of the best-case retrofit SUDS proposals presented in Chapter 4, for the alleviation of flooding within the Meanwood catchment.

* It should be noted that MicroDrainage's new Source Control module is now a fully integrated part of the WinDes suite of urban drainage modelling software tools, and it is claimed that this can support the design and analysis of a number of source control devices, including: infiltration trenches, ponds, porous pavements, soakways and swales. However, this software was not available early enough to be utilised within this study.

5.2. BASIC PRINCIPLES OF HYDRAULIC MODELLING

5.2.1. Background

This Section introduces the HydroWorks v.5.0, the main urban drainage model used in conjunction with this research, and outlines the basic principles upon which it is founded.

The HydroWorks v.5.0 (Wallingford Software, 1999) urban drainage software package was adopted as the main modelling tool for this thesis. HydroWorks, and its sister package InfoWorks, are both well established within the UK water sector, and consequently have a large pool of experienced users and existing catchment data (i.e. from which case studies could be drawn). This was a key factor in the selection of HydroWorks as the main modelling package for this thesis. One limitation of the HydroWorks package is that most of its verified HydroWorks catchment models are pure hydraulic models. The lack of field-based water quality data has lead to a shortage of verified water quality models within the UK (Harremoes, 1997). However, this is a problem common to all urban drainage models, and not just HydroWorks. Section 5.2.2 outlines the basic principles of the HydroWorks model.

5.2.2. HydroWorks – Basic Hydraulic Principles

5.2.2.1. Introduction

HydroWorks is a deterministic model, which can simulate both hydraulic and water quality mechanisms within the urban water cycle. The hydraulic model comprises three interrelated

modules, which individually represent the 'Rainfall', 'Runoff' and 'Sewer System' processes inherent within the urban drainage catchment (Figure 5.1).

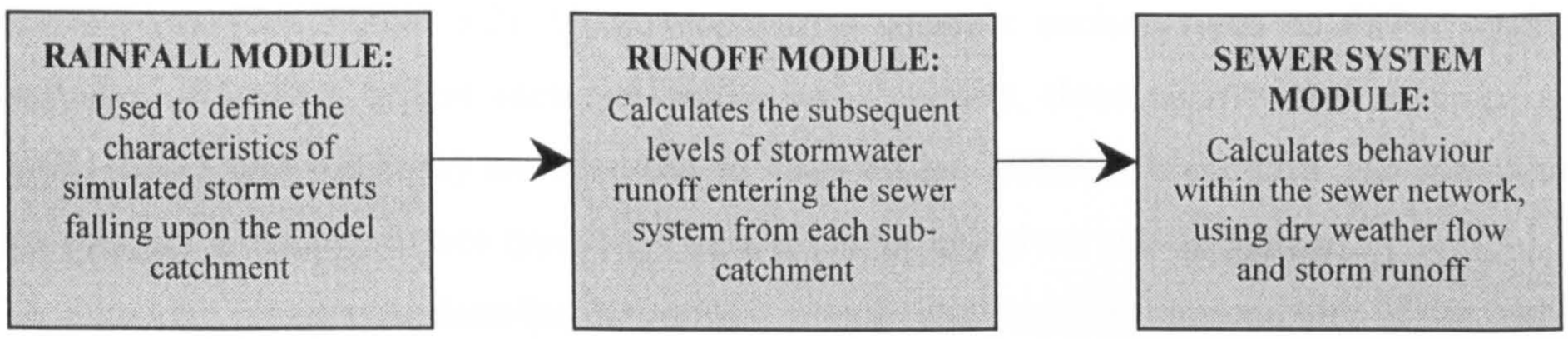


Figure 5.1 Simplistic flow-diagram of the HydroWorks process modules used to represent the Urban Water Cycle

5.2.2.2. Rainfall/Runoff Processes

The 'Rainfall' and 'Runoff' process modules are particularly relevant to the modelling of SUDS, since these determine how much of the rainfall falling on the catchment is considered to become runoff and how quickly this then enters the drainage system. The HydroWorks 'Runoff' process module comprises three distinct sub-modules: i.) Initial losses module, ii.) Runoff Volume (net rainfall) module and iii.) Runoff Routing module (See Figure 5.2).

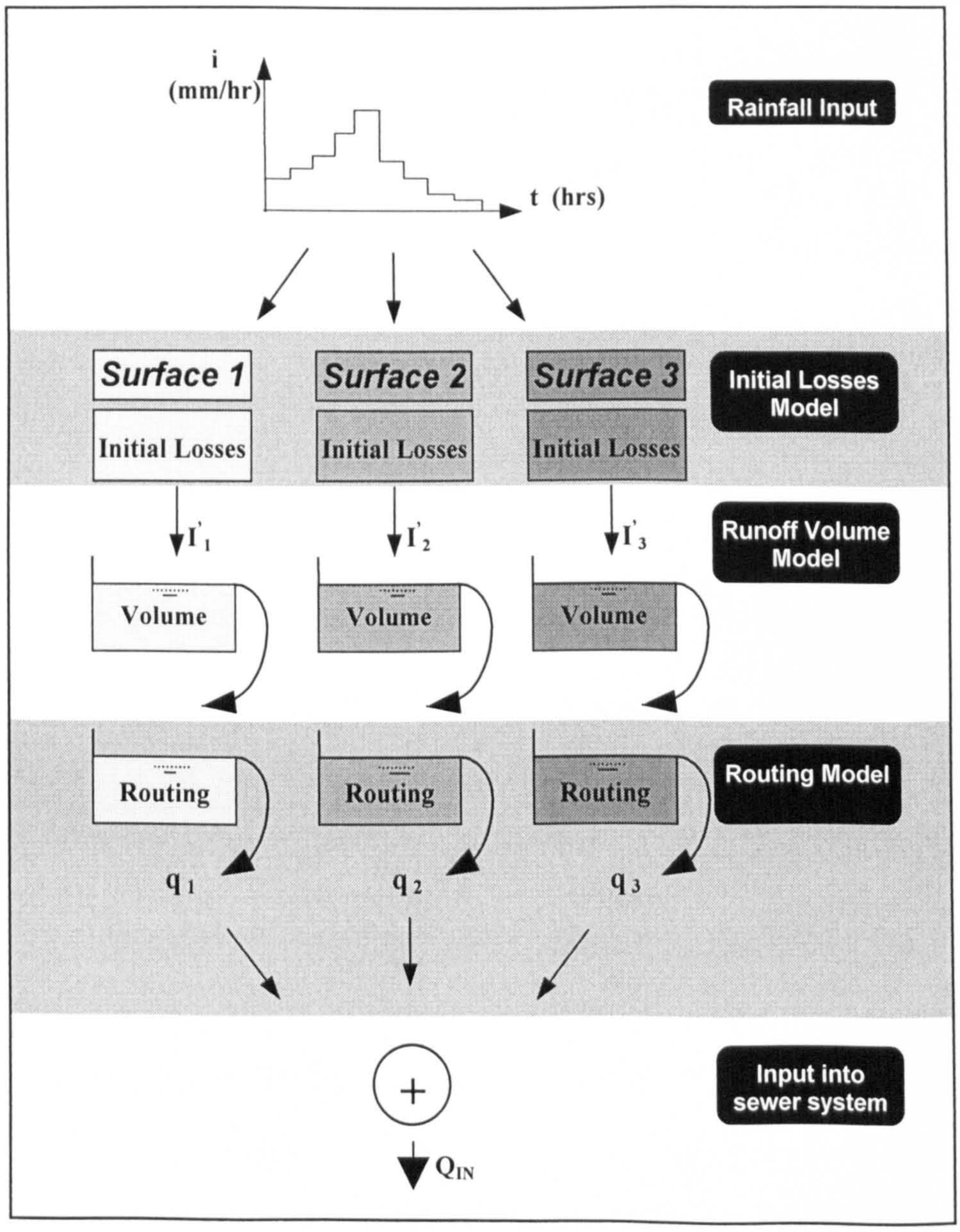
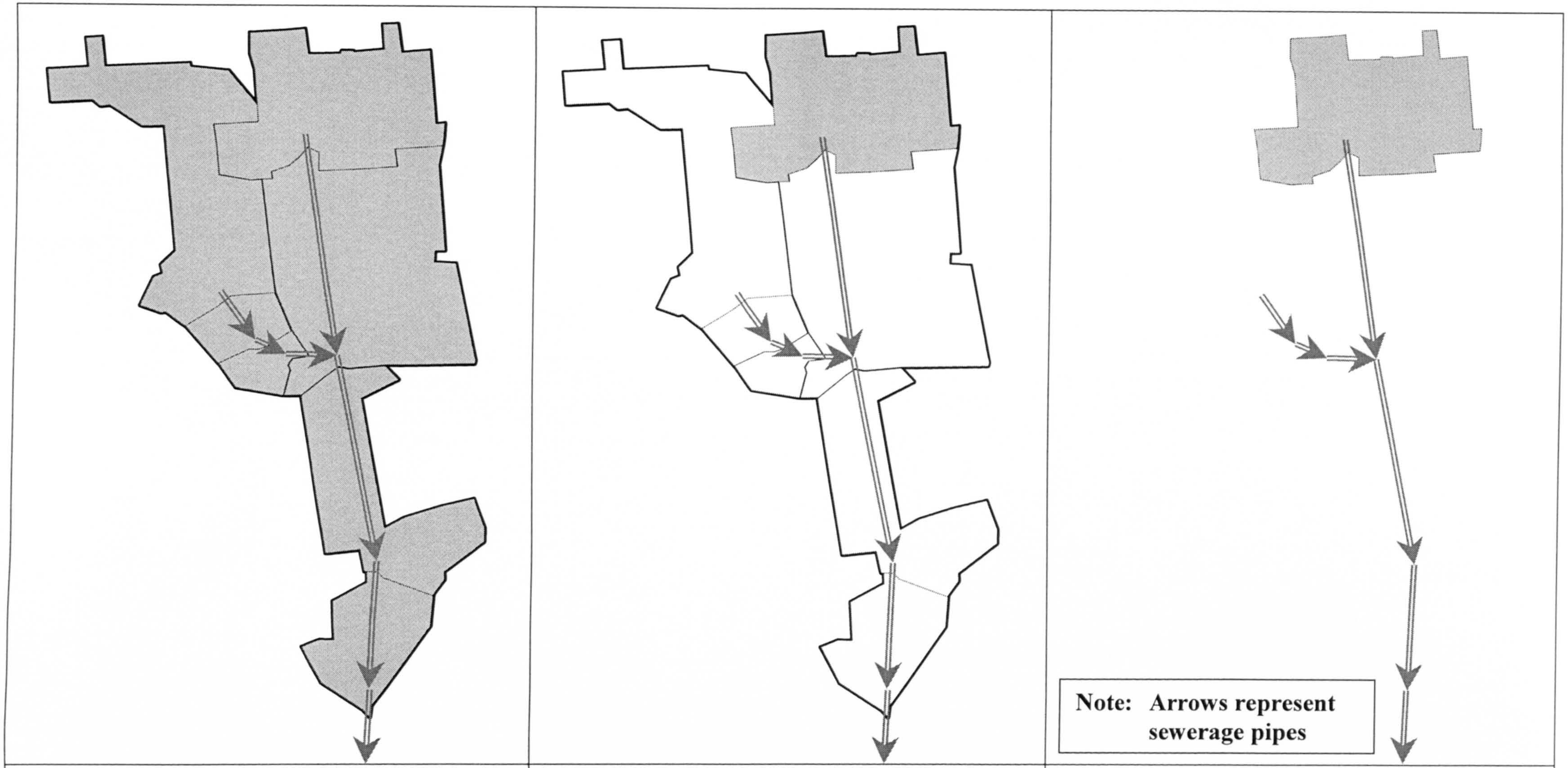


Figure 5.2 Simplistic Flow-diagram representing the 3 distinct sub-modules of HydroWorks' runoff module

HydroWorks assumes that a catchment is divided into a series of sub-catchments (Figure 5.3). The rainfall input falling upon one such sub-catchment is divided between 3 surface types (See Figure 5.2). HydroWorks uses separate surface types to define distinct categories of surface, within each sub-catchment. Typically, three default surface types (i.e. paved, roofed and pervious) are adequate to describe the different areas of a sub-catchment. However, up to twelve surface types may be defined for any given sub-catchment.

The following paragraphs describe the rainfall module and the three sub-modules of the runoff module.



1. URBAN DRAINAGE CATCHMENT SYSTEM: with constituent sub-catchments indicated by dashed boundary	2. URBAN DRAINAGE SUB-CATCHMENT SYSTEM: individual sub-catchment area indicated by shaded area	3. URBAN DRAINAGE SUB-CATCHMENT SYSTEM: individual sub-catchment isolated from rest of catchment

Figure 5.3 The concepts of catchment and sub-catchment

Rainfall input – There are three main rainfall input types that are used in conjunction with urban drainage modelling applications:

Synthetic Design Storms

Intensity-Duration-Frequency Curves

Time Series data (either historical, or stochastically generated, data)

Appendix 5A presents further information on each of these rainfall input types.

Initial losses model – The initial part of a storm event is generally assumed to cause no runoff because it is lost in wetting the ground surface and in depression storage (i.e. forming puddles). The quantity of rainfall required to just cause overland flow might be described as 'initial losses'. These losses are generally considered to depend upon surface type and slope.

HydroWorks (Ver.5.0) contains 3 initial losses models. The default 'initial losses' model is the 'slope model', which relates depression storage to ground slope(s) using the expression:

$$D = k / \sqrt{s}$$

Equation 5.1

Where:

D	-	*Average depth of initial losses*	*(m)*
S	-	*Slope*	*(m/m)*
k	-	*Coefficient*	*(m)*

The 'k' value is used to represent a number of factors, such as the surface micro-topography and layout. Typical 'k' values are: 7.1 x 10^{-5} m for paved and roof surfaces and 2.8 x 10^{-5} m for pervious surfaces (Wallingford Software Ltd, 1999). The HydroWorks model assigns the same 'k' coefficient to pitched roof surfaces as to road surfaces, but adopts a slope value (s_{roof}) of 0.05.

HydroWorks also contains the 'Absolute model', which allows an absolute initial loss value (D) to be assigned independently of surface slope.

It is worth noting that depression storage values generated by either of these initial losses models may be partly or wholly taken up by rainfall that is considered to occur immediately before a simulated storm event; within HydroWorks this is represented by the antecedent rainfall parameter.

Runoff Volume (net rainfall) models – Runoff volume models are used, after 'initial losses' have been accounted for, to determine how much of the rainfall runs off the sub-catchment into the drainage system. These models are generally used to account for continuing losses, such as those associated with infiltration or interception (Read and Vickridge, 1997). The default HydroWorks' runoff volume model is the Wallingford Procedure (Fixed) PR model, this calculates runoff for a given sub-catchment using Equation 5.2, and distribution between different surfaces types is achieved using weighting coefficients (See Equation 5.3).

$$PR = 0.829\,PIMP + 25.0\,SOIL + 0.078\,UCWI - 20.7$$

Equation 5.2

Where:

PR	-	*Percentage Runoff*
PIMP	-	*Percentage of catchment area that is Impermeable*
SOIL	-	*Soil Coefficient*
UCWI	-	*Urban Catchment Wetness Index*

The weighting procedure for different sub-catchment surfaces is defined by the following expression:

$$PR = \frac{f_i A_i}{\sum_{n=1,3} f_n A_n}.PR$$

Equation 5.3

Where:

PR_i	-	*Percentage runoff (surface)*
A	-	*Area of Surface*
f	-	*Weighting coefficient*

The default parameters, used by HydroWorks, for the weighting coefficients are shown in Table 5.1

Table 5.1 HydroWorks default weighting coefficients

Weighting coefficient	Surface	Value
f1	Paved	*1.0*
f2	Roofed	*1.0*
f3	Pervious	*0.1*

HydroWorks' alternative 'Runoff Volume (net rainfall)' models are outlined within Appendix 5B.

Runoff Routing module – HydroWorks' runoff routing module contains five alternative models that may be used to predict how quickly the surface runoff emanating from a given rainfall event enters the drainage system. The default model is the 'Double linear reservoir' (Wallingford) model. This model is based on the use of two conceptual linear storage reservoirs that are combined in series and applied to each surface type with an equivalent storage-output relationship for each reservoir. This relationship between storage volume (S) and flow (q) is described by the equation:

$$S = k \times q$$

Equation 5.4

where $k = Ci_x^{-0.39}$, in which $i_x = 0.5(1+i_{10})$, where i_{10} is the ten minute moving average of rainfall intensities and **C** is a constant coefficient. Combining the two storage relationships with the continuity equation leads to a second order ordinary differential equation in the form:

$$k\frac{d^2q}{dt^2} + 2k\frac{dq}{dt} + q = i_t$$

Equation 5.5

Where:

q	-	*Flow rate*	*(mm/hr)*
i_t	-	*Rainfall intensity at time t*	*(mm/hr)*
k	-	*Coefficient depending on surface type*	*(hr^{-1})*
t	-	*Time*	*(hr)*

This equation is used to model runoff attenuation caused by the combined effects of surface storage and storage in minor drains that is not explicitly modelled within the in-sewer model. The double linear reservoir methodology generates a time lag between the time of rainfall on the catchment surfaces and the resultant flow of storm runoff into the sewer system.

HydroWorks' four alternative runoff routing models are outlined in Table 5.2.

Table 5.2 Runoff Routing Models Available in Hydroworks Ver. 5.0

Model file	Comments
Large contributing area runoff model	A double linear reservoir model developed for UK sub-catchments of up to 100 ha.
SPRINT runoff model	A single linear reservoir model developed for the European SPRINT project.
Desbordes runoff model	The standard routing model used in France. It is a single linear reservoir model.
SWMM runoff model	A non-linear reservoir model developed in the USA.

5.2.2.3. Sewer system processes

HydroWorks represents the urban drainage system using a network of links and nodes. Nodes are used to represent manholes, and a range of other ancillary structures, such as attenuation tanks, sewer overflows and pumping stations. Conduit pipes are represented as links, which interconnect the network nodes.

HydroWorks generates dry weather flows, and combines these with the storm runoff component described above. The simulation of these in-sewer flows is based on the solution of the Saint-Venant equations, which enables the detailed analysis of sewer flow at any point of the drainage network. Further details of this derivation are presented within Appendix 5C, along with a simple validation of the default HydroWorks methodology.

5.3. MODELLING RETROFIT SUDS

This Section explores the modelling issues associated with representing the behaviour of retrofit SUDS. The modelling issues associated with the representation of infiltration-based SUDS are discussed within Section 5.3.1 and applied to the Meanwood catchment in Section 5.3.2, and the modelling issues associated with storage-based SUDS are discussed in Section 5.3.3 and applied to Meanwood in Section 5.3.4.

5.3.1. Modelling infiltration-based SUDS

5.3.1.1. Background

This Section explores the issues associated with using urban drainage models to simulate the behaviour of 'infiltration-based' SUDS. The installation of infiltration SUDS may significantly reduce the levels of runoff contributed to the sewer system. The effects of such measures are likely to be especially dramatic if applied within highly pervious soils, such as loams or sand.

Unlike most storage SUDS (Section 5.3), well designed infiltration devices can be assumed to completely remove the runoff component of design storm events from the local sewer. However, poorly designed infiltration devices will tend to pond during extreme rainfall events, and in some cases generate a delayed runoff component into the local sewer system. In such cases, the surface runoff component will start to appear in the sewer at some point after ponding starts to occur, and will gradually increase as less stormwater is infiltrated.

It is also worth noting that groundwater penetrates into many sewer systems via cracks/damaged pipes. HydroWorks can represent this phenomenon, using a constant infiltration flow parameter value, regardless of prevailing storm conditions. This approach is acceptable when the flows penetrating the sewer system are small. However, the widespread use of infiltration SUDS within a catchment may significantly increase the levels of flow penetrating the local sewer system, and make such events more closely connected to prevailing rainfall conditions. It is not possible to represent these factors using HydroWorks v. 5. The latest version of InfoWorks has the capacity to represent such varying groundwater flows into the sewer (Swan *et al.*, 1999). However, due to financial constraints, it was not possible to use InfoWorks in conjunction with this research project – HydroWorks modelling options are presented within the next Section.

5.3.1.2. HydroWorks modelling options

Careful assessment of the modelling options available in HydroWorks suggested 3 alternative mechanisms that may be used to represent infiltration process:

1. The Horton infiltration runoff volume model
2. The Green-Ampt infiltration volume model
3. The disconnection of all areas that are considered appropriate for infiltration (this may be achieved using the Wallingford (Fixed) PR model).

Horton Infiltration model – The Horton infiltration model may be applied to HydroWorks surfaces to simulate the effects of infiltration on the rainfall-runoff process. The Horton model (1940) was derived from studies of rainfall-runoff responses in small catchments. This model uses an empirical expression (Equation 5.6) that only simulates runoff when rainfall intensity exceeds the capacity of the soil to infiltrate it. However, in practice, runoff can occur following rainfall events in which the rainfall intensities are less than the infiltration capacity of the soil. Consequently, the Horton infiltration model is generally only used in catchments where short intense rainfall events produce an almost instantaneous overland flow (Wallingford Software,

1999). The Horton model is considered appropriate for application to urban catchments because their surfaces generally have low infiltration capacities.

The Horton equation expresses infiltration rate as a function of time:

$$f = f_c + (f_o - f_c)e^{-kt}$$

Equation 5.6

Where :

f	=	infiltration rate at time t (mm/hr)
f_o	=	initial infiltration rate (mm/hr)
f_c	=	final (limiting) infiltration rate (mm/hr)
k	=	coefficient of exponential term (1/hr)

The initial infiltration rate (f_o) is subject to an exponential decrease until it reaches a constant limiting rate (f_c) when the soil becomes saturated. The (k) constant expresses the non-linear rate of decay of infiltration after the beginning of a rainfall event. It should be noted, that as the equation is expressed as a function of time, it is not generally considered suitable for application to continuous TSR simulations. Within HydroWorks the Horton model cannot be used in conjunction with the default (Wallingford Procedure) fixed PR runoff model. This factor limits the general applicability of approach as most of the UK's HydroWorks models are typically generated using HydroWorks default settings.

The Green-Ampt infiltration model – HydroWorks adopts the Green-Ampt infiltration equation (Mein & Larson, 1973) for use in conjunction with the SWMM runoff model. The Mein & Larson methodology is a two-stage model. The first stage estimates the volume of water that is infiltrated prior to saturation of the surface. The second stage uses the Green-Ampt equation to estimate the infiltration capacity when the soil is saturated.

The model is represented by the following expressions:

If $F < F_s$

If $i > K_s$: $$F_s = \frac{S.IMD}{\frac{i}{K_s} - 1}$$

: $f = i$

If $i =< K_s$ No calculation of F_s is made

If $F >= F_s$

: $$f_p = f = K_s\left(1 + \frac{S.IMD}{F}\right)$$

Where:

f	=	infiltration rate	(mm/hr)
f_p	=	infiltration capacity	(mm/hr)
i	=	rainfall intensity	(mm/hr)
F	=	cumulative infiltration	(mm)
F_s	=	cumulative infiltration required for saturation	(mm)
S	=	average capillary suction	(mm)
IMD	=	initial moisture deficit	(dimensionless)
K_s	=	saturated hydraulic conductivity	(mm/hr)

The HydroWorks package contains an integrated form of the Green-Ampt equation, which is solved iteratively using a Newton-Raphson routine. The excess rainfall is routed into the drainage network. However, the Green-Ampt approach, like the Horton model, cannot be used in conjunction with HydroWorks default models.

Disconnection option – An alternative modelling approach for representing the behaviour of infiltration SUDS, is to perform preliminary design equations, such as those outlined within BRE 365 (1991) and CIRIA 156 (1996) to establish how much impervious area may be successfully drained using the proposed infiltration device, given prevailing catchment conditions and critical design equations. These devices may then be modelled by simply removing this amount of impermeable area from the HydroWorks catchment model, to represent its physical disconnection from the local sewer system. This approach is a relatively simple/transparent modelling methodology and incorporates the use of established infiltration-SUDS design methodologies (BRE 365,1991; CIRIA 156, 1996).

Overview – The 'disconnection option' was considered to be the most appropriate of the three techniques highlighted above. This relates to the fact that it incorporates the use of existing design guidelines for infiltration devices (see Chapter 2), which have been widely used and verified within the UK – as opposed to the two other techniques, which are both novel, and therefore unverified, modelling approaches for representing the behaviour of infiltration devices. Furthermore, the disconnection option is a transparent approach. This transparency means that results may be easily checked, and therefore treated with a higher degree of confidence than results obtained from the other approaches. The 'disconnection option' may also be used in conjunction with a number of other urban drainage modelling tools, such as the SIMPOL or Win-Dap packages.

5.3.2. Modelling infiltration-based SUDS: Application to Meanwood

5.3.2.1. Introduction

The performance of a range of retrofit infiltration SUDS proposals was investigated using HydroWorks analysis of the Meanwood catchment in conjunction with the 10 year design storm.

This catchment model was compiled, and verified against monitored flow data, by Leeds City Council, as part of a drainage area survey that was conducted in 1994. An independent evaluation of this catchment model was conducted as part of this thesis (See Appendix 5D).

5.3.2.2. Use of HydroWorks to model a range of infiltration scenarios for Meanwood

HydroWorks simulations were undertaken to establish the critical duration 10 year design storm (see Appendix 5E) with respect to sewer flooding within the Meanwood catchment. These investigations established that the critical storm was the M10-60S.

An additional fifteen simulations were conducted to assess the impact of a range of disconnection scenarios upon Meanwood's flooding problems under the critical M10-60S design storm. These scenarios investigated the 0, 25, 50, 75 and 100% disconnection of all roofed areas, in conjunction with the 0, 50 and 100% disconnection of all paved areas. These areas were disconnected uniformly across every sub-catchment of the Meanwood system, and were used to crudely represent the disconnection of contributing surfaces associated with well-designed infiltration devices. The results of this analysis are presented within Table 5.3. This data was also used to generate the 3D plot presented within Figure 5.4.

Table 5.3 Meanwood flood volumes (m^3) from a M10-60S design storm – Range of disconnection scenarios for paved and roofed areas

%age of Roads Connected	%age of Roofs connected				
	100%	**75%**	**50%**	**25%**	**0%**
100%	1304 m^3	1022 m^3	723 m^3	476 m^3	248 m^3
50%	618 m^3	388 m^3	159 m^3	51 m^3	0 m^3
0%	87 m^3	5 m^3	0 m^3	0 m^3	0 m^3

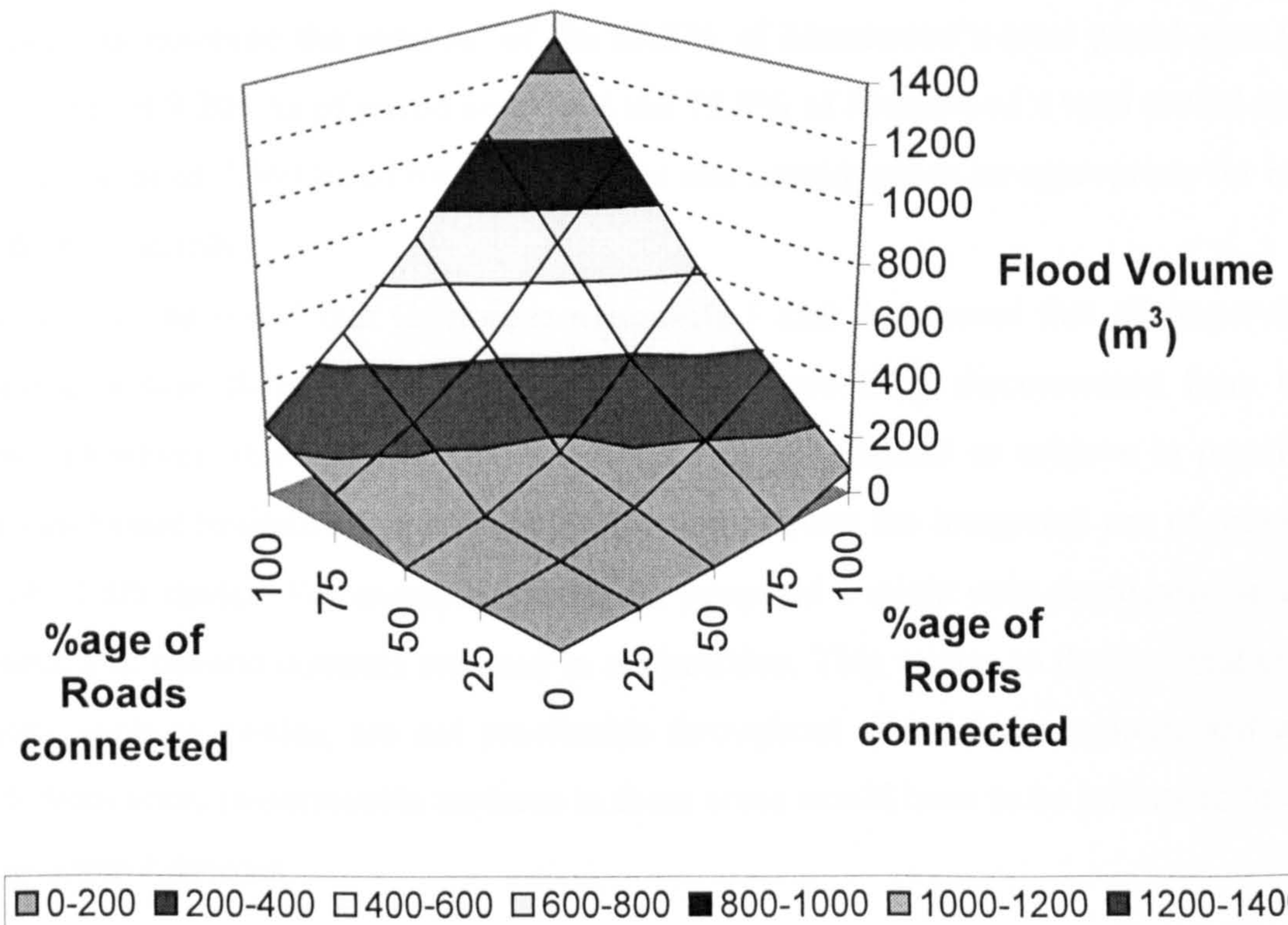


Figure 5.4 3D plot of Meanwood flood volumes (m^3) associated with the critical M10-60S design storm and a range of disconnection scenarios for paved and roofed areas

Note: Figure 5.6 suggests that the complete removal of flooding problems is feasible through the use of retrofit infiltration-based SUDS. However, this would require high levels of disconnection. The practical feasibility of achieving such high levels of disconnection is explored within the following Section.

Appendix 5F illustrates that these results are consistent with the results of a much smaller set of simulations that were conducted for the Meanwood catchment by Leeds City Council (Walker, 2000:b).

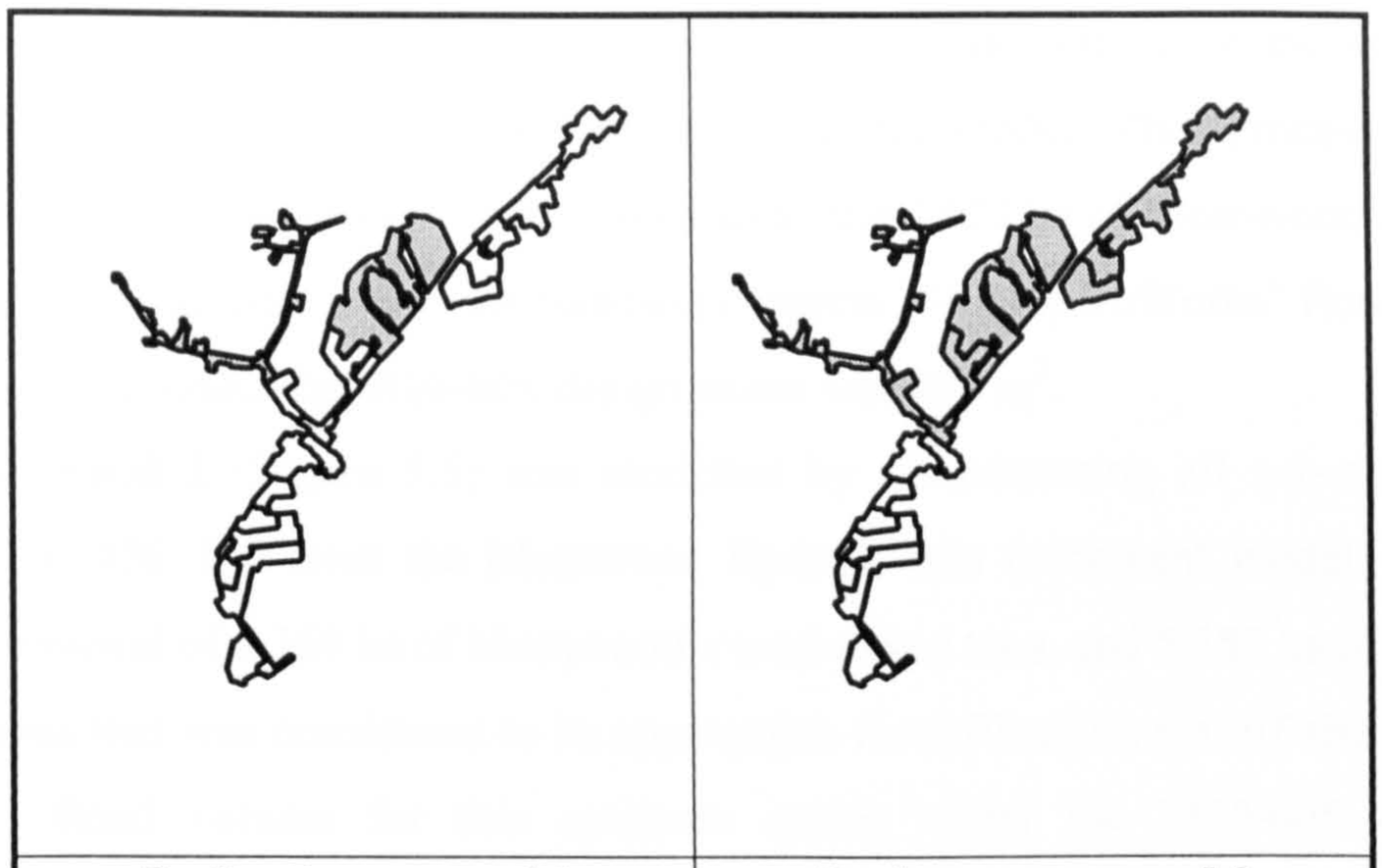
5.3.2.3. Extrapolated flood volumes for Optimum infiltration proposals

Flood volumes associated with **Optimum proposal 1** (infiltration-based source-controls) and **Optimum proposal 2** (infiltration-based source and/or off-site controls) proposals (Chapter 4) for the application of infiltration devices to the Meanwood catchment were obtained by extrapolating values from Table 5.3 (i.e. for percentage roofed and paved areas assumed to be connected to the system after each proposal had been implemented).

Optimum proposal 1 (infiltration-based source-controls) (Figure 5.5) entailed the removal of **37.20%** of Meanwood's total paved area (3.423 ha from a total of 9.202 ha of paved area), and **41.01%** of Meanwood's total roofed area (3.022 ha from a total of 7.369 ha of roofed area), that were contained within the Sandstone region.

Optimum proposal 2 (Figure 5.5) involved the disconnection of all 'infiltratable' impervious areas that were upstream of what was considered to be the last (i.e. in terms of being the most down-stream) viable location for an off-site control facility within the Meanwood catchment. This process involved the removal of the **69.2%** of Meanwood's total paved area (6.369 ha from a total of 9.202 ha of paved area), and the **75.8%** of Meanwood's total roofed area (5.583 ha from a total of 7.369 ha of roofed area) that was considered to be appropriate for infiltration via off-site controls.

It should also be noted that **Optimum proposals 1 and 2** assumed that all impervious areas contained within these 'disconnectionable' regions are fully disconnected from the sewer system. However, this complete disconnection may be difficult to achieve in practice due to other catchment limitations, and if achievable may require the integrated use of more than one type of SUDS device. For example, **Optimum proposal 2** might only practically be achievable if source and off-site controls are used in conjunction. This relates to the fact that conveyance systems, such as swales, are not practicable throughout all of these regions, and as a result runoff from some impermeable surfaces in these areas would have to be infiltrated locally using source control devices.



Optimum proposal 1 (source control): Disconnection of all impervious surfaces contained within Meanwood's sandstone region	**Optimum proposal 2 (off-site control): Disconnection of all Meanwood's 'infiltratable' impervious surfaces**

Figure 5.5 Optimum proposals 1 and 2 using infiltration SUDS for the Meanwood catchment (reproduced from Figure 4.6)

The extrapolated values for these scenarios and the critical M10-60S storm (from Table 5.3) indicated that **optimum proposal 1** would reduce flood volume from **1304 m^3** to **383 m^3**, and **optimum proposal 2** would reduce flood volume from **1304 m^3** to **37 m^3**.

It should be noted that these results represent a crude approximation of catchment flooding. This relates to the fact that Table 5.3 represents the uniform disconnection of roof and paved areas across every sub-catchment of the Meanwood system, whereas these optimum scenarios represent the concentrated removal of roof and paved areas in specific parts of the catchment. In other words, this 'extrapolation' approach accurately represents the quantity of roof and paved areas that would be disconnected in conjunction with the optimum scenarios, but fails to represent this surface disconnection in the specific parts of the catchment in which it should occur. This approach was adopted due to its simplicity and the speed of its simulation times. These factors meant that rapid comparisons of alternative proposals could be performed. The next Section presents a more detailed/accurate modelling analysis that was applied to the **optimum proposals 1 and 2**.

Section 5.3.2.5 applies these 'extrapolation' techniques to the SUDS technology specific options that were highlighted within Chapter 4.

5.3.2.4. HydroWorks flood volumes for Optimum proposals 1 and 2

Detailed modelling exercises were undertaken for both the **optimum proposal 1** (source controls) and **optimum proposal 2** (offsite controls). This analysis was undertaken using HydroWorks, and sought to establish the accuracy of the crude procedures outlined in the previous Section.

Optimum proposal 1 (Figure 5.5) was modelled by disconnecting all of the sandstone sub-catchments from the Meanwood HydroWorks catchment model. This process entailed the removal of 3.423 ha of Meanwood's total paved area, and 3.022 ha of Meanwood's total roofed area, which were contained within the Sandstone region. The HydroWorks' flood volume for this optimum option under the M10-60S design storm was **480 m^3**.

Optimum proposal 2 (Figure 5.5) was modelled by disconnecting all sub-catchments up-stream of Node 450_150 from the Meanwood HydroWorks catchment model. This process involved the removal of 6.369 ha of Meanwood's total paved area, and 5.583 ha of Meanwood's total roofed area that was considered to be appropriate for infiltration via off-site controls. The HydroWorks' flood volume for this optimum option under the M10-60S design storm was **108 m^3**.

Table 5.4 compares the results of this analysis with corresponding results that were attained by extrapolation (see previous Section).

Table 5.4 Comparison of extrapolated Meanwood flood volumes (m^3) for Optimum Proposals 1 and 2 with corresponding events simulated using HydroWorks and a M10-60S design storm

Proposal (Infiltration)	Extrapolated flood volume (m^3)	HydroWorks flood volume (m^3)
Optimum source control	383 m^3	480 m^3
Optimum off-site control	37 m^3	108 m^3

The results presented in Table 5.4 confirm the crudeness of the 'extrapolation approach'. It is likely that the discrepancies between these two sets are the result of the simplistic assumptions made in relation to the 'extrapolation' approach. These relate to the fact that 'extrapolation' approach accurately represents the quantity of roof and paved areas disconnected in conjunction with the optimum scenarios, but fails to represent this surface disconnection in the specific parts of the catchment in which it should occur.

However, it is felt that despite these significant shortcomings the 'extrapolation approach' has some value for the initial comparison of alternative proposals, to highlight those options worth further/more detailed investigation. This relates to the speed of its simulation times, and the fact that its provides some indication as to the comparative performance of alternative proposals. Detailed SUDS design proposals would ultimately be modelled using the more sophisticated HydroWorks techniques to assess compliance with stipulated performance criteria (see Chapter 2).

5.3.2.5. Extrapolated flood volumes for technology-specific SUDS proposals (Chapter 4)

This Section presents extrapolated flood volumes for each of the 'best case' disconnection scenarios highlighted within Chapter 4. Unlike the generic investigations presented within the previous Section, these simulations relate to the application of specific infiltration SUDS technologies to the Meanwood catchment. The results of this analysis are presented in Table 5.5.

These technology specific infiltration SUDS proposals were modelled using the crude extrapolation techniques, and not detailed HydroWorks-based analysis. This approach was adopted to in order to reduce simulation times, and because this was a comparative study that only required a crude approximation of a proposal's hydraulic performance.

Table 5.5 Extrapolated Flood volumes for technology specific SUDS proposals for Meanwood catchment (See Chapter 4)

Columns from Table 4.24				*New Column*
Proposal	*Roofed,* *(Paved)* or **Total Imp.** area served by proposal (ha)	*Roofed,* *(Paved)* or **Total Imp.** area connected to combined sewer system (ha)	*Roofed,* *(Paved)* or **Total Imp.** area connected to combined sewer system (%)	*Extrapolated Flood volume (m^3)*
Optimum Proposal 1 Disconnection of all impervious areas in sandstone sub-catchments of Meanwood catchment	*3.022 ha* *(3.423 ha)* **6.445 ha**	*4.346 ha* *(5.779 ha)* **10.125 ha**	*59.0 %* *(62.8 %)* **61.1 %**	*383*
Source control proposal 1: Soakaways to every roof *(426 properties)* in **sandstone** region	*3.022 ha* *(0 ha)* **3.022 ha**	*4.346 ha* *(9.202 ha)* **13.548 ha**	*59.0 %* *(100 %)* **81.8 %**	*831*
Source control proposal 2: Construction of 1065m of infiltration trenches to serve *86 properties* in **sandstone** region	*0.473 ha* *(0 ha)* **0.473 ha**	*6.896 ha* *(9.202 ha)* **16.098 ha**	*93.6 %* *(100 %)* **97.2%**	*1236*
Optimum Proposal 2 Disconnection of all impervious areas in Meanwood subcatchments u/s of Node 450_150 (i.e. the most d/s location that is considered appropriate for an off-site control facility within the Meanwood catchment)	*5.583 ha* *(6.369 ha)* **11.952 ha**	*1.786 ha* *(2.833 ha)* **4.619 ha**	*24.2 %* *(30.8 %)* **27.9 %**	*37*
Swales Option A: *Offsite control proposals 1,2&3:* Disconnection of all ROOFS adjacent to swales *(246 properties)*	*1.900 ha* *(0 ha)* **1.900 ha**	*5.469 ha* *(9.202 ha)* **14.671 ha**	*74.2 %* *(100 %)* **88.5 %**	*1010*
Swales Option B: *Offsite control proposals 1,2&3:* Disconnection of all PAVED areas adjacent to swales	*0 ha* *(2.886 ha)* **2.886 ha**	*7.368 ha* *(6.316 ha)* **13.684 ha**	*100 %* *(68.6 %)* **82.6 %**	*879*
Swales Option C: *Offsite control proposals 1,2&3:* Disconnection of both ROOFED and PAVED areas adjacent to swales *(246 properties)*	1.900 ha *(2.886 ha)* **4.786 ha**	5.469 ha *(6.316 ha)* **11.785 ha**	74.2 % *(68.6 %)* **71.1 %**	*619*

Note:
Off-site control proposals 1, 2 and 3 relate to the use of infiltration trenches, porous pavements and infiltration basins respectively.
Existing-case flood volume is 1304 m^3.

It is worth nothing that these results should be treated with extreme caution because they were generated using the crude 'extrapolation approach' (see Section 5.3.2.3). However, it is clear that the performances of the technology specific proposals are significantly worse than those of the corresponding optimum proposals. The reasons for these discrepancies are outlined below:

Optimum Proposal 1 – The optimum infiltration source control scenario involved the disconnection of all impervious (paved and roofed) areas contained within the sandstone region, whereas source control proposal 1 (Soakaways) only disconnected roofed areas. Source control proposal 2 only served 86 of the 426 roofs contained within this sandstone region. Therefore these proposals do not achieve the full coverage levels assumed within the optimum infiltration source control proposal.

Optimum Proposal 2 – Not all roads within this region are considered to be appropriate for retrofitting SUDS conveyance systems (e.g. swales) (See Chapter 4). Subsequently, these proposals do not achieve the full coverage levels assumed within the optimum off-site infiltration option.

5.3.3. Modelling storage-based SUDS

5.3.3.1. Introduction

There are a wide variety of 'storage-based' SUDS, ranging from simple garden water butts or tanks through to large off-site detention ponds. However, most storage devices may be crudely considered to behave in a similar manner – i.e. retaining a given storage volume of rainfall before contributing overflow into the sewer system. This overflow contribution may either be directly or indirectly connected into the sewer system. These similarities mean that comparable modelling techniques may be applied to a whole range of different storage SUDS devices.

Section 5.3.3.2 explores the generic issues associated with modelling the behaviour of storage devices at the urban catchment level. Section 5.3.3.3 explores the more specific modelling options for representing storage SUDS using HydroWorks.

5.3.3.2. Modelling Background

Example 1: Single tank – The introduction of 'storage-based' SUDS to a catchment may significantly reduce the levels of surface runoff that are contributed to the local sewer system. The effects of such measures may be especially dramatic if applied to a catchment's impervious surfaces, such as roofs or paved areas. This point is illustrated by the example shown in Figure 5.6, which demonstrates the potential benefits of applying stormwater storage facilities to a typical domestic roof (0.3 m^3). Figure 5.6 was generated using a simplistic Excel model, which simulates the rainfall, runoff, storage and overflow mechanisms associated with a simple roof and collection tank system. This model was developed from hydraulic first principles (i.e. initial losses, fixed percentage runoff and mass balance models) (Swan *et al.*, 1999).

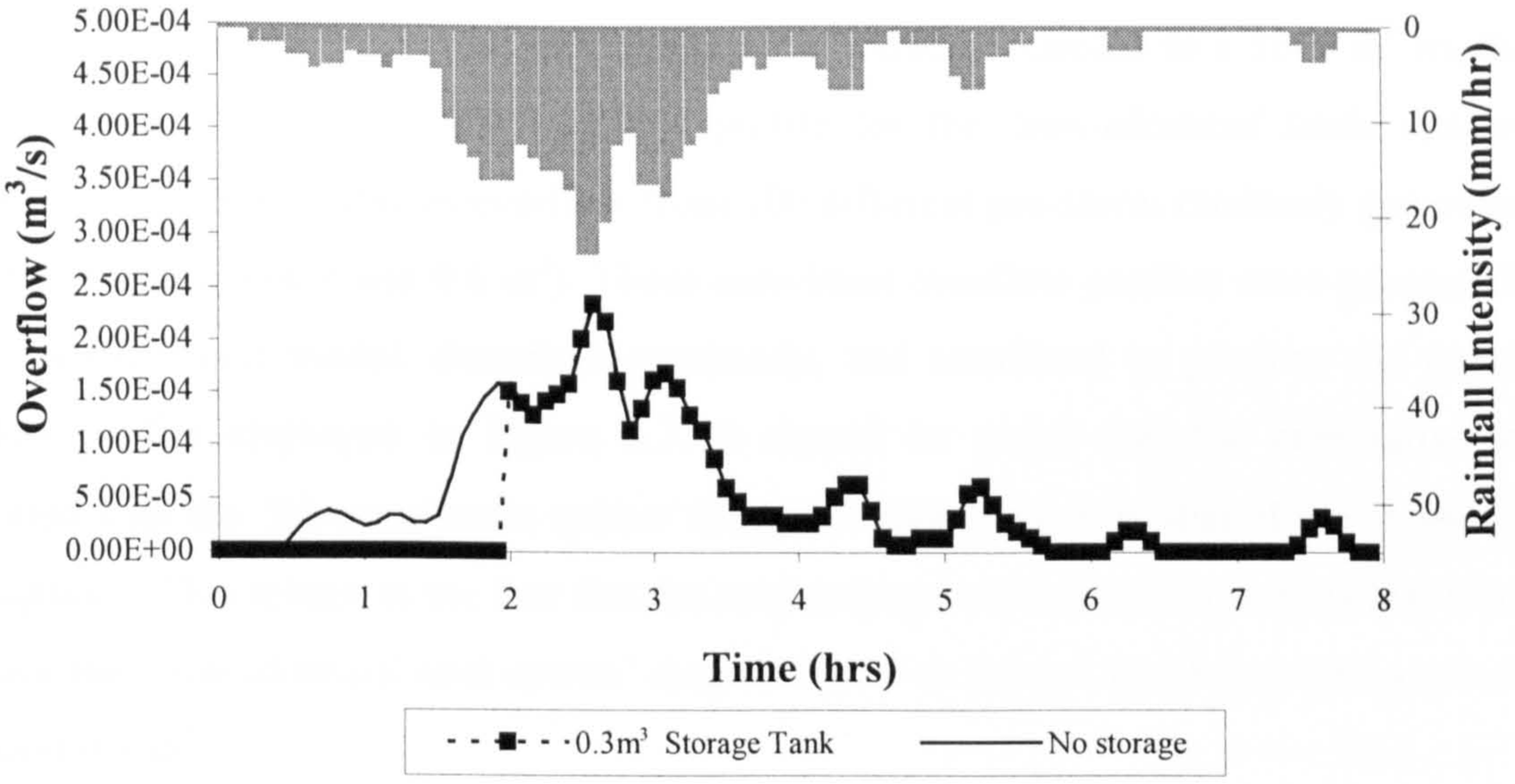


Figure 5.6 Comparison of runoff emanating from a single 50m² roof with: i.) 0.3m³ of available storage ii.) no storage

These results were generated with respect to a roofed area of 50 m^2 connected to a storage facility with 0.3 m^3 available storage prior to the start of a sample TSR storm event. In practice it is unlikely that such a device would be empty prior to a storm event, due to water retained from previous rainfall. This example therefore represents an empty 0.3 m^3 storage device (e.g. water butt or tank) prior to the start of a storm event; or a more realistic representation of a 0.6 m^3 tank that is half full due to a previous rainfall event.

It may be observed in this example that the impact of roof-water storage is to retain roof runoff during the first 2 hours of the storm. Therefore widespread introduction of a number of such facilities might be expected to produce attenuation and volumetric reduction of runoff flows emanating from a sub-catchment's roofed surfaces. The magnitude of these impacts would obviously depend upon the number of roof-water storage tanks introduced, and their individual properties (capacities, feeder and overflow mechanisms).

Example 2: 100 tanks – Simulating the more widespread effects of such storage facilities is a more complex task. From a modelling perspective, there are two approaches to representing the combined overflow of a number of stormwater storage devices. The first approach assumes that all storage facilities within a given sub-catchment are identical (i.e. in terms of capacity, volume of contents and connected roof area), subject to uniform prevailing conditions and hence overflow simultaneously into the local sewer system; this may be described as the *'identical tanks option'*. The second approach assumes that each storage device within a sub-catchment is unique (i.e. in terms of capacity, volume of contents and connected roof area) and hence likely to spill at different times during the storm event; this may be described as the *'non-identical tanks option'*.

Both of these approaches are illustrated by an example, portrayed in Figure 5.7, which considers the combined overflow into the local sewer from 100 storage facilities. In this example, the overflow profile for the '*Identical tanks option*' was generated by directly scaling up the

overflow profile for the single 0.3 m^3 tank, from Figure 5.6, by a factor of 100. In essence, this simulates the hydraulic behaviour of a single 30 m^3 tank, connected to a 5000 m^2 roofed area (50 m^2 x 100 = 5000 m^2). The overflow profile for the *'non-identical tanks option'* was generated using the cumulative overflow from 100 different pre-storm randomly generated tank capacities (of between 0 and 0.6 m^3). These individual overflow profiles were generated using the simplistic Excel model, described previously, and combined to produce the cumulative overflow profile displayed in Figure 5.7. It should be noted that the cumulative storage associated with the *'Identical tanks option'* is approximately equal to that of the *'Non-identical tanks option'*. This relates to the fact that the randomly generated tank capacities that were used to derive the '*Non-identical tank option'* ranged from 0 to 0.6 m^3, and hence had a mean value of around 0.3 m^3.

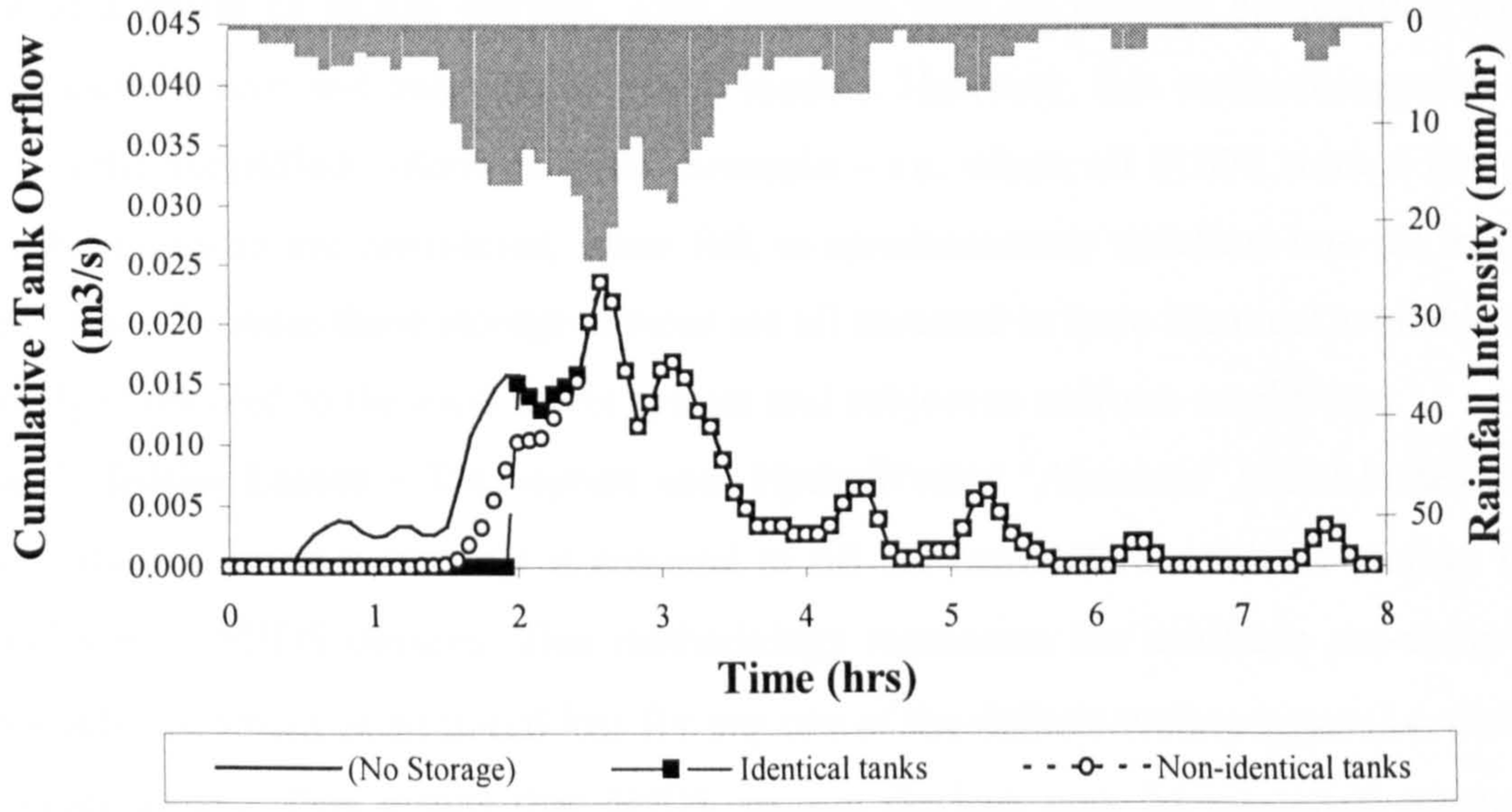


Figure 5.7 Comparison of runoff emanating from 100x 50 m^2 roofs: i.) with No Storage; ii.) Identical Tanks (0.3 m^3) and iii.) Non-identical Tanks (randomly generated capacities between 0 and 0.6 m^3)

Non-identical tanks produce a gradual transition from full retention of storm-water to full surface runoff contribution, in contrast to the very sudden transition that characterises the '*identical tanks*' scenario. It may be argued that the '*non-identical tanks*' scenario represents real catchment processes more closely than the 'identical tanks' assumption. However, given that the *'non-identical tanks option'* requires more analysis to establish appropriate pre-storm tank capacities, a pragmatic approach might be to use the *'identical tanks option'* to explore the best, worst and average pre-storm available tank storage scenarios – as this may be applied to both: 1.) a sub-catchment that contains a number of identically sized storage facilities subjected to non uniform conditions; and 2.) a sub-catchment that contains un-identically sized storage facilities.

Although this modelling example specifically relates to roof-water storage facilities, the same issues equally apply to the modelling of stormwater storage facilities for other surface types, such as roads or paved areas.

5.3.3.3. HydroWorks modelling options for Storage SUDS

This Section presents and explores the merits of two alternative HydroWorks modelling options for representing storage-based SUDS. It should be noted that both options seek to represent the *'identical tanks'* scenario described previously, as it was considered impracticable to accurately represent a *'non-identical tanks'* scenario using the HydroWorks modelling tools (Swan *et al.*, 1999). Descriptions of these options are presented below:

Option 1: Dummy storage – This option uses a single dummy storage tank, for each sub-catchment of the HydroWorks model, to represent the hydraulic behaviour associated with all of the SUDS storage devices within that sub-catchment (i.e. regardless of the size, type and the surface they serve). This dummy storage is inserted in the HydroWorks sewer system (i.e. entered within the *.dsd* file of the sewer module) and is used to represent the cumulative storage of a group of SUDS devices. This approach may be used in conjunction with both HydroWorks' default and non-default runoff models. However, this methodology can only be applied to the simplified *'identical tanks'* scenario – i.e. where all SUDS storage devices in a given sub-catchment are considered, when full, to simultaneously overflow into the local sewer system. This is because these storage devices are all assumed to have identical available storage, be directly connected to the local sewer system and subject to uniform conditions.

Option 2: Initial Losses – This option uses HydroWorks' 'Absolute' initial losses model to represent the net storm-water that is required to fill the cumulative available storage within a sub-catchment's SUDS devices. This methodology represents the available pre-storm storage within a sub-catchment as an initial loss for any one of the default surface types (i.e. paved, roof or pervious areas). This means that SUDS storage devices may be modelled separately for paved, roofed and impervious surfaces (i.e. by amending the *.rpf* file of the runoff module). This approach may also be used in conjunction with HydroWorks' default and non-default runoff/routing volume models. It should be noted that this option should only be used to represent the simplified *'identical tanks'* scenario.

5.3.3.4. One-node case study modelling exercise: Methodology

A simple one-node case study sub-catchment was used to investigate the performance of these modelling options for representing SUDS storage. This sub-catchment was assumed to consist of 5000 m^2 of roofed area, directly connected to stormwater collection tanks (with a cumulative volume of 30 m^3). These tanks were assumed to overflow directly into the local sewer network. The catchment configuration is illustrated within Figure 5.8. This scenario was intended to represent the roofed area in a sub-catchment containing 100 x 50 m^2 roofs, each connected to an individual 0.3 m^3 collection tank.

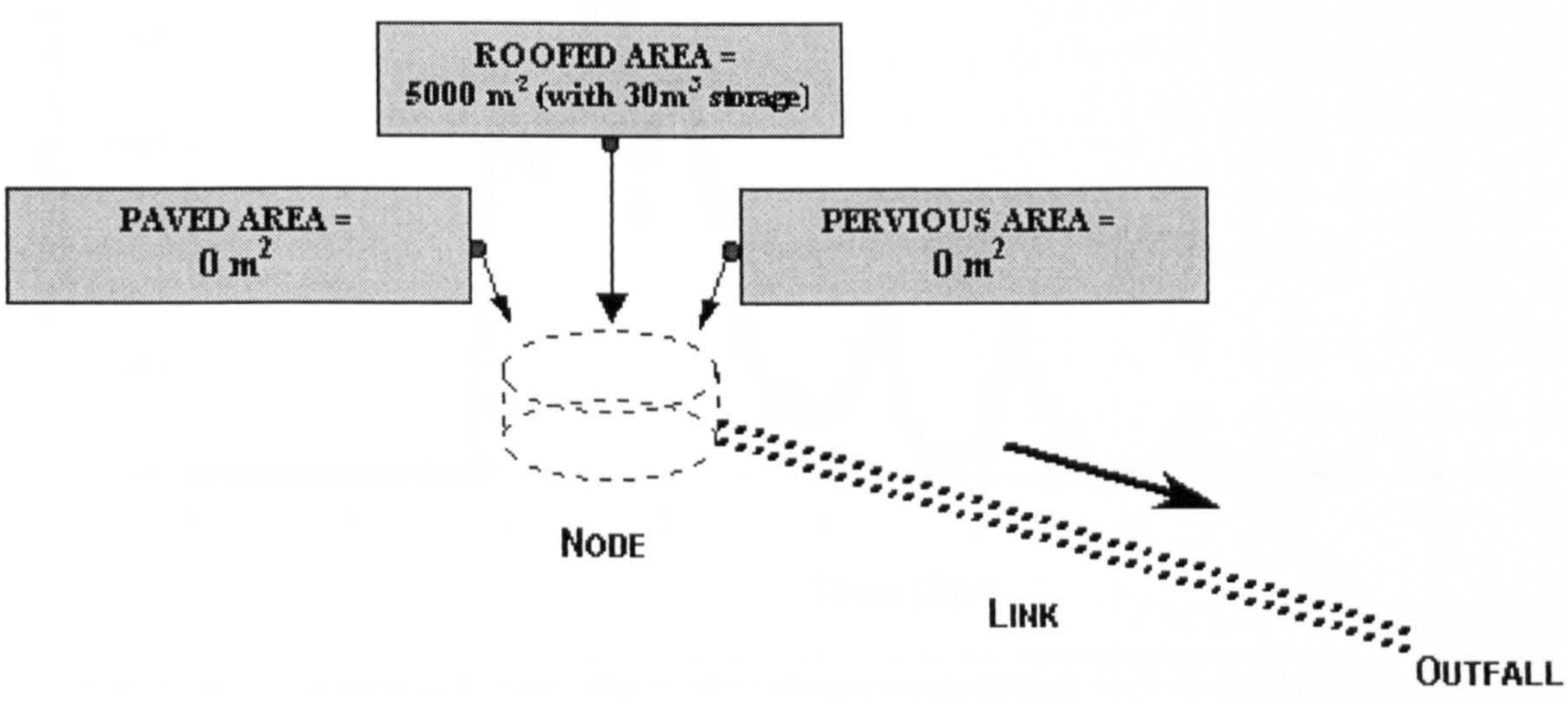


Figure 5.8: One-node case study sub-catchment

The two modelling options presented in Section 5.3.3.3 were used to simulate the outflow hydrograph corresponding to ten separate input rainfall events. These scenarios were also simulated using the simplistic Excel model described in 5.3.3.2.

The two main aims of this comparative modelling exercise were: firstly, to provide a quantitative comparison between the results obtained from each of these proposed modelling techniques; and secondly, to allow an assessment to be made relating to the logistical implications associated with each option.

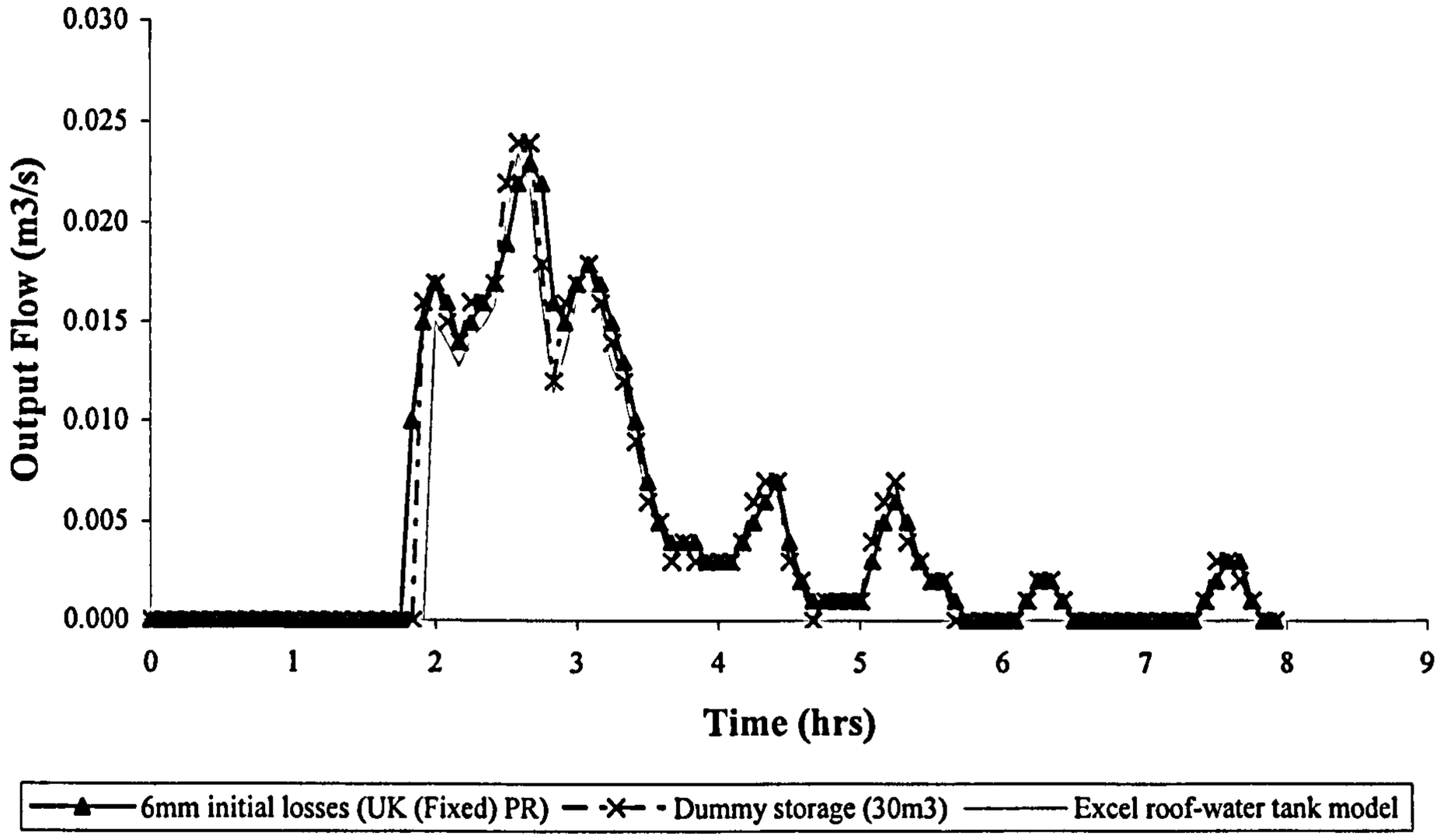
5.3.3.5. One-node case study modelling exercise: Results

The results of this exercise (presented in Figure 5.9) indicated that the ***'Initial Losses'*** option was the most appropriate of the potential modelling options. The rationale behind this decision was as follows.

The ***'Initial Losses'*** option was considered to form the most direct and transparent technique. It is possible to use this approach to define tank storage directly as an initial loss corresponding to an existing sub-catchment surface, whereas the alternative approach relied on more in-direct methods of defining tank storage within HydroWorks. In essence, this approach may be implemented to existing HydroWorks catchments data with minimal changes having to be made to the original model. This transparency means that results obtained using this method may be

easily checked, and hence treated with a higher degree of confidence than results obtained from the other approaches.

Figure 5.9 Comparison of alternative modelling options for representing spill overflow from a group of rainwater tanks - (Rainfall Input: Low3.red) (Cumulative roofed area: 5000m^2 and Cumulative tank storage: 30 m^3)



The 'initial losses' solution was hence identified as the most appropriate HydroWorks modelling approach for localised roof-water detention schemes. However, it is recognised that the results of this exercise are limited to a simple one-node catchment and for TSR storm event.

5.3.4. Modelling storage-based SUDS: Application to Meanwood

This Section presents a set of HydroWorks studies that were undertaken to investigate a range of optimum source-control storage scenarios for the Meanwood catchment.

As described in Chapter 4, no additional analysis was undertaken to investigate the optimum performance of off-site storage scenarios for the Meanwood catchment, because all viable locations for such facilities had already been earmarked for off-site infiltration facilities, and it was evident that infiltration-based off-site facilities had greater potential for reducing/eliminating catchment flooding than storage-based facilities.

Previous HydroWorks investigations (Section 5.3.2.4) demonstrated that the off-site infiltration proposals reduced catchment flooding from 1304 m^3 to 108 m^3 for the critical M10-60S storm event. It was therefore considered that the same level of performance could be achieved using adequate off-site storage facilities within the same locations – as there were large amounts of available space in which they could be constructed.

The remainder of this Section presents a set of HydroWorks studies that investigated a range of optimum source-control storage scenarios for the Meanwood catchment.

5.3.4.1. HydroWorks modelling for Optimum Proposal 5 (source control storage to all Meanwood's IMP areas)

HydroWorks simulations were conducted to investigate the affect of **Optimum Proposal 5** (i.e. the catchment-wide use of source control storage – in the form of water butts for roofs and porous pavements for paved areas) on Meanwood flooding. These investigations initially investigated the provision of 0 to 6 litres/m^2 of source control storage for all roofed areas, and 0 to 10 litres/m^2 for all paved areas within the Meanwood catchments. The rationale for these ranges was as follows:

The practicable range of retrofit source control storage that is considered to be achievable for roofed areas is between 1.5 to 6 litres/m^2 – these values equate to an available storage capacity of between 150 to 600 litres for a 100 m^2 roofed area, or 75 to 300 litres for a 50 m^2 roofed area. An indication as to the practicable level of source control storage provided by permeable surfaces is presented within SUDS design manual (CIRIA, 2000), which reports that a typical porous pavement has a depression storage value of 5 mm. This would equate to a retrofit-source control unit storage of 5 litres/m^2 if permeable surfaces were retrofit to roads within the Meanwood catchment.

The results of this analysis are presented in the shaded part of Table 5.6. It should be noted that these simulations were conducted using the HydroWorks 'initial losses technique' (See Section 5.3.3.3), the Meanwood catchment model and the critical M10-60s design storm.

Table 5.6 Meanwood flood volumes (m^3) from a M10-60S design storm – For Optimum Proposal 5 and a range of source control storage scenarios for paved and roofed areas

Storage to Paved surfaces (litres/m^2)	*Storage to all Roofed surfaces (litres/m^2)*				
	0	*3*	*6*	*9*	*12*
0	1304 m^3	1220 m^3	1146 m^3	1071 m^3	997 m^3
5	1013 m^3	986 m^3	922 m^3	849 m^3	771 m^3
10	641 m^3	622 m^3	568 m^3	509 m^3	449 m^3
15	327 m^3	318 m^3	280 m^3	236 m^3	190 m^3
20	86 m^3	78 m^3	58 m^3	41 m^3	26 m^3
25	64 m^3	56 m^3	35 m^3	18 m^3	5 m^3

It is evident that the provision of source control storage to paved surfaces had a much greater impact on reducing the Meanwood catchment's flooding problems than the provision of source control storage to roofed surfaces (see Section 4.2.3.2). Therefore the paved option was subsequently investigated through a greater range, to the point where catchment flooding was practically eliminated (i.e. the use of 12 litres/m^2 of pre-storm storage for roofed areas, in conjunction with 25 litres/m^2 for paved areas). The results of this exercise are presented in the remainder of Table 5.6, and in the form of a 3D plot (Figure 5.10). However, it should be noted that source control storage levels higher than 10 litres/m^2 would not be feasible to retrofit to most paved areas within the Meanwood catchment.

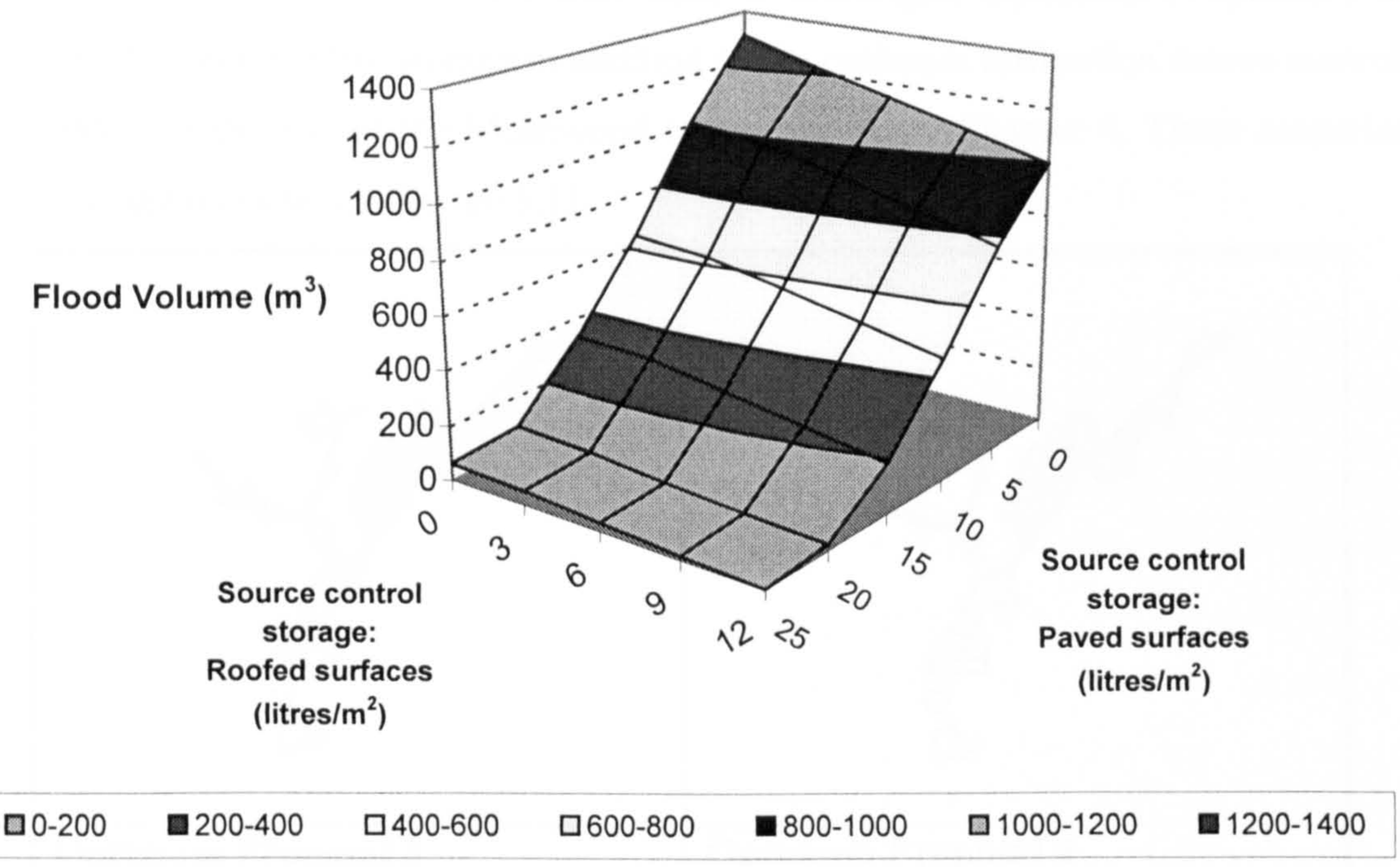


Figure 5.10: 3D plot of Meanwood flood volumes (m^3) from a M10-60S design storm – Range of Source Control storage scenarios for paved and roofed areas

The best 'practically feasible' retrofit source control option (i.e. the use of 6 litres/m^2 storage for roofed areas in conjunction with 10 litres/m^2 for paved areas) was estimated to reduce critical catchment flooding from 1304 m^3 to 568 m^3 (i.e. a reduction of 44%). This level of improvement is significantly worse than those of the optimum infiltration options presented within Section 5.3.2.3. It is therefore evident that the use of storage-based source controls alone does not represent a feasible proposal for the elimination of Meanwood's flooding problems.

The following Sections explore **Optimum Proposals 3 and 4** (Chapter 4). These combined scenarios assume that source control storage is provided to those impervious areas not included within the optimum infiltration scenarios.

5.3.4.2. HydroWorks modelling of Optimum Proposals 3 and 4

Further HydroWorks simulations were undertaken to investigate **Optimum Proposals 3 and 4** (i.e. the use of source-control storage in addition to the optimum infiltration source control and off-site control proposals for the Meanwood catchment) from Chapter 4. These scenarios are illustrated on the maps within Figure 5.11.

	
Optimum Proposal 3 **Combined infiltration/storage** Optimum source control (infiltration) proposal in addition to: Storage to all impervious surfaces not contained within Meanwood's sandstone region ***(S/C storage to all impervious areas contained within un-shaded region)***	**Optimum Proposal 4** **Combined infiltration/storage** Optimum off-site control (infiltration) proposal in addition to: Storage to all impervious surfaces not considered to be 'infiltratable' ***(S/C storage to all impervious areas contained within un-shaded region)***

Figure 5.11 Optimum Proposals 3 and 4 (reproduced from Figure 4.7)

Four source control storage options were investigated for both of these proposals using the HydroWorks initial losses technique (Section 5.3.3). The results of this analysis are presented in Table 5.7 and Table 5.8, for Optimum Proposals 3 and 4 respectively. These results were generated directly using detailed HydroWorks modelling techniques, because the simplistic extrapolation techniques employed in Section 5.3 were not deemed appropriate for storage-based, or integrated (infiltration and storage-based) SUDS proposals.

Table 5.7 Flood volumes (m^3) from M10-60s design storm for Optimum Proposal 3

Source- control storage to paved Surfaces (litres/m^2)	*Source control storage to Roofed surfaces (litres/m^2)*	
	0	*6*
0	480 m^3	427 m^3
10	206 m^3	178 m^3

Table 5.8 Flood volumes (m^3) from M10-60s design storm for Optimum Proposal 4

Source- control storage to paved Surfaces (litres/m^2)	*Source control storage to Roofed surfaces (litres/m^2)*	
	0	*6*
0	108 m^3	97 m^3
10	38 m^3	35 m^3

The range of storage options explored in this analysis reflects the viable levels of source control storage that were considered to be feasible within these parts of the Meanwood catchment. It is evident that while neither Optimum Proposal 2, or 4, completely eliminates the catchment's flooding problems, both proposals do significantly reduce the level of flooding from its existing value of 1304 m^3. However, it is worth noting that these proposals, which supplement the use of infiltration SUDS with storage, achieve much higher levels of system performance than Optimum Proposals 1 and 3, which purely rely on infiltration-based approaches. This highlights the complexity of identifying optimal approaches where multiple-technology SUDS schemes are likely to be required.

It is worth noting that in order to completely eliminate catchment flooding it would therefore be necessary to pursue hybrid solutions (i.e. to use SUDS in conjunction with some additional in-sewer storage – to remove the small amount of flooding that remains). The results of this exercise support the findings of a corresponding modelling exercise that was undertaken by Leeds City Council (Walker, 2000:a), and presented in the next Section.

5.4. HYDROWORKS MODELLING: COMPARATIVE DESIGN EXERCISE (WALKER, 2000:b)

Walker (2000:b) undertook a comparative modelling exercise to assess the performance of a range of conventional and SUDS-based proposals for alleviating flooding problems within the Meanwood catchment.

5.4.1. Conventional stormwater management proposals (Walker, 2000:b)

Three conventional proposals for alleviating flooding problems within the Meanwood catchment were developed. Leeds City Council's Department of Highways and Transportation conducted all costings and design work associated with these proposals (Walker, 2000:b). These options are presented within Table 5.9.

Table 5.9 Conventional Proposals for Meanwood Catchment (Walker, 2000:b)

Conventional Option 1.	The complete re-sewerage of all inadequate pipe-work along Meanwood Road and Stonegate Road. This option would require 2.1 km of new pipe-work (600 mm to 1200 mm diameters) – with 1.3 km of this new sewerage laid under the main highway.
Conventional Option 2.	Significant re-sewerage in conjunction with the construction of additional upstream storage in the park area located to the south of Southgate Road. This option would require 500 m^3 of off-line storage and 1.9 km of new sewerage (525 to 900 mm diameters). As with the previous option much of this new sewerage would be laid under the main highway – causing significant disruption to traffic and services.
Conventional Option 3.	Limited re-sewerage work combined with increased storage. This would require 500 m^3 of off-line storage as outlined in Option 2, used with an additional 1950 m^3 of storage at the junction of Parkside Road and Stonegate Road. Leeds City Council's investigations showed that this would require a total storage volume of 2450 m^3 with 0.7 km new sewerage (600mm).

It should be noted that all of these options required the implementation of major construction works within a busy highway.

5.4.2. SUDS proposals (Walker, 2000:b)

Two SUDS scenarios were explored; the first assumed the application of retrofit SUDS to all impermeable surfaces that Walker (2000:b) considered to be viable for disconnection from the Meanwood catchment, and the second assumed a 75% take-up rate for these disconnectable surfaces. A comparison of these SUDS-based options is presented in Table 5.10.

Table 5.10 Meanwood SUDS options – Areas of Disconnection (from Walker, 2000:b)

Proposal	Housing	Area connected (ha)	No. of houses Disconnected (of 1280 houses in catchment)	Road	Area connected (ha)	Approx. Length of Road connected (km)
Existing case	*Existing case*	7.37	0	*Existing Case*	9.20	20.2
SUDS_100 Option	*100% of Walker's (2000:a) viable surfaces disconnected*	4.02	275 (1) + 72 (2)	*100% of Walker's (2000:a) viable surfaces disconnected*	6.04	12.5
SUDS_75 Option	*75% of Walker's (2000:a) viable surfaces disconnected*	4.63	206 + 54	*75% of Walker's (2000:a) viable surfaces disconnected*	7.42	15.3

(1) Number of dwellings that can be totally disconnected
(2) Number of dwellings that can be partially disconnected

Figure 5.12 compares the impermeable (IMP) surface contribution to the Meanwood sewer system associated with Walker's Meanwood SUDS options (2000:a) and the Infiltration SUDS presented in Table 5.5. It is worth noting that the **SUDS_100 option** is very similar to the optimum source control (infiltration) proposal, this relates to the fact that both schemes aim to disconnect all impervious surface areas contained within the Meanwood sandstone sub-catchments from the local sewer system.

A further four hybrid (i.e. part SUDS / part conventional) solutions were developed and investigated; these are presented in Table 5.11.

Table 5.11: Meanwood Hybrid (SUDS/conventional) options

	Description
Hybrid Option 1	SUDS_100 option + re-sewerage
Hybrid Option 2	SUDS_100 option + 500m^3 storage + re-sewerage
Hybrid Option 3	SUDS_75 option + re-sewerage
Hybrid Option 4	SUDS_75 option + 500m^3 storage + re-sewerage

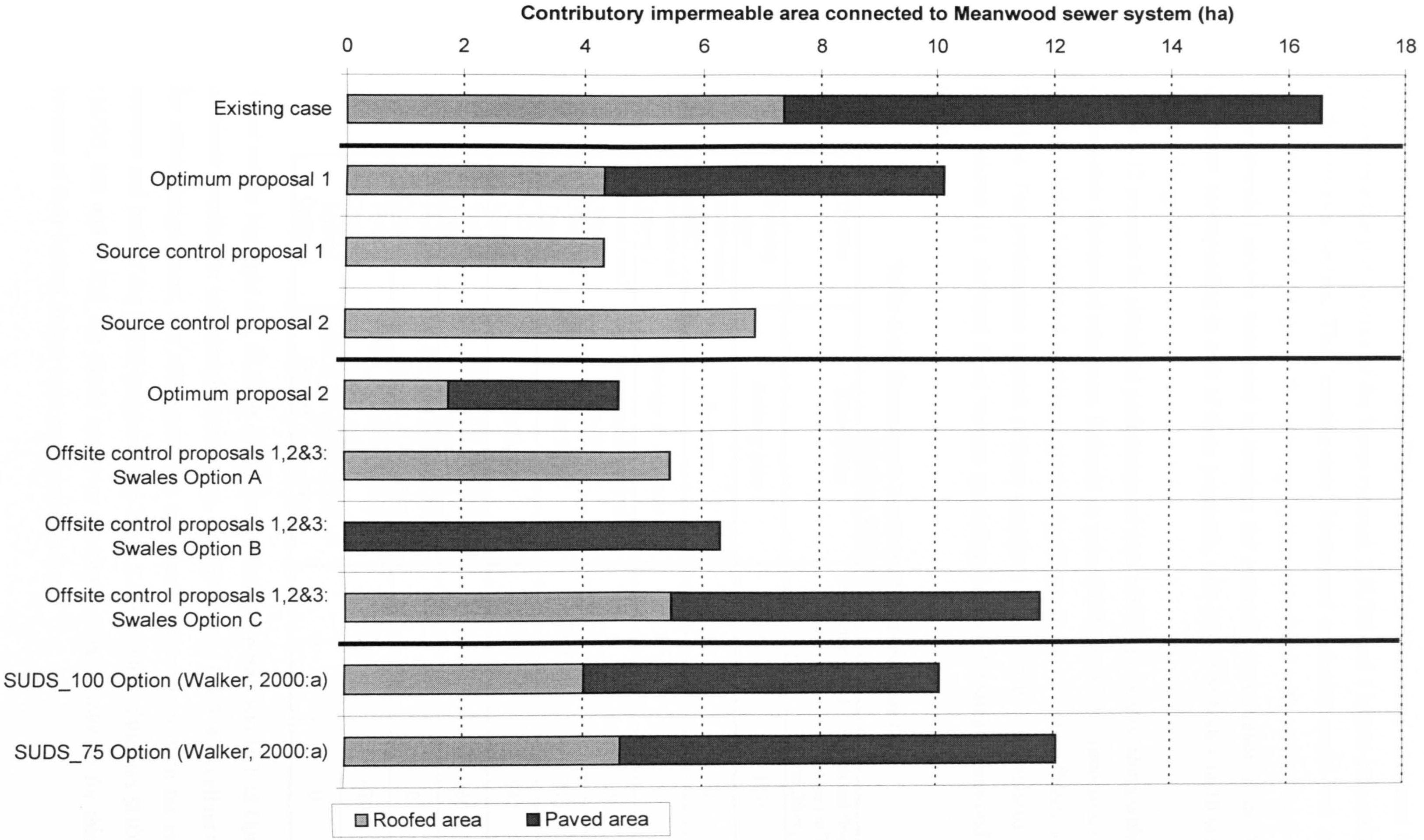


Figure 5.12 Comparison of Meanwood SUDS proposals

5.4.3. Comparison of hydraulic performance of alternative proposals

Walker (2000:b) used a verified HydroWorks model of the Meanwood catchment to simulate and compare the performance of the 3 conventional, 2 SUDS and 4 hybrid proposals presented in the previous Section. This 'existing-state' Meanwood catchment model was amended to reflect the proposed changes to the sewerage system associated with each of these proposals. These amended models were used to simulate the hydraulic performance of the Meanwood catchment corresponding to each of these proposals, with respect to both 1 in 10 year and 1 in 30 year design storms.

Table 5.12 presents the simulated performance of each of these proposals, along with that of the existing-state Meanwood catchment. It should be noted that HydroWorks simulations conducted for the existing Meanwood catchment predict significant levels of system flooding from four locations. The performance of each of these proposals is defined by its simulated cumulative flood volume (i.e. the total flood volume emanating from all flooding Meanwood catchment nodes).

Table 5.12: Meanwood: Predicted flood volumes (m^3) (Walker, 2000:b)

Option	Description	Predicted flood volume (m^3) [1 in 10yr]	Predicted flood volume (m^3) [1 in 30yr]
Existing state	*Existing state*	1302	1730
Conventional Option 1	*Re-sewer*	0	0
Conventional Option 2	*Storage & Re-sewer*	0	0
Conventional Option 3	*Increased Storage & Re-sewer*	0	0
SUDS_100 Option	*100% SUDS*	397	713
SUDS_75 Option	*75% SUDS*	600	947
Hybrid Option 1	*SUDS_100 option & Re-sewer only*	56	160
Hybrid Option 2	*SUDS_100 option & 500 m^3 Storage & Re-sewer*	0	0
Hybrid Option 3	*SUDS_75 option & Re-sewer only*	216	420
Hybrid Option 4	*SUDS_75 option & 500 m^3 Storage & Re-sewer*	0	0

These results highlight that all three of the conventional proposals and Hybrid Options 2 & 4 eliminate flooding for both design storm inputs. Hybrid Options 1 & 3 fail to eliminate flooding for either design storm, but still represent a significant improvement upon the existing case scenario and both of the SUDS proposals (see Table 5.12). Neither of the two SUDS proposals (SUDS_100 and SUDS_75) would appear to constitute a viable solution for this catchment because of their limited impact upon catchment flooding.

It is evident that these results are consistent with those presented for Optimum Proposals 1, 2, 3 and 4. This factor provides added confidence in both sets of results.

The following Chapter explores the financial costs associated with retrofit SUDS, and Chapter 7 presents a decision-making procedure for the design of retrofit SUDS.

6. RETROFIT SUDS EVALUATION – ECONOMIC ISSUES

6.1. INTRODUCTION

The high level of uncertainty associated with the financial costs (e.g. for construction, operation and maintenance) of SUDS schemes is considered to be a major factor that limits their use in the UK. This uncertainty is exacerbated by the limited UK experience of SUDS schemes, and the lack of published UK costing data for such devices. The SUDS design manual (CIRIA C522, 2000) acknowledges that cost is an important factor in the evaluation of conventional and alternative SUDS proposals, but fails to provide any specific information as to how those costs might be obtained. Furthermore, the manual provides no indication as to the comparative costs of the different SUDS technologies that it presents. Conversely, the financial costs associated with the construction and operation of conventional urban drainage are well understood, and documented. For many UK designers/engineers the uncertainty associated with the costs of SUDS schemes makes them a far less attractive option than tried and trusted conventional approaches.

This Chapter proposes methodologies for costing a range of retrofit SUDS technologies, and applies these in the context of representative contributory areas and the Meanwood urban drainage catchment. Unit construction costs were developed for a range of retrofit SUDS technologies (further details of this exercise are presented within Section 6.2). These generic unit costs were subsequently used to create specific costings for a set of representative contributory areas (Section 6.3) and the Meanwood catchment (Section 6.4).

It is worth noting that the costs associated with implementing new SUDS schemes might vary significantly from those highlighted in this Chapter for retrofit SUDS.

6.2. DEVELOPMENT OF UNIT CONSTRUCTION COSTS

6.2.1. Background

Unit construction costs were developed for a range of retrofit SUDS technologies. These unit costs were largely based upon basic cost data from the SPONS price guidelines for Civil Engineering and Highways Works (SPONS, 2001:a) and Landscape and External Works (SPONS, 2001:b) – both of these publications present costs for a wide range of basic Civil Engineering work items, such as excavation, back-filling and re-grassing. It should be noted that the costs presented within these SPONS publications exclude Value Added Tax (VAT), contractor's profit margins, design or supervisory works. All cost estimates presented within this Chapter include a contractor's profit margin of 10%, and VAT (17.5%), but exclude additional costs such as those associated with design, supervision and compensation payments to injured parties. OFWAT's set of published set of capital works unit costs for the water industry (1998) was another document used in this exercise.

6.2.2. Presentation of example unit costs for retrofit SUDS

Table 6.1 presents the unit costs that were compiled for a number of retrofit SUDS technologies – the quoted appendices contain more detailed explanations of how these costing methodologies and finalised costs were generated. It should be noted that the retrofit SUDS examples presented in this table were selected because they were considered to represent appropriate design dimensions for typical urban applications. For example, the infiltration trench and soakaway examples presented in Table 6.1 correspond to the design examples adopted in the BRE (1991) guidelines (i.e. in terms of the design dimensions).

Table 6.1 Generic construction unit costs for Retrofit SUDS

Technology	Items included in costing	Unit construction cost		Appendix: for further details (Notes)
		High (£/item)	Low (£/item)	
Water butt (0.3 m^3)	• Water butt (0.3 m^3) • Installation • Connection of feeder pipe	£242.93 /property	£100 /property	**6A**
Infiltration Trench: *BRE365 (1991) design example dimensions:* 0.6 m (width) x 2.5 m (depth) *(1.5 m effective depth)*	• Excavation • Placing of filter material • Horizontal distributor pipe • Geotextile filter membrane • Back-filling • Reinstatement Note: all pipework 225 mm Excludes costs of connections	£99.16 /m length	£73.88 /m length	**6B**
Swales: *2 m wide by 200 mm deep to be excavated in existing grass verges*	• Excavation (by hand) • Disposal of excavated soil • Reinstatement • Grassing (Turfing) Excludes cost of connecting Paved or Roofed areas	£20.28 /m *Compacted Soil*	£17.71 /m *Loose material*	**6C**
Soakaway: *BRE365 (1991) design example dimensions:* 2.4 m (long) x 1.5 m (width) x 2.5 m (depth) *(1.5 m effective depth)*	• Excavation (by hand) • Geotextile filter membrane • Back-filling • Reinstatement Excludes costs of connections	£551.80 /soakaway *Compacted Soil*	£453.67 /soakaway *Loose material*	**6D** *To drain 95m^2 imp. area into a soil with $f = 3.3x10^{-5}$ m/s*
Porous car-park: Using Grasscrete precast concrete units filled with top soil and grass seeded	• Lighting • Drainage • Forecourts • Aprons • Access areas But excludes approach roads	-	£ 63.33 /m^2	**6E**
Ponds	• All excavation • Pipeworks	£55 /m^3	£35 /m^3	**6F**
Separate Sewerage	• 150 mm pipe ~ 1m depth below paved surface • Reinstatement to paved	£173.84 /m	-	**6G**
Storage Tanks	• All excavation • Fill • Structural work • Valves • Pipeworks	£518.29 /m^3	£448.50 /m^3	**6H**

It is worth noting that when high and low unit costs are presented for a specific technology, these correspond to cost differences that result from different soil conditions or materials.
Many of the unit costs presented in this table are not standalone items, but would generally be used in conjunction with one, or more of the other items to produce integrated SUDS solutions. For example, the cost of swales would typically be considered in conjunction with the costs of an off-site control facility.
It is not appropriate to compare these unit construction costs with one another at this stage, as the area served by each is not consistent

6.3. RETROFIT SUDS COSTINGS FOR REPRESENTATIVE CONTRIBUTORY AREAS – DIFFERENT URBAN SURFACE TYPES

Further investigations were undertaken to explore the design and cost issues associated with the application of retrofit SUDS to four representative contributory impervious areas (50 m^2, 200 m^2, 500 m^2 and 2000 m^2). These examples were considered as representing typical contributory areas to which retrofit SUDS might be applied. The costings developed for these representative contributory areas were subsequently adopted for use in conjunction with the decision-making framework presented in Chapter 7.
For the purpose of these investigations, a single residential roof was considered to have a contributory surface area of 50 m^2, and an institutional roof a contributory surface area of 200 m^2.
These investigations explored the use of retrofit SUDS devices as source control strategies to serve single residential/institutional roofs (e.g. 50 m^2/200 m^2), or as offsite controls to serve groups of ten residential/institutional roofs (e.g. 500 m^2/2000 m^2). Further investigations explored the use of retrofit SUDS for both source control and off-site control applications in relation to a paved surface area of 500 m^2 (i.e. adopted to represent a small car-park/stretch of road). A summary of these representative contributory impervious areas is presented in Table 6.2.

Table 6.2 Summary of representative contributory areas used to generate comparative costs for different SUDS technologies

Scenario No.	Surface Type	Description	Contributory Area (m^2)
1.	Residential roofs	*A.) Source control option:* Considered for a 50 m^2 residential roof	50 m^2
		B.) Offsite control option: Considered for 10 x 50 m^2 residential roofs	500 m^2
2.	Institutional roofs	*A.) Source control option:* Considered for a 200 m^2 residential roof	200 m^2
		B.) Offsite control option: Considered for 10 x 200 m^2 residential roofs	2000 m^2
3.	Car parks & Roads	*A.) Source control option:* Considered for a 500 m^2 car park / road	500 m^2
		B.) Offsite control option: Considered for a 500 m^2 car park / road	500 m^2

Specific SUDS technologies were designed to drain runoff for each of these representative contributory areas. The design work for these SUDS proposals was undertaken in accordance with relevant UK design guidelines, and these were used to generate appropriate design dimensions for each technology specific proposal. Tables 6.3 to Tables 6.6 present the design dimensions that were developed for each of these representative scenarios. It should be noted that these design dimensions were generated using a critical 10 year rainfall event, and a prevailing soil percolation rate of 4.63×10^{-6} m/s.

Table 6.3 SUDS design dimensions required to drain 50 m^2 of contributory area (e.g. a single residential roof)

Technology	Relevant Design Guidelines	Design Dimensions
Soakaways	BRE 365 (1991)	1.5 x 1.8 x 1.8 m *(Effective depth x length x width)*
Infiltration Trenches	CIRIA 156 (1996)	0.6 x 1 x 7.5 m *(Width x depth x length of base)*
Basins	CIRIA 156 (1996)	1 x 1 x 1 m *(Width x depth x length)*
Ponds	10 yr storm (FoS = 2)	5.3 m^3 (*Volume*)
Porous Pavements	CIRIA 156 (1996)	16 m^2 (*Area*) 4 x 4 m *(Length x width)*

Table 6.4 SUDS design dimensions required to drain 200 m^2 of contributory area (e.g. a single institutional roof)

Technology	Relevant Design Guidelines	Design Dimensions
Soakaways	BRE 365 (1991)	2.5 x 2.9 x 2.9 m *(Effective depth x length x width)*
Infiltration Trenches	CIRIA 156 (1996)	1 x 1.5 x 14 m *(Width x depth x length of base)*
Basins	CIRIA 156 (1996)	4 m^3 *(Volume)* 1 x 2 x 2 m *(Width x depth x length)*
Ponds	10 yr storm (FoS = 2)	21.3 m^3 (*Volume*)
Porous Pavements	CIRIA 156 (1996)	63 m^2 (*Area*) 7.95 x 7.95 m *(Length x width)*

Table 6.5 SUDS Design Dimensions required to drain 500 m^2 of contributory area (e.g. a group of ten residential roof, or a small car park / stretch of road)

Technology	Relevant Design Guidelines	Design Dimensions
Swales	CIRIAC522 (2000)	0.4 x 0.2 m (1:4) *Base x depth (Side-slopes)*
Filter drains	Highway Construction Details (Highways Agency, 1998)	1.5 x 0.6 m x length *(Depth x width) (+150mm Dia. pipe)*
Separate sewerage	Manning's formula	150 mm *(Diameter)*
Soakaways	BRE 365 (1991)	2 x 5.3 x 5.3 m *(Effective depth x length x width)*
Infiltration Trenches	CIRIA 156 (1996)	1 x 1 x 51 m *(Width x depth x length of base)*
Basins	CIRIA 156 (1996)	1 x 3.2 x 3.2 m *(Depth x length x width)*
Ponds	10 yr storm (FoS = 2)	53.3 m^3
Porous Pavements	CIRIA 156 (1996)	157 m^2 (*Area*) 12.5 x 12.5 m *(Length x width)*

Note: Shaded rows denote conveyance options

Table 6.6 SUDS Design Dimensions required to drain of 2000 m^2 contributory area (e.g. a group of ten institutional roofs)

Technology	Relevant Design Guidelines	Design Dimensions
Swales	CIRIAC522 (2000)	0.4 x 0.2 m (1:4) *Base x depth (Side-slopes)*
Filter drains	Highway Construction Details (HMSO, 1998)	1.5 x 0.6 m x length *(Depth x width) (+225 mm Dia. pipe)*
Separate sewerage	Manning's formula	225 mm *(Diameter)*
Soakaways	BRE 365 (1991)	2.5 x 9.65 x 9.65 m *(Effective depth x length x width)*
Infiltration Trenches	CIRIA 156 (1996)	1 x 1.5 x 143 m *(Width x depth x length of base)*
Basins	CIRIA 156 (1996)	1 x 6.6 x 6.6 m *(Depth x length x width)*
Ponds	10 yr storm (FoS = 2)	213.3 m^3
Porous Pavements	CIRIA 156 (1996)	629 m^2 (*Area*) 25 x 25 m *(Length x width)*

Note: Shaded rows denote conveyance options

See Notes on Table 6.3 to 6.6 (Appendix 6) for further details on the derivation of these design dimensions.

Costings were subsequently generated for each of these design solutions and then compared for each contributory area. The estimated construction costs of each of these scenarios are presented in Table 6.7. High and low cost estimates are presented for those technologies that have a large degree of uncertainty attached to their cost. Further details of these costing calculations are presented within the cited appendices.

Table 6.7 Construction costs of alternative SUDS technologies

Technology	Design option (Surface area served)	Construction Costs (£)		Appendix
		Highest	Lowest	
Soakaways	50 m^2	324.53	268.94	**6D**
	200 m^2	767.48	623.18	
	500 m^2	3055.77	2413.15	
	2000 m^2	11819.15	9156.17	
Infiltration Trenches	50 m^2	638.78	503.26	**6B**
	200 m^2	1622.13	1210.19	
	500 m^2	4959.63	3853.54	
	2000 m^2	16568.86	12361.26	
Basins	50 m^2	91.20	80.51	**6F**
	200 m^2	266.57	223.81	
	500 m^2	588.11	478.65	
	2000 m^2	2071.69	1606.08	
Ponds	50 m^2		391.10	**6F**
	200 m^2		1365.30	
	500 m^2		3413.30	
	2000 m^2		4716.10	
Porous Pavements (costs for new car parks)	50 m^2		1013.32	**6E**
	200 m^2		3989.95	
	500 m^2		9943.20	
	2000 m^2		39836.14	
Porous Pavements (replacement surface)	Price per m^2		27.13	**6E**
Swales	Price per m	20.28	17.71	**6C**
Filter drains	Price per m		61.44	**6B**
Separate sewerage	Price per m		173.84	**6I**

Table 6.7 presents direct construction costs that were generated for these infiltration devices, and neglects the secondary costs associated with the connection of the contributory impermeable surface to these devices. An indication of the conveyance costs is presented (in unit terms) in the shaded part of the table. Figure 6.1 graphically portrays the comparative construction costs of alternative SUDS technologies to drain a 50 m^2 contributory impervious area.

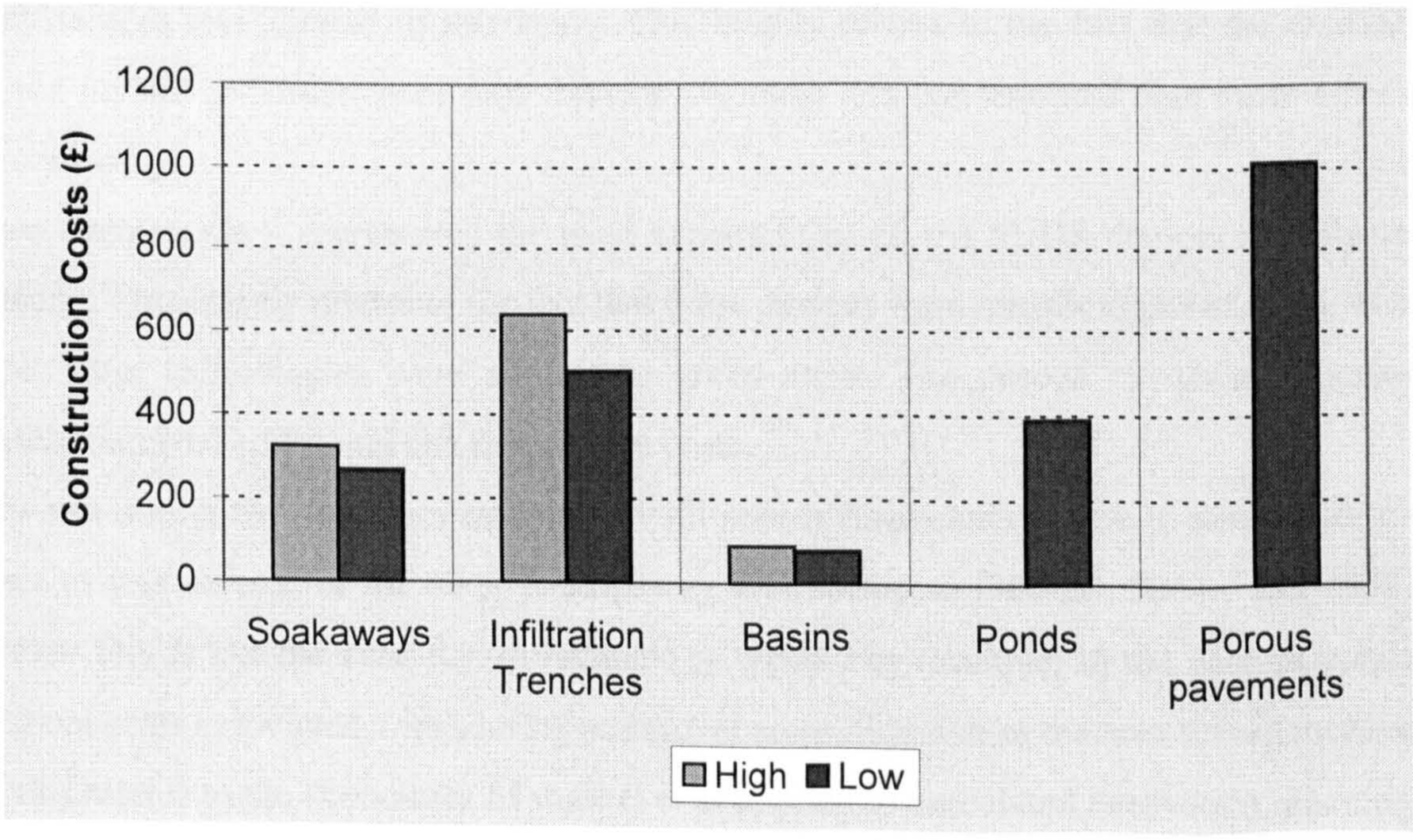


Figure 6.1 Construction costs of alternative SUDS technologies – 50 m^2 contributory area

These results indicate that infiltration basins represent the cheapest form of SUDS device, followed by soakaways, ponds, infiltration trenches and porous pavements. For example, in the 50 m^2 contributory area scenario the cheapest options are basins, soakaways are 3.3 times more expensive, ponds are 4.9 times more expensive, infiltration trenches are 6.3 times more expensive and porous pavements are 12.6 times more expensive (these comparisons are based upon the high costs for specific technologies). The large variation in these different technology costs underlines the need for accurate SUDS costings, and reinforces the fact that economic issues can have a significant bearing on the viability/feasibility of potential SUDS schemes.

These results are discussed in further detail within the following paragraphs:

Basins – It is not surprising that infiltration basins proved to be the cheapest form of SUDS technology, as they require less excavation than other surface-based SUDS devices (e.g. ponds) and fewer additional materials for backfilling than sub-surface SUDS (soakaways, infiltration trenches and porous pavements).

Soakaways – Similarly, there is little surprise that soakaways were the next cheapest option after basins. This largely relates to the fact that they are the cheapest sub-surface option because excavations are concentrated in a specific location rather than being spread across a much larger area, as with infiltration trenches and porous pavements.

Ponds – Ponds represent the more expensive of the two surface-based SUDS devices investigated in this study, and were also shown to have higher construction costs than soakaways. The high comparative costs of ponds schemes largely relate to the safety factor (FOS) of 2 that was included into their design in order to allow runoff from previous storms to be accommodated in such structures. Planting and landscaping are other factors that increase the costs associated with ponds.

Infiltration trenches – represented the second most expensive of the three sub-surface based SUDS devices investigated in this study. This largely relates to the fact that the excavations required for the construction of such devices are much less concentrated than those associated with soakaways.

Porous pavements – represented the most expensive of all the SUDS devices investigated in this study. This largely relates to the fact that these devices were retrofit to paved areas, whereas all the other technologies were applied to green areas. The porous pavements approaches therefore incurred additional site preparation costs.

It is worth noting that the costs associated with porous pavements appear to vary linearly with respect to area served for the other contributory area scenarios (200 m^2, 500 m^2 and 2000 m^2). However this is not the case for all technology types. For example, in the case of ponds the additional costs associated with serving additional areas diminish as the area served increases in size, this relates to the economics of scale (i.e. as applied to associated excavation, planting and waterproof lining costs).

These costings formed the basis for the comparative costs of alternative SUDS technologies used in the flow-chart methodologies that are presented in the next Chapter.

6.4. RETROFIT SUDS COSTINGS FOR MEANWOOD CATCHMENT

6.4.1. Background

This Section presents a further set of construction costs that was specifically developed for the Meanwood catchment. These costings were generated for each of the technology-specific SUDS proposals presented for the Meanwood catchment in Chapter 4, and comprise of a combination of unit costs (e.g. cost per soakaway) and secondary unit costs. An example of a secondary unit cost is the costs associated with connecting typical Meanwood property roofs to local swales. Once again, detailed descriptions of the cost estimates are presented in the cited appendices.

Table 6.8 illustrates how construction costs were developed for the example of a soakaway 1.5 m (depth) x 1.8 m (width) x 1.8 m (length). These soakaway costs were specifically developed for residential properties in the Meanwood catchment – this is demonstrated by the fact that costs were generated for sandstone conditions, and that turf was adopted in preference to grass seeding for the reinstatement of excavated gardens. Customised costs generated for alternative SUDS devices applied to Meanwood are presented in Table 6.9. Once again, all design work was conducted in accordance with relevant UK guidelines, and all costs presented in this table were generated using the same basic costing methodologies as adopted for the previous Section. Complete workings for each of these costings are presented in the cited appendices.

A secondary set of construction unit costs was also developed for application to the Meanwood catchment (Table 6.10) – these relate to the secondary unit costs that were considered to be associated with each of the technology-specific SUDS design proposals presented in Chapter 4.

Table 6.8 Construction costs for soakaway of: 1.5 m (depth) x 1.8 m (width) x 1.8 m (length)

Work items	Unit cost	*(£/Unit)*	Required Quantity	*(Unit)*	Item Cost (£)	Reference
Excavation (by hand)						
Sand stone	21.96	*£/m^3*	*4.86*	*m^3*	106.73	*SPONS, (2001:a) page 180*
Backfilling						
Rock (imported rock - general) *(Assuming 1.732m x 1.732m = 3m^2 plan)*	10.16	*£/m^3*	*4.86*	*m^3*	49.38	*SPONS, (2001:a) page 171*
Geotextile						
Filtram 1B1 (drainage applications)	5.45	*£/m^2*	*14.04*	*m^2*	76.52	*SPONS, (2001:a) page 174*
Reinstatement						
Preparation of filled soils	1.02	*£/m^2*	*3.24*	*m^2*	3.30	*SPONS, (2001:a) page 172*
Grassing						
Turfing	3.03	*£/m^2*	*3.24*	*m^2*	9.82	*SPONS, (2001:a) page 175*
Total					245.74	
Total + VAT					288.75	
Total + VAT + 10% profit margin					**317.62**	

Assuming application to a sandstone sub-strata

Table 6.9 Specific unit cost data that relates to retrofitting SUDS technologies to the Meanwood catchment

Technology	Items included in costing	Unit cost of technology (Using SPONS, 2001:a)	For further details see:	Comments
Soakaways: ***Sandstone*** *(1.5 m x 1.8 m x 1.8 m Vol.) (Eff. Depth x Length x Width) (For source control proposal 1)*	- Excavation (by hand) - Geotextile filter membrane - Back-filling - Reinstatement	£ 317.62 / *soakaway*	Appendix 6D	Calculated using BRE365 for Sandstone; M10-Critical, r = 0.35 and contributory impermeable area = 50 m^2
Infiltration Trench: 0.6 m (width) x 1 m (depth) *(For source control proposal 2)*	- Excavation - Placing of filter material - Horizontal distributor pipe - Geotextile filter membrane - Back-filling - Reinstatement Note: all pipework 225 mm	Low: £67.10 */m* High: £85.17 */m* *Note: variations in geotextiles And reinstatement*	Appendix 6B	-
Infiltration Trench: 1 m (width) x 3 m (depth) *(For offsite control proposals)*	Up to 3 m deep x 1m wide - Excavation - Placing of filter material - Horizontal distributor pipe - Geotextile filter membrane - Back-filling - Reinstatement Note: all pipework 225 mm	Low: £133.77 */m* High: £181.16 */m* *Note: variations in geotextiles And reinstatement*	Appendix 6B	Comparable unit cost generated by Walker (2000:b) Grassed areas: £157 /m Note: These calculations are based upon sandstone soils

Table 6.10 Specific secondary cost data that relates to retrofitting SUDS technologies to the Meanwood catchment

Technology	Items included in costing	Unit cost of technology (Using SPONS, 2001:a)	For further details see:	Comments
Typical unit cost (Meanwood) of connecting a residential roof to an infiltration trench: **18.85 m**	- Excavation by hand - Preparation of filled surfaces - 10 m of Concrete Gulley - Bedding, jointed and pointed in cement mortar - Disconnection of property's downpipe	£ 241.53 / property	Appendix 6B	Calculated for a typical Meanwood property: **18.85 m** connection from roof to swale
Typical unit cost (Meanwood) of connecting a residential roof to a roadside swale: **10 m**	- Excavation by hand - Preparation of filled surfaces - 10 m of Concrete Gulley - Bedding, jointed and pointed in cement mortar - Disconnection of property's downpipe	£ 144.55 / property	Appendix 6C	Calculated for a typical Meanwood property: **10 m** connection from roof to swale:
Concrete Gulley Bedding, jointed and pointed in cement mortar	- Excavation by hand - Preparation of filled surfaces - Concrete gulley - Bedding, jointed and pointed in cement mortar	£10.94 /m length	Appendix 6D	-
Typical unit cost (Meanwood) of connecting a residential roof to a soakaway: **6 m**	- Excavation by hand - Preparation of filled surfaces - 6m of concrete gulley - Bedding, jointed and pointed in cement mortar - Disconnection of property's downpipe	£ 100.65 /no	Appendix 6D	Calculated for a typical Meanwood property: **6 m** connection from roof to soakaway:

6.4.2. Results

The construction unit costs presented within the previous Sections were subsequently used to generate costings for each of the 'technology specific' SUDS proposals presented within Chapter 4.

Source control proposal 1: Retrofit Soakaways – Table 6.11 presents the expected construction costs for the Retrofit Soakaways proposal (Option 1) highlighted within Chapter 4. This estimate was generated on the premise of 426 properties and unit costs for a 1.5 x 1.8 x 1.8 m volume soakaway and for the connection of a typical residential roof (Meanwood) to a soakaway.

Table 6.11 Source control proposal 1 – Soakaway Costs

Proposal	Roofed area and No. of properties served by soakaways	Soakaways dimensions required *(BRE, 1991)*	Unit costs: A. Soakaway B. Roof connection	Total costs (£)
Soakaways to every roof within **sandstone** region*	3.0221 ha (426 properties)	1.8 x 1.8 x 1.5 m	A.) £ 317.62 /soakaway B.) £ 100.65 /roof	**£ 178,183**

*See Appendix 6D for more details

These soakaway dimensions were generated using the BRE (1991) guidelines for a 1:10 year design storm event and the prevailing conditions of the Meanwood catchment.

Source control proposal 2: Retrofit Infiltration trenches – Table 6.12 presents the anticipated construction costs for the Retrofit Infiltration Trench proposal (Option 2) highlighted in Chapter 4. This estimate was generated using unit costs for infiltration trenches, and secondary connection costs (i.e. the connection of a typical residential roof to an infiltration trench). These secondary unit costs were based upon an average distance of 18 m between a typical roof and the proposal infiltration trench. The derivation of this average distance is presented with Appendix 6B.

Table 6.12 Source control proposal 2 – Infiltration Trench Proposal Costs

Proposal	Roofed area and No. of properties served by infiltration trenches	Required dimensions *(BRE, 1991)*	Unit costs: A. Per metre of trench B. Roof connection	Total cost (£)
Construction of 1065m of infiltration trenches to serve 86 properties within **sandstone** region*	0.4728 ha (86 properties)	*Width* 0.6 m x *Depth* 1 m x *Length* 1065 m (BRE 365, 1991)	A.) High:£85.17 /m B.) £ 241.53 / roof	**£ 111,478**

*See Appendix 6B for more details

These infiltration trench dimensions were generated using the BRE (1991) design guidelines for a 1:10 year design storm event and the prevailing conditions of the Meanwood catchment.

Conveyance Component: Retrofit swales – The costs generated for the swale component of the off-site proposals highlighted within Chapter 4 are presented within Table 6.13. These estimates were generated using unit costs for swales, and secondary connection costs (i.e. the connection of a typical roof/paved area to swale). The derivation of these costings is presented within Appendix 6C.

Table 6.13 Best case Meanwood Swales Proposal Costs

Proposal	Roofed or (Paved) area and No. of properties served by soakaways	Length of Swale required (m)	Unit costs 1. Swale / m 2. Roof connection 3. Paved inlet	Total cost
Swales Option A: Disconnection of all ROOFS adjacent to swales	1.8998 246 properties	4930	*1.)* £19.94 /m* *2.)* £ 144.55 / roof	£ 133,864 + costs of offsite control
Swales Option B: Disconnection of all PAVED areas adjacent to swales	(2.8860)	4930	*1.)* £19.94 /m* *3.)* £ 232 / 20 m of swale length**	£ 155,492 + costs of offsite control
Swales Option C: Disconnection of both ROOFED and PAVED areas adjacent to swales	1.8998 (2.8860)	4930	1., 2. & 3. from above	£ 191,052 + costs of offsite control

* *£ 19.94 /m length – Swales within sandstone soils*

** *£ 232.00 /m – Remove kerbstone, and replace with kerb drainage unit (assume 1 every 20 m of swale)*

Off site control proposals 1, 2 and 3 – Costs were generated (Table 6.13) for the infiltration component of the Chapter 4 'off-site' proposals (Infiltration trenches, Porous pavements, and Infiltration basins). These costs were compiled using the primary unit costs from Table 6.1 and Table 6.9, and additional costings presented in Appendices 6B, 6E and 6F. Three scenarios, which related to the three different conveyance strategies highlighted above, were explored for each of these 'off-site' control devices.

The combined costs of these off-site proposals with the corresponding conveyance proposal are presented within the next Section (Table 6.14), alongside a summary of the other Meanwood SUDS proposals highlighted within Chapter 4.

6.4.3. Summary

Table 6.15 presents the construction costs that were generated for each of the Chapter 4 technology specific SUDS proposals for Meanwood. This table also presents the amount of impervious area that was disconnected by each proposal, and its subsequent level of performance. It should be noted that the system performance indicators generated in Chapter 5 were used for this analysis.

Table 6.14 Costs associated with Meanwood offsite controls

Technology	Contributory area (m^2)	Required dimensions	Unit costs (£ / item)	Total cost (£)
Infiltration trenches *(See Appendix 6B)*	**1.8998 ha (Roofs)** 246 properties	720 x 1 x 3 m (l x w x d)	£181.16 /m	£130,433
	2.8860 ha (Paved)	1090 x 1 x 3 m (l x w x d)	£181.16 /m	£197,461
	4.7858 ha (Both) (1.8998ha + 2.8860ha)	1800 x 1 x 3 m (l x w x d)	£181.16 /m	£326,088
Porous pavement *(See Appendix 6E)*	**1.8998 ha (Roofs)** 246 properties	77 x 77 x 0.2* m (l x w x d) Area = 5929 m^2	63.33 £ /m^2	£375,484
	2.8860 ha (Paved)	95 x 95 x 0.2* m (l x w x d) Area = 9025 m^2	63.33 £ /m^2	£571,553
	4.7858 ha (Both) (1.8998ha + 2.8860ha)	123x 123x 0.2* m (l x w x d) Area = 15129 m^2	63.33 £ /m^2	£958,120
Infiltration basin *(See Appendix 6F)*	**1.8998 ha (Roofs)** 246 properties	50 x 50 x 0.5** m (l x w x d) Area = 2500 m^2 Vol. = 1250 m^3	-	£63,983
	2.8860 ha (Paved)	65 x 65 x 0.5** m (l x w x d) Area = 4225 m^2 Vol. = 2112.5 m^3	-	£107,699
	4.7858 ha (Both) (1.8998ha + 2.8860ha)	80 x 80 x 0.5** m (l x w x d) Area = 6400 m^2 Vol. = 3200 m^3	-	£162,733

* Porous pavement: 0.2 m deep: (50 mm bedding layer + 150 mm sub-base).
Typical figures for permeable concrete block paving

** 0.5 m is the minimum design depth recommended within SUDS CD (UWTC, 2000)
CIRIA 156 design calculations that were conducted for these proposals indicated that a minimum depth of 0.3 m was required for each of these cases

None of the technology specific proposals presented in Table 6.15 achieve a level of coverage that is comparable with the Optimum Proposals highlighted in Chapter 4. This relates to the fact that it is unfeasible to completely serve either of the two optimum infiltration-based proposals (Optimum Proposals 1 and 2), using a single technology type.

Table 6.15 presents construction costs in both direct, and unit terms (i.e. per square metre of impermeable area disconnected).

It is evident from Table 6.15 that Source Control Proposal 1 represents the cheapest of the infiltration options reviewed in this Section (i.e. at 5.90 £/m^2 in terms of unit costs). However, this approach is only applicable to the 3.022 ha roofed areas contained in Meanwood's Sandstone region.

It should be noted that, although infiltration basins were demonstrated to be the cheapest retrofit source control SUDS by the representative surface area investigations presented in the last Section, they were not considered as appropriate for source control applications in the Meanwood catchment due to space restrictions in residential plots.

Table 6.15 Summary of the costs

Option			Spill Volume (m^3)	Paved IMP area Disconnected (ha)	Roofed IMP area Disconnected (ha)	Combined IMP area Disconnected (ha)	Cost	Cost / Disconnected m^2 of IMP area
Optimum proposal 1			383	3.423	3.022	**6.445**	-	-
Source control proposal 1	Soakaways* to every roof within sandstone region		831	0	3.022	**3.022**	£178,183	5.90
Source control proposal 2	Construction of 1065 m of infiltration trenches region to serve 86 properties within sandstone region		1236	0	0.473	**0.473**	£111,478	23.57
Optimum proposal 2			-	6.369	5.583	**11.952**	-	
Swales Option A	Swales to all grassed verges (Roofs only)	**Offsite control proposal:** 1) Infiltration trenches 2) Porous pavement 3) Infiltration Basin	1010 1010 1010	0 0 0	1.900 1.900 1.900	1.900 1.900 1.900	£264,297 £509,348 £197,847	13.91 26.81 10.41
Swales Option B	Swales to all grassed verges (Paved areas only)	**Offsite control proposal:** 1) Infiltration trenches 2) Porous pavement 3) Infiltration Basin	879 879 879	2.886 2.886 2.886	0 0 0	**2.886** **2.886** **2.886**	£352,953 £727,045 £263,191	12.23 25.19 9.12
Swales Option C	Swales to all grassed verges (Both paved and roofed)	**Offsite control proposal:** 1) Infiltration trenches 2) Porous pavement 3) Infiltration Basin	619 619 619	2.886 2.886 2.886	1.900 1.900 1.900	**4.786** **4.786** **4.786**	£517,140 £1,149,172 £353,785	10.81 24.01 7.39

It is considered that these off-site scenarios may be applied to 2.886 ha of paved area and/or 1.900 ha of roofed area within the Meanwood catchment. Infiltration basins are the cheapest, in terms of unit costs, of the three off-site scenarios options considered.

Chapter 7 explores the issues associated with compiling multi-technology retrofit SUDS proposals. This process obviously requires a decision to be made as to which SUDS technology takes precedence, when two or more devices are considered viable for a particular location. In most cases it is likely that this decision will be determined by cost effectiveness. An indication of cost effectiveness is presented in the last column of Table 6.15 (i.e. the unit cost to disconnect one m^2 of IMP area) for each of these technology specific proposals.

It is interesting to note that Source Control Proposal 1 is cheaper than all of the off-site based proposals. This observation supports the 'treatment train concept' (Chapter 2), in which source-based solutions would be preferred to the use of off-site controls. However, the cost of disconnecting 1 m^2 of IMP using Source Control Proposal 2 (infiltration trenches) is more than four times that associated with Source Control Proposal 1 (soakaways), and perhaps surprisingly considerably more expensive than many of the off-site controls. This reflects the fact that this approach requires its own conveyance network (i.e. to convey runoff from the roof to the property's boundary with the field, with the infiltration trench is located). It might be fair to consider Source Control Proposal 2 as an off-site approach. However, for the purposes of this study this proposal was considered a source control approach because the length of the conveyance devices it required were much smaller than those required for the other off-site control proposals. This factor means that care should be exhibited when applying these observations as a blanket guide.

None of the technology specific proposals explore the application of retrofit storage-based SUDS to the Meanwood catchment, or the associated costs. This relates to the fact that the simplistic modelling techniques employed for optimum and best-case infiltration SUDS proposals in Chapter 5 (Section 5.3.2), were not deemed appropriate for storage-based, or integrated (infiltration and storage-based) SUDS proposals. It was considered that these SUDS proposals should be modelled explicitly using the HydroWorks catchment model, but this avenue was not pursued due to the time constraints of this project.

However, it is envisaged that the technology specific proposals, and associated cost data, presented in this Chapter for infiltration/conveyance SUDS could be used as a starting point that could be supplemented with storage-based SUDS. A similar concept was presented in Chapters 4 and 5, in which Optimum Proposals 3 and 4 both consider the use of supplementary SUDS storage in addition to the infiltration SUDS considered in Optimum Proposals 1 and 2. The costings procedures associated with storage-based devices (e.g. ponds and tanks) are already well established, and presented explicitly in the SPONS (2001) publications. Further details of the unit costs of storage SUDS are presented in Appendices 6A, 6F and 6H.

It should be recognised that the costings presented in this Chapter largely relate to the primary costs associated with construction, and do not reflect more long term (whole-life) cost issues such as maintenance and replacement, and need to address catchment-wide implications of surface disconnection. It is worth noting that reduced sewer flows and volumes to treatment may have important implications in some catchments, either for operational performance or cost or both. The importance of whole life costs to the assessment of retrofit SUDS is acknowledged, but the subject is not directly addressed here due to the time constraints of this research project. It is therefore recommended that further work be undertaken to more fully explore these whole life cost issues. It should be noted that some cost data appropriate to the maintenance of SUDS is presented in the SPONS guides (2001), including items such as grass-cutting. However, there are other SUDS maintenance costs (e.g. costs associated with cleaning filter-drains or porous pavements) that may need to be derived by other means.

The following Chapter presents a decision-making framework that was developed for the design of retrofit SUDS using the methodologies outlined within this and preceding Chapters. This decision-making framework is subsequently reapplied to the Meanwood catchment, and used to generate a multi-technology retrofit SUDS proposal.

7 RETROFIT SUDS EVALUATION – DECISION MAKING FRAMEWORK

7.1 INTRODUCTION

7.1.1 Background

The design of cost-effective SUDS-based solutions for problem urban catchments is not a straightforward process. The design work conducted in conjunction with the Gipton and Meanwood case studies (highlighted in previous Chapters) incorporated the use of site visits and map-based investigations. Site visits were required to establish a number of catchment characteristics, such as the density of buildings and availability of public and private green space; and map-based investigations to determine other catchment characteristics, such as slope and geology/soil conditions. The data collected from these investigations underpinned the decisions as to which (if any) SUDS technologies were considered feasible – i.e. this data was assessed against SUDS design constraints (such as land-take, slope, infiltration capacity and local Building Regulations) in order to rule out inappropriate technologies.

However, the main problem with the approach outlined above is that the process of assembling the relevant information and designing the SUDS-based rehabilitation works was time-consuming and not well structured. Although the case study catchments were both found to be amenable to SUDS-based solutions, considerable time might have been spent in assembling information only to discover that SUDS-based proposals were basically unsuited to the catchment.

Added to these problems is the fact that the UK designers currently lack both experience and guidance in relation to the financial costs associated with SUDS technologies. The importance of financial issues to the design of SUDS has been highlighted by previous UK design guidelines (CIRIA 124, 1992; CIRIA 522, 2000). However, none of these publications have attempted to quantify the costs associated with these devices.

It is likely that these high information requirements, and the uncertainty surrounding the design and cost of retrofit SUDS, may be discouraging practitioners from considering such proposals, even where they might represent a cost-effective alternative to conventional rehabilitation procedures.

This Chapter presents a 'decision making' framework/methodology that is intended to address some of these problems. It is envisaged that this framework could be used as a design tool to assist designers/engineers compile both retrofit SUDS and integrated (SUDS/conventional) solutions for comparison with conventional storm water management solutions. This methodology builds upon the experience attained through the case studies and investigations that have been conducted in conjunction with this thesis. The methodology also draws from other independent investigations that were reported in Chapter 2 (Literature Review) and

technical guidance provided in relevant UK design guidelines (CIRIA C522, 2000; CIRIA 124, 1992; CIRIA 156, 1996; BRE 365, 1991).

7.1.2 Structure of Chapter

This Chapter consists of three distinct Sections. The first Section presents the retrofit SUDS decision-making tool, and outlines the basic rationale upon which this is based. The second part explores the present and future contexts in which this tool might be used; and the last Section applies this tool in the context of the Meanwood case study catchment.

7.2 PRESENTATION & JUSTIFICATION OF PROPOSED DECISION-MAKING TOOL

7.2.1 Conceptual basis for Proposed decision-making tool

The decision-making tool presented in this Chapter provides a crude framework for compiling and ranking alternative SUDS-based options. This framework is based upon four key concepts/criteria that are considered to affect the design of retrofit SUDS:

1. The ***Type of urban surface*** to which the SUDS device is to be applied
2. The ***Surface water management train*** concept – i.e. whether the SUDS device is intended for use as a source control, conveyance structure or an off-site control
3. The ***Mode of operation*** by which the SUDS device manages stormwater runoff
4. The **Costs** associated with the SUDS device.

The following paragraphs highlight the importance of each of these criteria to the viability of retrofit SUDS, and way in which they were incorporated into the proposed decision making tool.

Type of urban surface – The case study investigations indicated that the viability of retrofit SUDS might be strongly influenced by the type of urban surface to which they are applied. For instance, it has been speculated (Sections 4.2.1.1 and 4.2.12) that the application of retrofit SUDS schemes to large-scale contributory surfaces, such as institutional roofs or car parks, would be easier to promote, implement, manage and monitor than alternative schemes intended for smaller contributory surfaces, such as residential roofs.

For the purposes of this study it was considered that all urban catchments could be broadly sub-dived into four impermeable surface types:

1. ***Institutional roofs*** – hospitals, schools, offices, churches, (for the purposes of this study any single roof larger than 200 m^2 is defined as being an institutional roof)
2. ***Car parks and other lightly trafficked paved areas*** – such as pedestrianised streets and school playgrounds
3. ***Residential roofs*** – for the purpose of this study any single roof smaller than 200 m^2 is defined as being a residential roof
4. ***Roads and all other well trafficked paved areas***

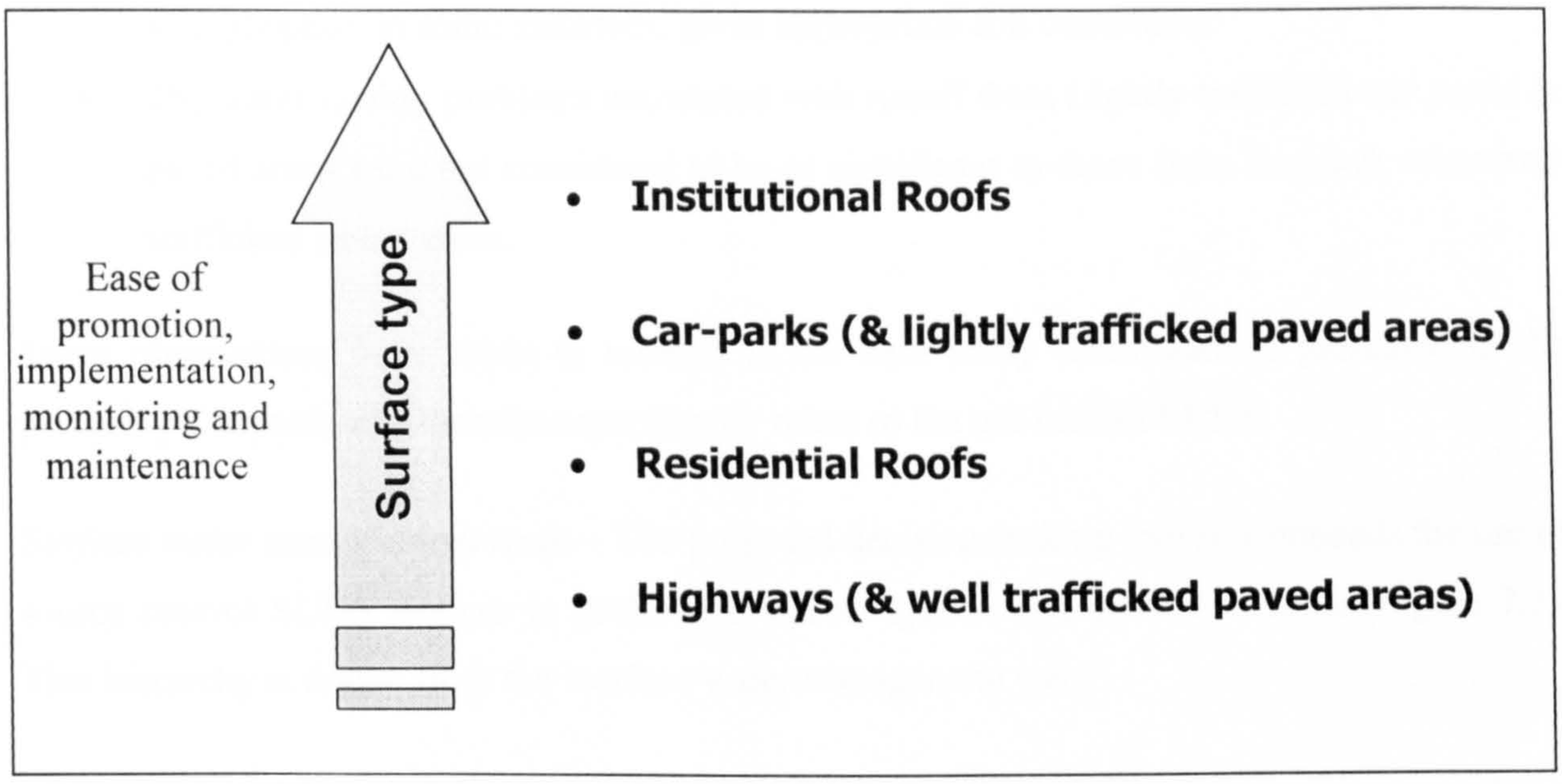


Figure 7.1 Preferred ranking of impermeable urban surface types

The proposed decision-making tool recommends a preferred ranking of these impermeable surface types, in relation to their perceived suitability for use in conjunction with retrofit SUDS devices (Figure 7.1). The tool recommends the use of retrofit SUDS devices in conjunction with institutional roofs in preference to car parks, then residential roofs and finally highways. The rationale that supports this recommended hierarchy follows:

- The application of retrofit SUDS to *Institutional Roofs* and *Lightly trafficked car parks/other paved areas* was considered to be preferential to their use with other surface types. This relates to the assumption that a few large-scale schemes would be easier to implement, manage and monitor than many small-scale schemes (Sections 4.2.1.1 and 4.2.12).
- *Institutional Roofs* were considered to be more appropriate for use in conjunction with retrofit SUDS than *Lightly trafficked car parks/other paved areas.* This relates to the additional water quality problems associated with paved runoff. Additional pre-infiltration treatment facilities are usually required for runoff infiltrated from paved areas. Furthermore, storage facilities that receive runoff from paved areas often develop sedimentation/water quality problems.
- The benefits of applying source control SUDS to *institutional*, rather than *residential*, properties were discussed previously (Sections 4.2.1.1 and 4.2.12). These largely relate to the comparative ease of construction, monitoring and maintenance associated with their application in an Institutional rather than a Residential context.
- The use of retrofit SUDS in association with *Residential roofs* was considered to be less viable than for *Institutional roofs* and *car parks* due the inherent logistical problems associated with managing/monitoring such schemes, and the limited opportunities for

introducing large infiltration or storage facilities. However, soakaways might constitute a valid option in some instances, given appropriate soil conditions.

- The water quality problems associated with runoff from Lightly trafficked *car parks* & paved areas were not considered to be as significant as those from *Roads* & other well trafficked paved areas.

These observations were made in relation to the case study investigations presented in the preceding Chapters, and therefore specifically relate to the use retrofit SUDS.

Surface water management train – The proposed decision-making tool recommends the use of source control SUDS devices in preference to conveyance and off-site controls (Figure 7.2). This hierarchy is drawn from the 'surface water management train'.

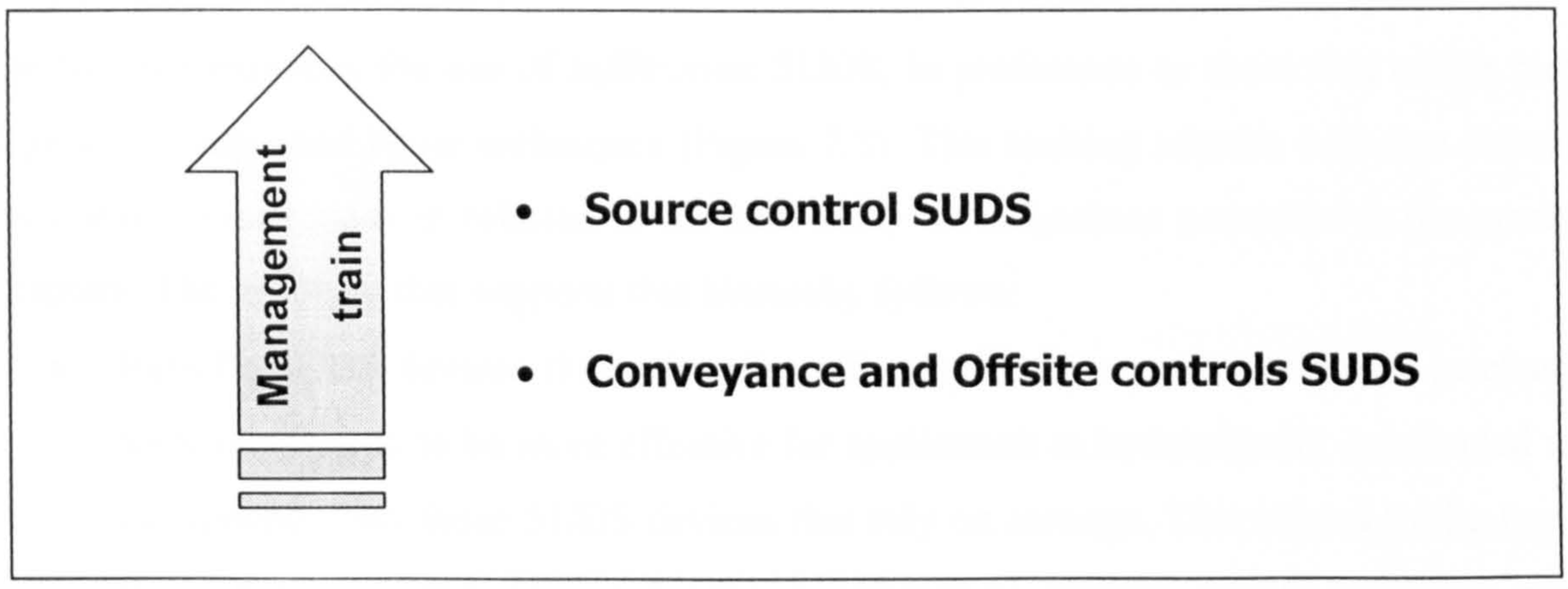


Figure 7.2 Preferred ranking of SUDS according to management train concept

The 'surface water management train' concept was originally developed as part of the SUDS design manuals (CIRIA, 2000), and illustrates how integrated SUDS schemes might be used to alleviate/eliminate flooding/pollution problems, and gives consideration to a number of sustainability criteria, including cost. It also demonstrates how SUDS technologies can be used in series to progressively change the quality, and/or quantity, of surface runoff passed down through the urban drainage catchment. Further details of the 'surface water management train' concept are presented in Section 2.5.10.1.

Mode of operation – The classification of SUDS according to their function (mode of operation) is not a new concept (CIRIA Report 124, 1992; EA/SEPA, 1997). However, the proposed decision-making tool develops this concept into a preferred '*Mode of operation*' ranking scheme for retrofit SUDS that is purely based upon their primary hydraulic mechanism (i.e. the main way in which they provide hydraulic control of peak storm runoff flows).

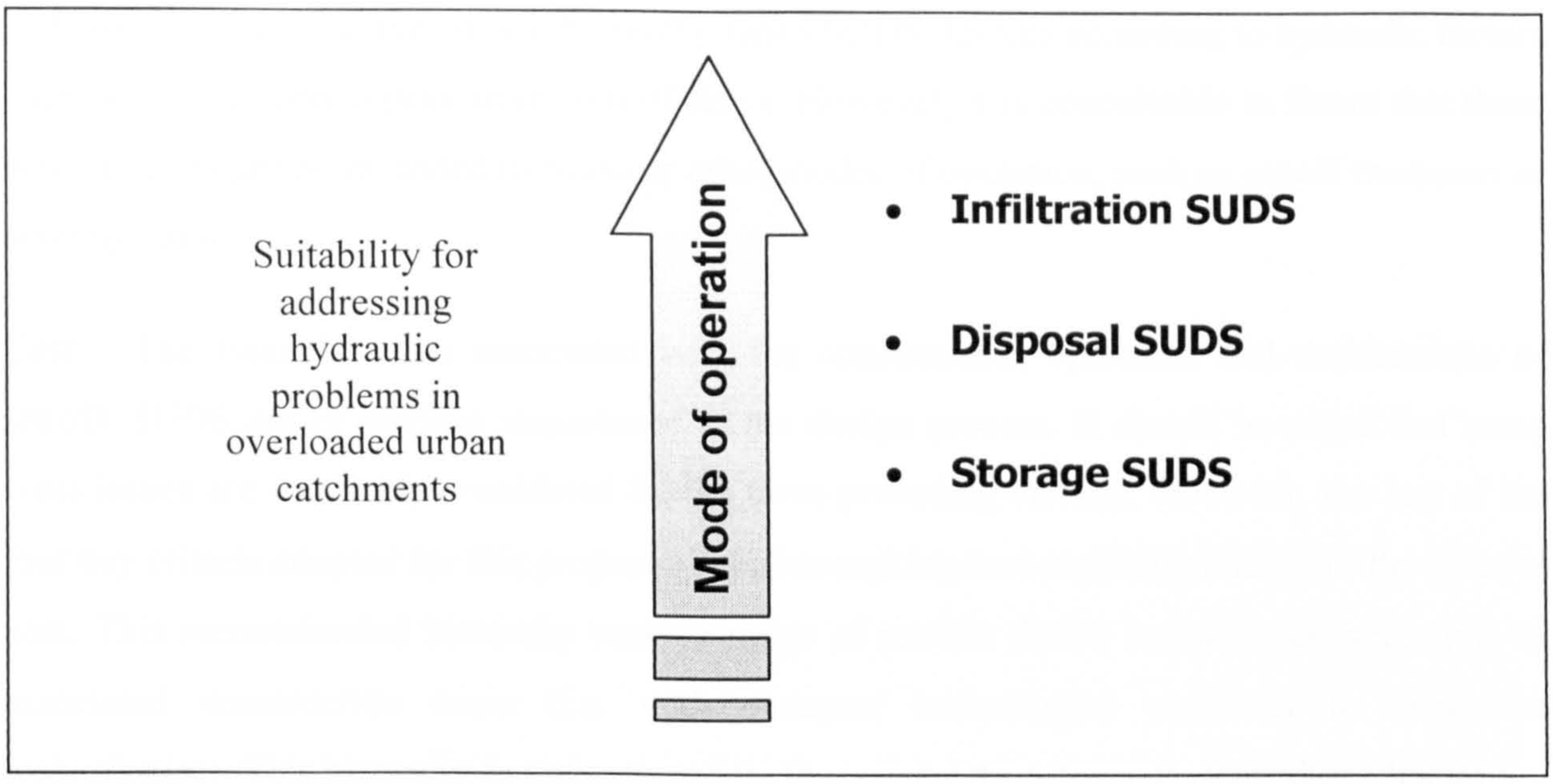


Figure 7.3 Preferred ranking of SUDS according to mode of operation

The tool recommends the use of *infiltration* SUDS, in preference to those that utilise *surface disposal*, *storage* and *reuse* techniques (Figure 7.3). This ranking scheme was also developed from observations made in relation to the case study investigations presented in the preceding Chapters. The rationale that supports this hierarchy follows:

- Retrofit SUDS devices that primarily utilise *Infiltration* and/or *Disposal* mechanisms were considered to be more effective for application to hydraulically overloaded urban catchments than those SUDS devices that rely on *storage*. This relates to the fact that the *Infiltration* and *Disposal* options effectively remove runoff from the surface water/urban drainage system, rather than attenuating it within the surface water system.
- *Infiltration*, *Disposal* and *Storage* SUDS options were all considered to be preferable to *Reuse* options due to high economic costs associated with most reuse options. It is acknowledged that less complex reuse options (such as schemes that reuse storage roof-water for irrigation purposes) may be more economically viable than other more complex systems. However, unless these schemes include large storage facilities (as described for the 'storage' option) it is likely that they will have a very limited affect on reducing/eliminating hydraulic problems within overloaded urban catchment (i.e. their use will have limited effect on peak stormwater flows).
- The *Infiltration* and *Local Disposal* options represent slight pollution threats to groundwater and surface water resources respectively, and as such may be subject to discharge restrictions within some sensitive locations (such as Source Protection Zones, SPZs – as described in Section 2.5.5.5). However, *Infiltration* options are considered to be lower risk than surface *Disposal,* due to the inherent water polishing effects associated with the infiltration process. Furthermore, it is considered that urban catchments will generally contain more opportunities for *Infiltration* devices than *Local Disposal* techniques.

It should be noted that the current hierarchy ranks SUDS devices according to hydraulic factors – i.e. how they control peak storm runoff flows. However, it is conceivable in future that these procedures might be extended to consider other modes of operation, such as runoff treatment or amenity value.

Cost – The financial costs associated with the construction, operation and maintenance of retrofit SUDS are of obvious importance to the design process. It should be noted that some costs issues are implicitly considered by the three preceding criteria. However, the last of the four key criteria adopted for this proposed decision-making tool explicitly addresses the issue of cost. This recommended hierarchy ranks a range of retrofit SUDS technologies according to associated construction costs (i.e. with cheapest technologies preferred to expensive technologies). This hierarchy is underpinned by the construction costs developed in Chapter 6.

7.2.2 Meta-hierarchy

The order in which these four criteria are presented above corresponds to the order in which they are implemented in the proposed decision-making tool. This meta-hierarchy was structured/ranked in terms of the level of detail/complexity associated with each of the four sub-hierarchies (**surface type, water management train, mode of operation** and **cost**).

The first hierarchy (**surface type**) provides a crude indication as to which impermeable surface types are considered most appropriate for the application of retrofit SUDS. The **management train** hierarchy recommends a preferred order for generic SUDS groupings (source controls, conveyance and off site controls) for application to the explored surface type. The **mode of operation** hierarchy presents a recommended set of rankings for different SUDS approaches, in relation to their primary hydraulic function. This ranks SUDS approaches in terms of those considered most appropriate for addressing the hydraulic problems associated with overloaded sewer systems. The final hierarchy uses the **costs** developed in Chapter 6 to recommend a preferred ranking scheme for specific SUDS technologies.

The fact that these hierarchies are ranked in terms of complexity (i.e. in terms of the catchment data required to perform the assessment) means that the initial top hierarchies may be used to perform crude viability assessments on a catchment. These crude investigations would indicate whether it was worth pursuing more detailed studies, which utilise subsequent hierarchies to explore specific SUDS groupings, mechanisms or technologies.

It should be noted that the proposed decision-making tool provides a crude framework for generating and ranking prospective SUDS options. This tool should not be viewed as a prescriptive set of design guidelines, but more as a flexible/adaptable set of procedures to assist designers compile and evaluate alternative SUDS-based options for problem catchments. It is not envisaged that designers would always adopt SUDS schemes that fully comply with the ranking schemes presented in this tool, as characteristics/circumstances that relate to specific

catchments may mean that designers have to adopt their own criteria for the design/comparison of alternative SUDS-based proposals.

7.2.3 Proposed decision-making flowcharts

Decision-making flowcharts were developed for each of the four main urban surface types highlighted in the previous Section. It is recommended that these flowcharts be employed in the following order: *Institutional roofs, car parks, residential roofs* and finally *highways*, as this corresponds to the preferred ranking scheme highlighted in the previous Section.

The following Sections present the decision-making flowcharts that were developed, from the previous discussions, for each of the four main urban surface types. These Sections contain basic guidance on how these flowcharts should be used. Issues that are common to all four surface types are discussed at length with respect to the 'institutional roofs' flowchart (i.e. the first of the four surface types discussed within the following Sections). Other issues that are more specific to individual surface types are discussed within the relevant Sections.

7.2.4 Decision making flowchart – Institutional roofs

This Section presents the 'decision-making' flowchart that was developed for the design of retrofit SUDS for application to Institutional roofs. This methodology was developed from the concepts/discussion presented in the previous Section.

The initial flowchart question: *'Are **roofs** connected to foul/combined system?'* is an important one, in so much that if the investigated surface type, in this case 'institutional roofs', is not connected to the local sewer system then there is little value in exploring their use in conjunction with retrofit SUDS.

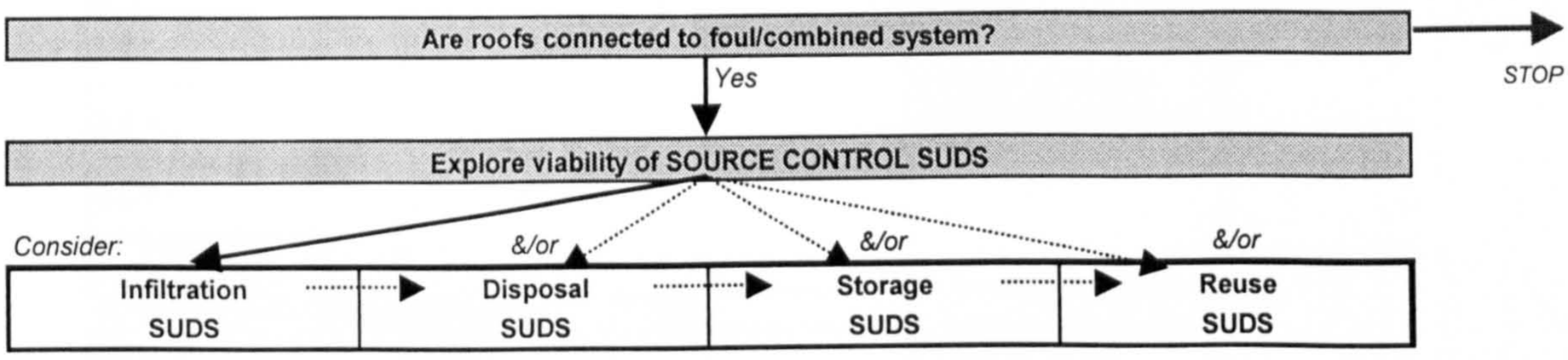


Figure 7.4 Outline of flowchart methodology for institutional roofs (Source control sub-section: Part 1)

7.2.4.1 Source-control SUDS sub-section

The second statement box recommends that the viability of source-control SUDS is explored. This statement box provides the heading for the first of three sub-sections considered in this flow-chart, the other two relate to the viability of conveyance and off-site controls. Source controls were considered first as their use was considered to be preferential to both conveyance and off-site control SUDS (see previous Section).

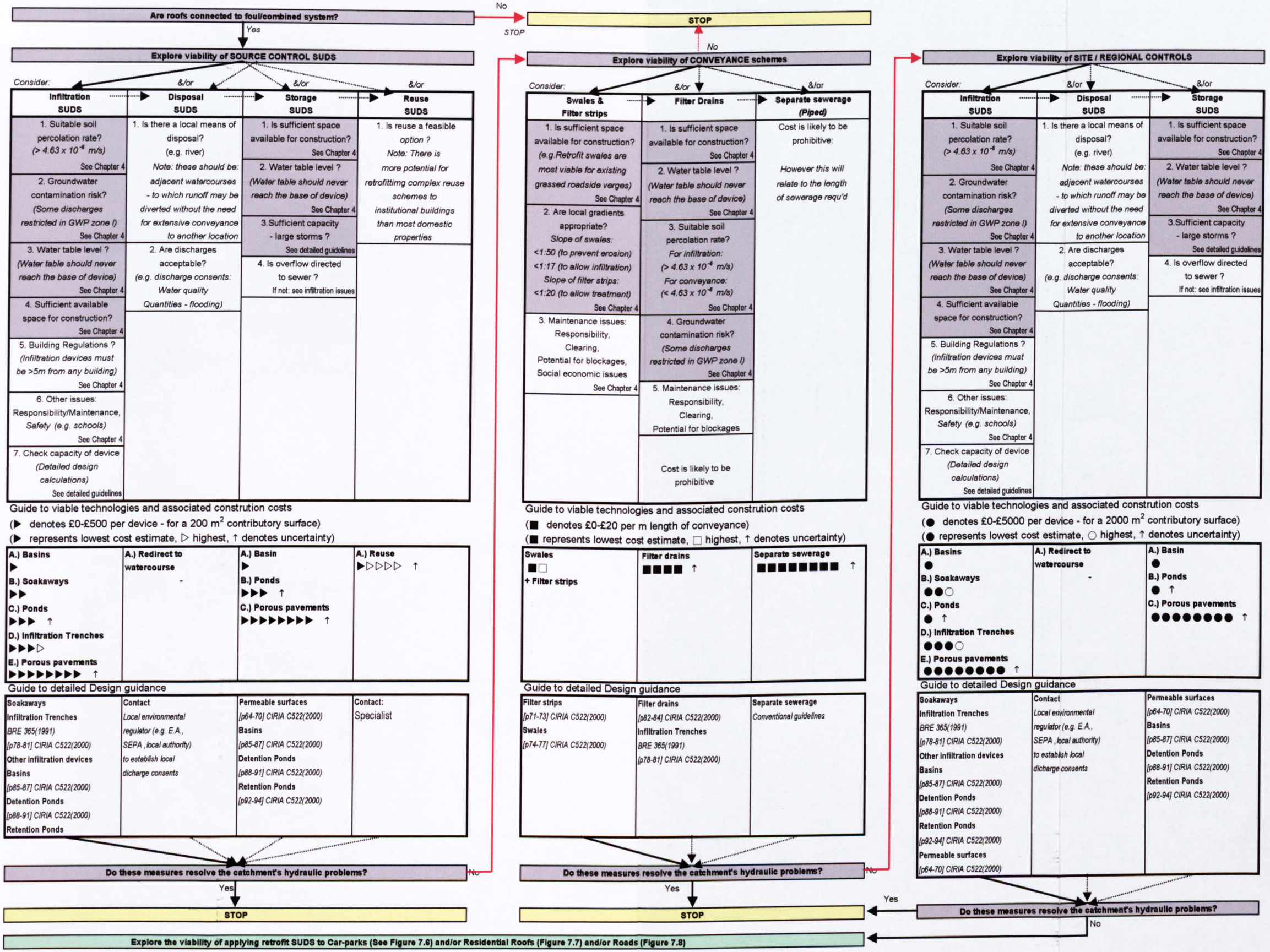


Figure 7.5 Proposed decision-making flowchart for the design of retrofit SUDS (with respect to Institutional Roofs)

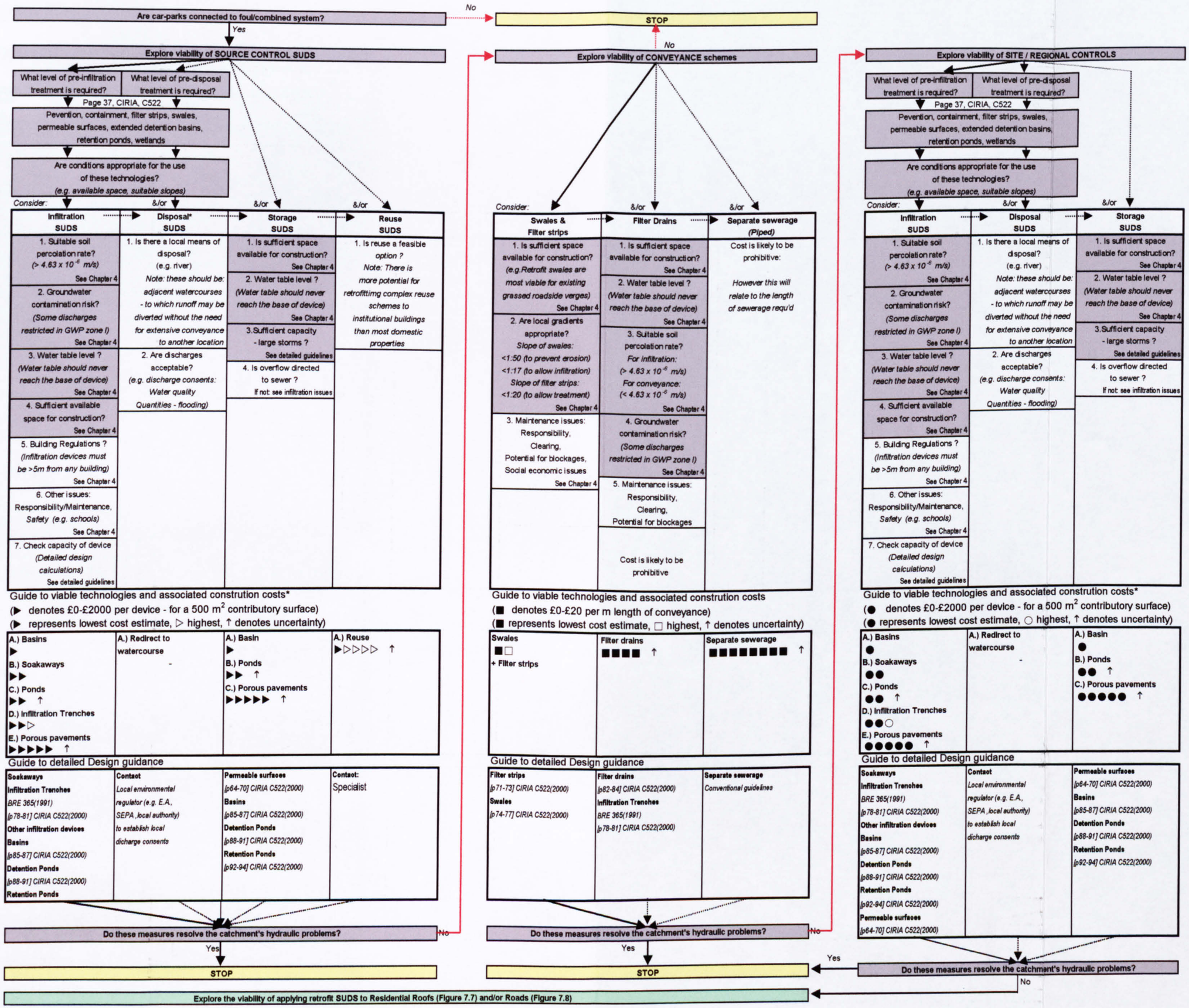


Figure 7.6 Proposed decision-making flowchart for the design of retrofit SUDS (with respect to Car parks)

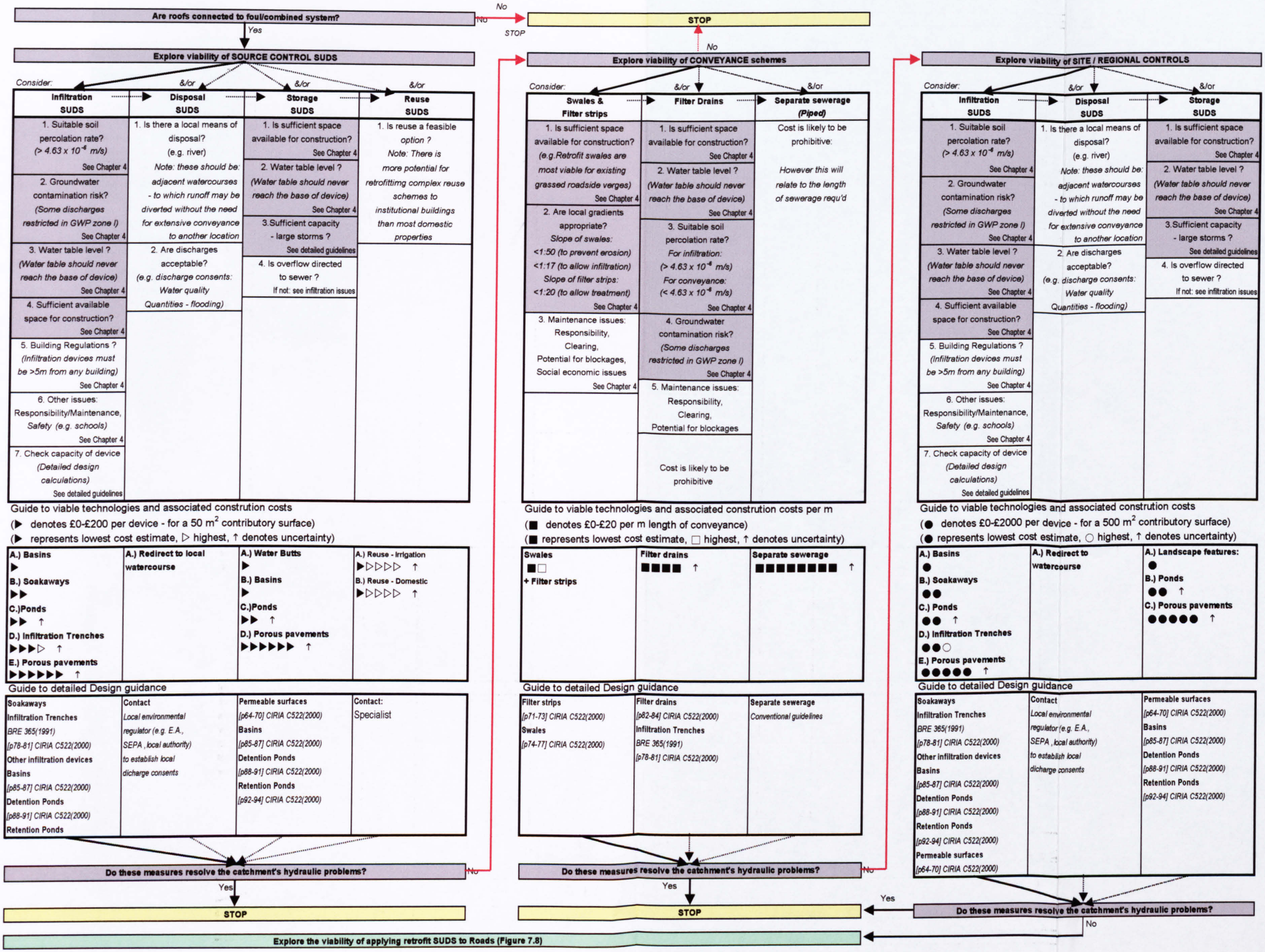


Figure 7.7 Proposed decision-making flowchart for the design of retrofit SUDS (with respect to Residential Roofs)

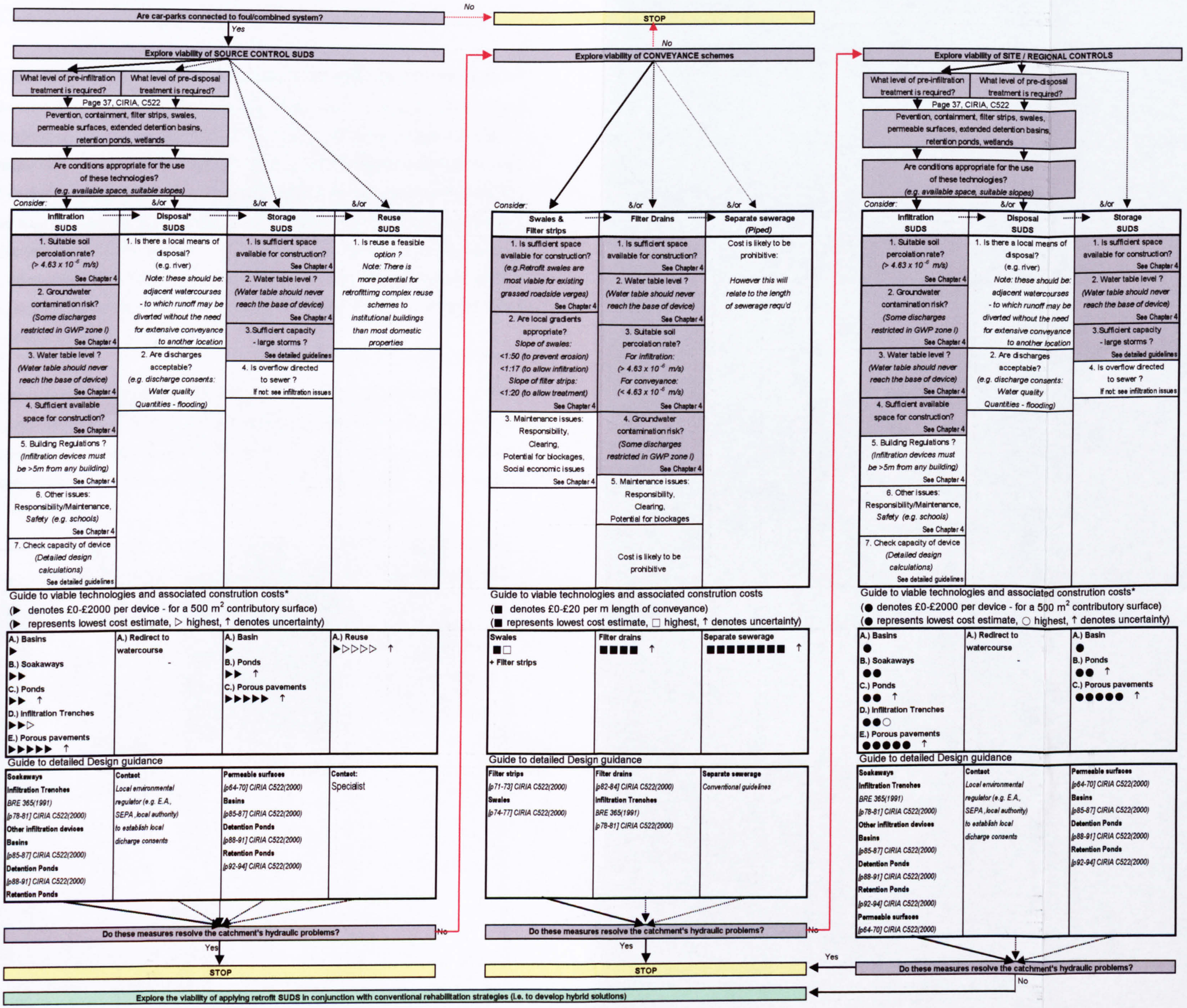


Figure 7.8 Proposed decision-making flowchart for the design of retrofit SUDS (with respect to Roads)

The significance of the arrow styles used for this, and other Sections of the flowchart methodology are explained below:

Bold arrow lines – indicate the preferred sequence for investigations to assess the viability of retrofit SUDS.

Feint arrow lines – denote alternative sequences, which may be pursued if the favoured path is not possible due to catchment constraints. For example in the case of source controls, the preferred procedure advocates the use of *infiltration devices* above *disposal, storage or reuse*. However, for instances when is it is not feasible to apply retrofit infiltration devices to all 'institutional roofs' under investigation, the next best approach would be to explore the use of disposal devices, and then storage techniques. It is apparent that this 'alternative path' approach may be used to derive integrated SUDS solutions (i.e. with some 'institutional roofs' served by infiltration devices, other roofs, that were not considered appropriate for infiltration, served by disposal techniques, and the remainder that were not considered appropriate for infiltration or disposal, served by storage techniques).

The next part of the source-control sub-section (Figure 7.9) presents design constraints for each of the four source-control SUDS groupings. These constraints are presented in terms of physical and non-physical constraints (i.e. physical constraints are denoted by dark shading). All of these constraints have been discussed in earlier Chapters – see flowchart for the relevant cross-references.

Infiltration SUDS	Disposal SUDS	Storage SUDS	Reuse SUDS
1. Suitable soil percolation rate? (> 4.63 x 10^{-6} *m/s*) See Chapter 4	1. Is there a local means of disposal? (e.g. river) *Note: these should be: adjacent watercourses - to which runoff may be diverted without the need for extensive conveyance to another location*	1. Is sufficient space available for construction? See Chapter 4	1. Is reuse a feasible *option? Note: There is more potential for retrofittimg complex reuse schemes to institutional buildings than most domestic properties*
2. Groundwater contamination risk? *(Some discharges restricted in GWP zone I)* See Chapter 4		2. Water table level? *(Water table should never reach the base of device)* See Chapter 4	
3. Water table level? *(Water table should never reach the base of device)* See Chapter 4	2. Are discharges acceptable? *(e.g. discharge consents: Water quality Quantities - flooding)*	3.Sufficient capacity - large storms? See detailed guidelines	
4. Sufficient available space for construction? See Chapter 4		4. Is overflow directed to sewer? If not: see infiltration issues	
5. Building Regulations? *(Infiltration devices must be >5m from any building)* See Chapter 4			
6. Other issues: Responsibility/Maintenance, *Safety (e.g. schools)* See Chapter 4			
7. Check capacity of device *(Detailed design calculations)* See detailed guidelines			

Figure 7.9 Outline of flowchart methodology for institutional roofs (Source control sub-section: Part 2)

It is intended that these design constraints could be used to help the designer rapidly assess whether these specific SUDS groupings are viable for the investigated surface.

Guide to viable technologies and associated construction costs

(▶ denotes £0-£500 per device - for a 200 m^2 contributory surface)

(▶ represents lowest cost estimate, ▷ highest, ↑ denotes uncertainty)

A.) Basins ▶ **B.) Soakaways** ▶▶ **C.) Ponds** ▶▶▶ ↑ **D.) Infiltration Trenches** ▶▶▶▷ **E.) Porous pavements** ▶▶▶▶▶▶▶▶ ↑	**A.) Redirect to watercourse** -	**A.) Basin** ▶ **B.) Ponds** ▶▶▶ ↑ **C.) Porous pavements** ▶▶▶▶▶▶▶▶ ↑

Guide to detailed Design guidance

Soakaways **Infiltration Trenches** *BRE 365(1991)* *[p78-81] CIRIA C522(2000)* **Other infiltration devices** **Basins** *[p85-87] CIRIA C522(2000)* **Detention Ponds** *[p88-91] CIRIA C522(2000)* **Retention Ponds**	**Contact** *Local environmental regulator (e.g. E.A., SEPA ,local authority) to establish local dicharge consents*	**Permeable surfaces** *[p64-70] CIRIA C522(2000)* **Basins** *[p85-87] CIRIA C522(2000)* **Detention Ponds** *[p88-91] CIRIA C522(2000)* **Retention Ponds** *[p92-94] CIRIA C522(2000)*

Figure 7.10 Outline of flowchart methodology for institutional roofs (Source-control sub-section: Part 3)

The third part of the source-control sub-section (Figure 7.10) presents a list of viable retrofit SUDS technologies for each of the source control sub-groups. For example, the **Infiltration** group contains Basins, Soakaways, Ponds, Infiltration trenches and Porous pavements. These individual technologies are crudely ranked according to their estimated construction costs from Chapter 6 (i.e. cheapest first, most expensive last). It should be noted that for many of these technologies, the uncertainties associated with the calculation of costs, meant that high/low estimates are presented. The flowchart represents the comparative costs of each SUDS technology graphically, using a set of shaded and un-shaded symbols. The shaded symbols represent the lowest cost estimates for a given technology, and the un-shaded symbols, the highest cost estimates. See Chapter 6 for further details of the comparative costs of these SUDS technologies.

The final part of source-control sub-section references the detailed design guidance that may be sought, if the designer wishes to pursue with a more detailed investigation of a given SUDS technology (i.e. subject to whether the crude level of analysis indicates that a given SUDS technology is feasible).

7.2.4.2 Conveyance SUDS sub-section

The second sub-section of the flowchart explores the viability of SUDS conveyance schemes. This part of the flowchart should only be consulted after it has been established that source-controls cannot be used to serve all of the investigated surface type (i.e. institutional roofs in this case).

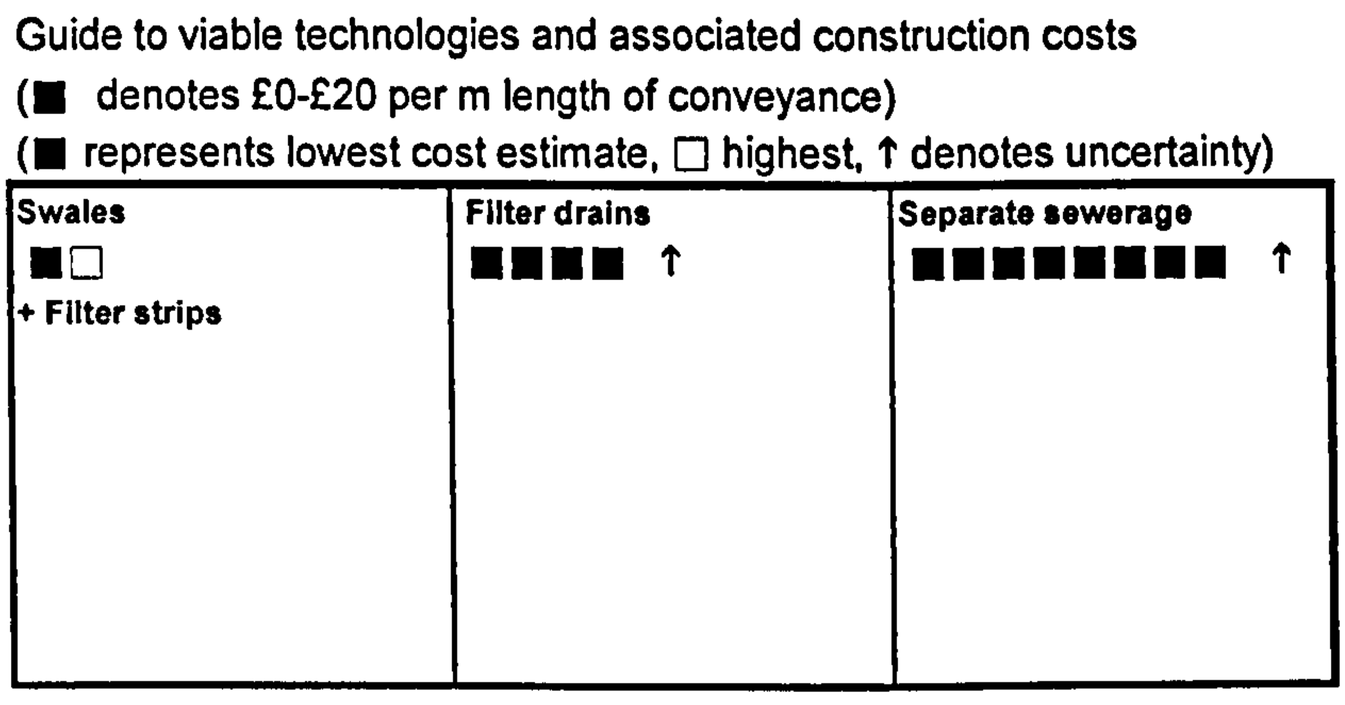


Figure 7.11 Outline of flowchart methodology for institutional roofs (Conveyance SUDS sub-section)

It is conceivable that in some catchments, it might be feasible to apply source controls to some institutional roofs and not others. However, it may be viable to drain those roofs not considered suitable for source controls, using conveyance systems and off-site controls. But whenever possible, it is favourable to pursue a source control approach rather than an integrated (source and off-site controls) approach, or a purely off-site approach – because source controls avoid the significant costs associated with conveyance and off-site facilities.

Costs – The comparative construction costs of alternative SUDS conveyance technologies indicate that swales are significantly cheaper than the alternative options. Therefore, it is assumed that in most cases swales represent the only practical retrofit conveyance technology, because filter drains and separate sewerage would appear to be prohibitively expensive. However, these devices might be appropriate for cases where runoff only needs to be conveyed relatively short distances. Note: these swale construction costings were compiled for retrofit application to unpaved sites. It is envisaged that corresponding costs for retrofit applications to existing paved sites would be significantly higher.

Constraints – Catchment slope is of particular significance to the viability of swales, since to prevent erosion their longitudinal slopes should not exceed 1:50 (see Section 2.5.2). Sufficient urban space is another important factor, because swales are considered to be most viable for retrofitting to existing grassed areas (i.e. due to issues of available space and economic factors). The other main constraints assumed to affect the viability of swales are similar to those described previously in relation to source control storage facilities.

Once again, generic constraints are presented for each alternative SUDS conveyance options. These constraints are also presented in terms of physical and non-physical constraints

(i.e. with physical constraints denoted by dark shading), and relate to previous Chapters (see flowchart for the relevant details).

It is intended that these flow-charts provide a rough indication to the viability of retrofit conveyance SUDS within a given catchment/part of a catchment. If this crude analysis indicates that a given SUDS technology is viable then more detailed design work may be undertaken in accordance to the relevant UK guidelines – cited at the bottom of the sub-section.

Note: The viability of retrofit conveyance schemes was considered prior to that of off-site facilities, as off-site devices are not viable without a means of conveying runoff to them.

7.2.4.3 Offsite controls

The third sub-section of the flowchart procedure explores the viability of off-site control SUDS. The main issues assumed to affect the viability of off-site controls are very similar to those described previously for source controls. The main differences between the two applications are those associated with scale, maintenance and ownership.

Larger scale off-site facilities obviously require large urban spaces for their construction (e.g. parkland, open land, sports fields). The absence of such available spaces means that large-scale off-site facilities are impracticable.

In terms of maintenance and ownership, off-site facilities are likely to be easier to promote, monitor and maintain than local source controls based within residential proposals. For example, it is envisaged that 50 source-control infiltration devices, at individual residential properties, are likely to be more difficult to maintain/monitor than a single corporate facility of equal capacity.

Similar flow-chart procedures were generated for the three remaining impervious urban surface types: Car parks; Residential Roofs; and Roads. Specific issues that relate to these surface types are discussed within the following Sections.

7.2.5 Decision making flowcharts – Other surface types

7.2.5.1 Decision making flowchart – Car parks

The car parks flowchart adopted a similar set of procedures to those presented previously for institutional roofs. The main differences related to the fact that car park surfaces are likely to contain significantly more pollutants than roofs (i.e. largely due to debris and spillages from motor vehicles). Therefore additional runoff treatment facilities are generally required for runoff emanating from paved areas to account for these increased pollution risks. Treatment facilities, such as those described in Section 2.5, should be used in conjunction with infiltration devices and disposal methodologies to protect against the pollution of the local water-table/water-course. Furthermore, treatment facilities may also be used in conjunction with attenuation/storage structures to reduce sediment deposition/siltation problems.

7.2.5.2 Decision making flowchart – Residential Roofs

The 'residential roofs' flowchart, like the 'institutional roofs' procedure (Section 7.2.4), considers source controls prior to conveyance systems and off-site controls – this reflects the fact that the source controls are assumed to be generally cheaper and more sustainable than conveyance and off-site approaches.

The decision-making processes utilised for the design of retrofit SUDS for application to 'institutional roofs' were also adopted for 'residential roofs'. The only significant modifications relate to differences in construction costs of alternative technologies, brought about by economics of scale.

The proposed design procedures for conveyance systems are almost identical to those presented previously for institutional roofs.

7.2.5.3 Decision making flowchart – Roads & Other paved surfaces

The flowchart methodology adopted for this surface type was very similar to that proposed for car parks. Again, the main differences relate to issues of scale, available land, and increased pollutant levels.

7.3 CONTEXT OF USE/LIMITATIONS/ADAPTABILITY OF FRAMEWORK

7.3.1 Implementation of proposed methodology in current context

This Section outlines how the proposed decision-making (flowchart) tools, for the design of retrofit SUDS, might be incorporated into the wider context of the design of rehabilitation schemes for problem urban catchments. Figure 7.12 outlines a conceptual design strategy for the rehabilitation of hydraulically overloaded urban catchments, which utilises the proposed flowcharts presented in this Chapter, and existing guidance for both conventional and SUDS-based rehabilitation technologies. This strategy contains a two-stage design process that incorporates a simplistic, followed by more detailed, level of analysis.

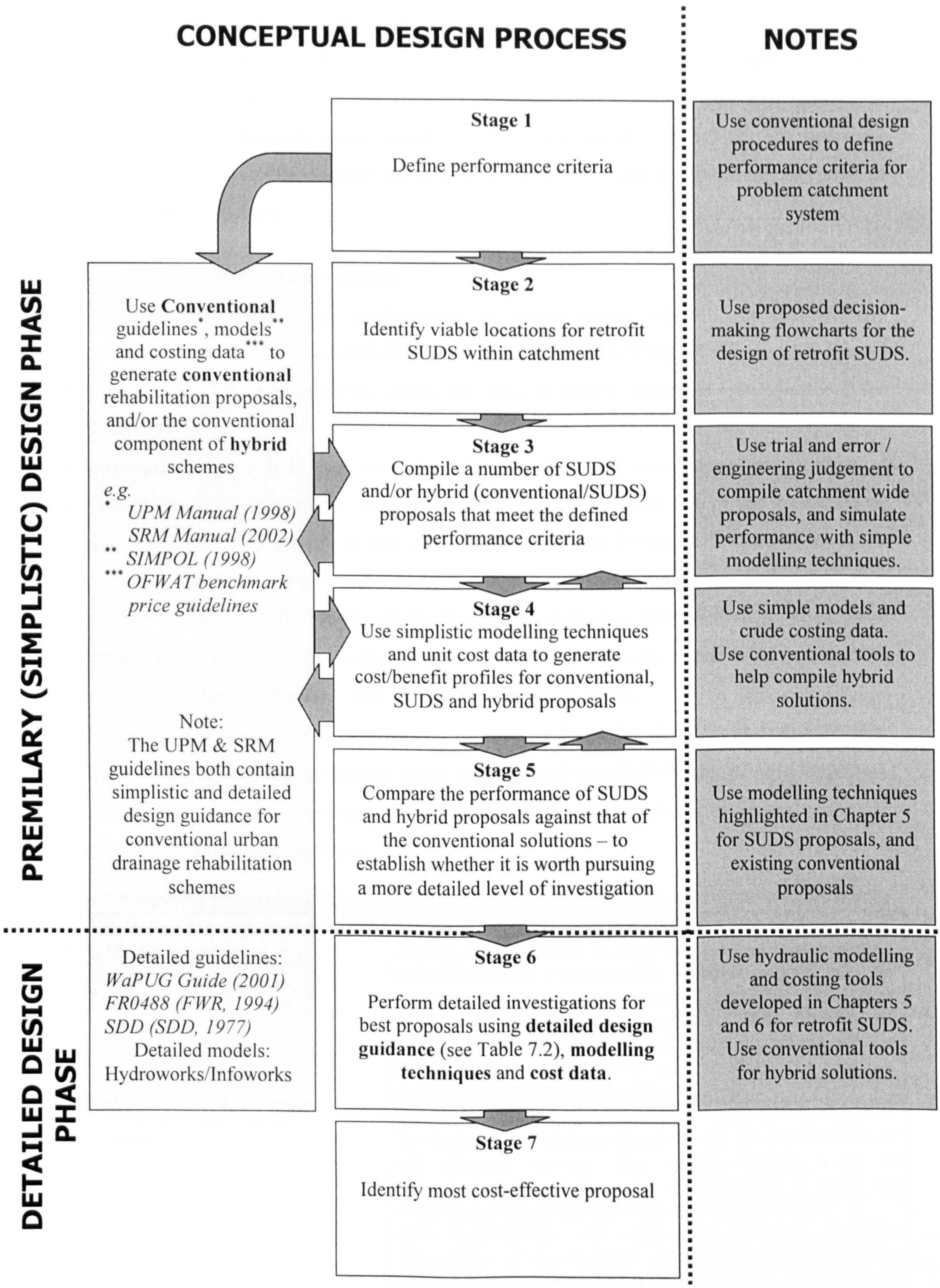


Figure 7.12 Conceptual design strategy (and notes) for the rehabilitation of hydraulically overloaded urban catchments

The following paragraphs provide an overview of each of the design stages presented in Figure 7.12. It should be noted that the decision-making tool presented in the earlier parts of this Chapter was developed to assist the designer to make well-informed choices/decisions in relation to stage 2 of the conceptual design strategy presented in Figure 7.12. The hydraulic modelling and costing methodologies presented in Chapters 5 and 6 respectively are also of relevance to Stages 3, 4 and 5.

Stage 1: Deriving performance criteria

It is envisaged that the design performance of rehabilitation schemes for hydraulically overloaded catchments would be derived from the UPM manual (FWR, 1998) for CSO related problems, and the SR manual (WRc, 2002) for other hydraulic problems (see Chapter 2 for further details).

Conventional design – It is also envisaged that the design of conventional components of sewer rehabilitation works would be conducted in accordance with one of the conventional strategies highlighted in Figure 7.12 and Table 7.1. Frameworks for the preliminary phase of the design of conventional sewer rehabilitation works are presented within the Urban Pollution Management Manual (FWR, 1994), and the Sewer Rehabilitation Manual (WRc, 2002). More detailed design guidance for conventional sewer rehabilitation works is presented in a number of technical guidelines (FR0488, 1994; SDD, 1977; WaPUG, 2001).

The hydraulic performance of conventional proposals could be simulated using simplistic (e.g. SIMPOL) or more detailed modelling tools (e.g. HydroWorks/InfoWorks or Win-Dap/Des). The costs associated with conventional rehabilitation proposals could be generated using the existing pool of financial experience.

Table 7.1 Review of existing design guidance for conventional sewer rehabilitation works

Urban Pollution Management Manual (FWR, 1994)	The UPM manual was compiled in 1994 with the intention of creating a cost-effective strategy that could adequately protect natural receiving waters against pollution, without the over provision of storage or treatment capacity. The UPM methodology has since been refined (1998). The second edition presents a similar set of design procedures for the development of cost-effective sewer systems, but adopts a more generic tone than the original manual.
Sewer Rehabilitation Manual (WRc, 2002)	The Sewer Rehabilitation manual (WRc, 2002) was compiled for designers and planners involved with the rehabilitation of UK sewerage systems. The manual contains a set of procedures and guidelines that were intended to assist the decision making process associated with such works. This methodology was originally developed for the comparison of conventional rehabilitation proposals (e.g. upgrading in-sewer storage, or CSO facilities). However, it is considered that the approach could be extended to include SUDS-based options.

Stage 2: Identify viable locations for retrofit SUDS within catchment

The proposed decision-making flowcharts outlined in this Chapter were developed to help designers/engineers identify potential opportunities for using retrofit SUDS in a problem

catchment. It is envisaged that these procedures would help the user compile a list of potential retrofit SUDS opportunities for the catchment. The hierarchal nature of the decision-making tool means that any list generated using these procedures should contain some inherent indication of cost-effectiveness – i.e. with most cost effective proposal likely to occur near the top of the list, and least effective near the bottom.

Stage 3: Compile a number of hybrid (conventional technologies/SUDS) proposals

Having established a list of potential retrofit SUDS opportunities the designer/engineer is required to use their engineering judgement, or a process of trial and error, to compile a group of proposals for addressing the catchment's hydraulic problems (i.e. that meet the defined performance criteria for flooding or excessive CSO discharges). It is likely that simplistic modelling tools may be required to simulate the hydraulic performance of these proposals. If it is established that a catchment's problems cannot be addressed solely using retrofit SUDS-based proposals, then it may be necessary to develop a set of hybrid proposals, which combine the use of retrofit SUDS with conventional sewer rehabilitation techniques.

Stage 4: Generate cost/benefit profiles for conventional and hybrid proposals (Using simplistic modelling techniques and approximate cost data)

It is recommended that cost/performance profiles are generated for each of the proposed rehabilitation schemes, in order to establish which are the most cost-effective options. At this stage of the design process it is envisaged that performance would be established through the use of simplistic modelling techniques (as described in previous Section), and associated costs through the use of crude financial analysis.

Simplistic modelling – It is envisaged that simplistic models, or modelling techniques, would generally be utilised within the preliminary stages of a project to help identify the best SUDS proposals, and how their performance compares to that of conventional solutions. The purposes of such investigations are to highlight which if any, SUDS proposals are worth pursuing in the more detailed phases of the design process. It is considered that simplistic models would be appropriate for this task because they may be used to perform rapid, yet crude, hydraulic calculations for large numbers of alternate retrofit SUDS proposals.

Simplistic HydroWorks modelling techniques were developed for the Gipton and Meanwoood case studies (see Chapter 5), which represented infiltration SUDS devices in terms of their associated disconnected contributory areas, and storage SUDS devices in terms of their equivalent initial losses.

Crude financial analysis – It is envisaged that undertaking a detailed cost comparison of alternative rehabilitation proposals would prove to be unnecessarily time consuming for the preliminary stage of the design process. It is therefore considered that crude cost comparisons, of the type presented in Chapter 6 for the Meanwood catchment, would be adequate at this

stage, to indicate which proposals were most cost-effective, and therefore merit further investigation.

Stage 5 – Compare the cost/performance profiles of hybrid proposals against that of the conventional solutions

The cost/performance profiles generated for each rehabilitation proposal in the previous phase allow the designer to establish the most cost-effective options, and those that are worth investigating through the use of more detailed investigations.

Stage 6 – Detailed investigations

This thesis has attempted to address the problems associated with preliminary phases of the design of retrofit SUDS. However, given the UK water industry's general reluctance to adopt SUDS-based schemes it is envisaged that a more detailed level of analysis will be required to fully justify the use of retrofit SUDS in preference to conventional sewer rehabilitation schemes. It is therefore likely that further work will be required to develop and verify deterministic SUDS modelling techniques, and more comprehensive guidance on the costs and design of retrofit SUDS approaches.

Deterministic SUDS Modelling techniques – It is envisaged that deterministic models would be used to perform detailed hydraulic simulations for the final comparison of alternative proposals. This relates to the fact that detailed/deterministic models may be used to perform more sophisticated simulations than simplistic models. The use of accurate modelling strategies is viewed as crucial to the development of detailed design guidance for retrofit SUDS (i.e. to accurately simulate the performance of such devices). Until recently, there were few verified hydraulic models that could be applied to the simulation of SUDS technologies. However, the emergence of detailed/deterministic SUDS models is beginning to allow their hydraulic performance to be compared to that of conventional solutions. Work has been underway, over the duration of this research project, to upgrade the source-code of existing deterministic urban drainage models to allow the simulation of various SUDS techniques. One such example is MicroDrainage's new Source Control module, which is now a fully integrated part of the WinDes suite of urban drainage simulation software, that can support the design and analysis of a number of source control devices, including: infiltration trenches, ponds, porous pavements, soakways and swales. This specific software tool was not available early enough to be used in conjunction within this study. However, it is important that such tools are adequately verified against monitored field data to increase confidence in these models.

Cost – It is considered that more detailed data need to be compiled on the inherent costs associated with SUDS schemes before such technologies can be widely used within the UK – i.e. to allow the comparison of conventional technologies and SUDS / retrofit SUDS proposals. The costs comparisons used in the proposed decision-making tool only relate to construction

costs of different SUDS technologies. It is envisaged that a fairer comparison of technology costs would consider secondary issues, such as maintenance, environmental benefits, safety issues, and institutional concerns about adoption. Many of these secondary issues relate more to whole life costs, than one off construction costs.

Design – Detailed technical design guidance is already available for most SUDS technologies in a number of key UK publications (See Chapter 2 and Table 7.2). These publications were developed for new SUDS applications. However, it is considered that much of the technical advice contained within these guidelines is equally applicable to the retrofit context. It is therefore recommended that further work be undertaken to verify that this is the case, and to upgrade these publications where necessary, so that they may be applied with confidence to the retrofit context.

Table 7.2 Review of existing design guidance for conventional SUDS

CIRIA C521-523 (2000)	Companion volumes (C521 and C522) discuss technical and planning issues surrounding SUDS in Scotland and Northern Ireland, and England and Wales respectively, whilst C523 covers the wider aspects of SUDS best practice, the legislative issues surrounding SUDS and explores how organisations may work jointly pursue the use of SUDS technologies. These guidelines contain generic guidance on the design of SUDS, although none specifically relates to retrofit SUDS.
CIRIA R124 (Vols. 1- 4) (1994)	Scoping report on the use of SUDS technologies for urban applications – addresses issues of. planning, funding, design, construction and maintenance
CIRIA R156 (1996)	Contains important guidance relating to the planning, funding, design, construction and maintenance of infiltration systems, and their use as stormwater control methodology.

Stage 7 – Selecting final proposal

Comparison of the costs and hydraulic performance associated with each of the detailed rehabilitation proposals will allow the designer to establish a final/preferred rehabilitation proposal. In most cases it is likely that the most cost-effective option would be selected as the preferred solution.

7.3.2 Future context

It is evident from previous discussions (Section 4.3.2.5) that the viability of retrofit SUDS, in the current UK context, is greatly affected by non-physical constraints, such as financial, institutional and regulatory issues. These factors mean that it is generally not possible to implement potential SUDS schemes to the full extent that would otherwise be achievable if physical factors were taken to be the only constraint. However, these non-physical constraints should not be considered as being irremovable. Many of these constraints could be eliminated by a change of institutional/regulatory policy. For example, financial backing from local or national government could be used to support the use of SUDS in the form of monetary incentives for sewerage operators to adopt retrofit SUDS rather than conventional technologies (e.g. comparable to the tax incentives that were used the promote the change over to unleaded

petrol within the UK in the 1990s). It is therefore conceivable that at some point in the future, the viability of retrofit SUDS might solely be influenced by physical constraints.

The proposed decision-making flowcharts are a flexible set of procedures rather than a prescriptive set of design guidelines. This coupled with the fact that the flowcharts distinguish between physical and non-physical design constraints for retrofit SUDS, make the tools inherently future proof against the potential scenarios described above.

However, it is recognised that the proposed tools also have inherent shortcomings and limitations – these are highlighted in the following Section.

7.3.3 Limitations

It is acknowledged that the guidelines/principles presented within this Chapter are only appropriate for limited applications. These guidelines were specifically developed for the design of retrofit SUDS applications for existing UK urban catchments. It is envisaged that retrofit SUDS schemes would generally constitute remedial works for problem urban drainage catchments. As such, these guidelines would be predominately limited to urban catchments, whose impervious surfaces are fully or partially connected to overloaded separate/combined sewer systems.

This methodology was developed for a UK, and more specifically for an English and Welsh context, and should, therefore, be limited for use within these settings.

The costings used in this methodology only apply in the context of the UK (i.e. because they were generated using the SPONS price guidelines), and retrofit SUDS applications. It is also worth noting that these costings were generated using 2001 prices.

The methodology was developed in light of relevant UK legislation and planning/environmental policy. It is also acknowledged that the application of these guidelines will be affected by 'Region/National' variations (e.g. variations in planning procedures, Governmental/Regulatory policy, legislation).

The methodology has attempted to account for (in an indirect manner) institutional issues, such as adoption, and reservations regarding safety. However, it should be acknowledged at this stage that many water/local authorities still perceive retrofit SUDS to represent a high risk option, and may not be persuaded by the hydraulic and economic justifications alone.

7.4 APPLICATION OF PROPOSED METHODOLOGY TO MEANWOOD

The flowchart methodologies highlighted in the previous Sections were applied to the Meanwood case-study catchment. A review of these investigations is presented in the following Sections; these relate to each of the four impervious urban surface types. The order in which these Sections are presented reflects the preferred order in which such investigations should be performed. Estimates of the amount of impermeable surface area that may be disconnected using each of these technologies (and given the constraints of the Meanwood catchment) are presented on a Section-by-Section basis.

7.4.1 Institutional roofs (Meanwood)

The potential for applying retrofit SUDS to large/institutional roofs (>200 m^2) was explored with respect to the Meanwood catchment. However, it was established that no large roofs (>200 m^2) were connected to the problem (overloaded) sections of the Meanwood sewer system (Walker, 2000:c).

Institutional roofs (Meanwood)

*Institutional roofed area viable for disconnection = **0 ha***

*Institutional roofed area disconnected = **0 ha***

7.4.2 Car-parks (Meanwood)

The potential for applying retrofit SUDS to car-parks in the Meanwood catchment was explored. These investigations established that no car parks were connected to the problem (overloaded) sections of the Meanwood sewer system (Walker, 2000:c).

Car-parks (Meanwood)

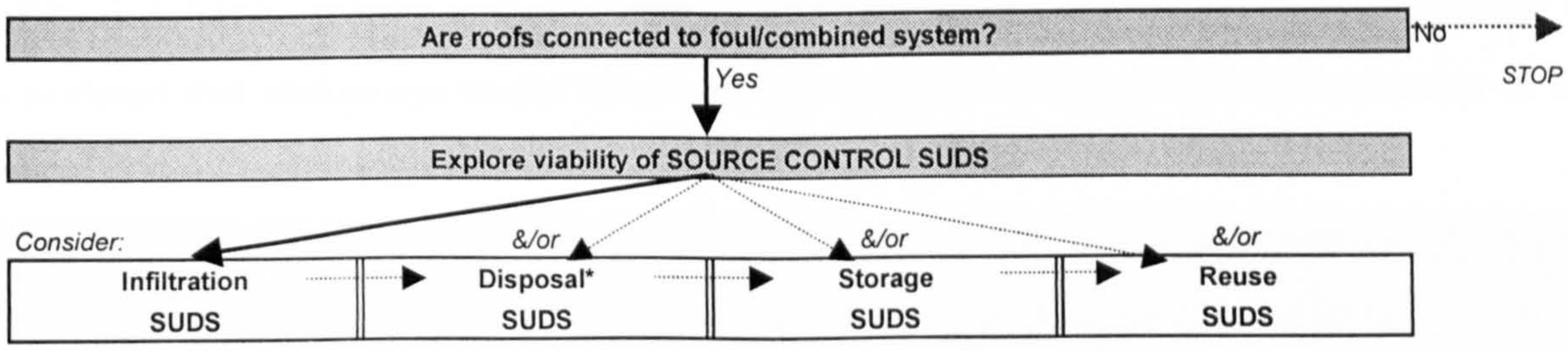
*Car-parking area viable for disconnection = **0 ha***

*Car-parking area disconneced = **0 ha***

7.4.3 Residential roofs (Meanwood)

It was established that most residential roofs within the Meanwood catchment are connected to the local combined sewer system, and therefore contribute to its flooding problems (Walker, 2000:c). The potential for applying retrofit SUDS to Meanwood's residential roofs was investigated using the flow-chart methodology highlighted in the previous Section.

Figure 7.13 Outline of flowchart methodology - Meanwood



The first sub-section of the 'Residential roofs' flow-chart methodology seeks to assess the viability of applying source controls to these surfaces types within the Meanwood catchment (See Figure 7.13). This is reflected by the 'Explore viability of source control SUDS' statement. It is recommended that the viability of each of the four SUDS sub-groups (i.e. infiltration devices, disposal devices, storage devices and reuse devices) be assessed separately. Each of these appraisals is presented in the following sub-sections:

7.4.3.1 Source control – Infiltration devices

The viability of applying infiltration-based retrofit SUDS to the Meanwood catchment was investigated. The central region (Figure 7.14) was the only part of the Meanwood catchment in which infiltration devices were considered to be valid. This relates to the fact that this region is

largely underlain by Sandstone, whilst the remainder of the catchment is underlain by less permeable strata. It is envisaged that retrofit infiltration source controls would be viable for most property roofs in this sandstone region – as preliminary investigations suggest that their viability would not be constrained by any of the other potential constraints presented in the flow-chart (e.g. building regulations, a high water table or catchment landscape).

Figure 7.14: Viable Region for Infiltration-based retrofit Source Controls

The residential roofs flowchart recommends the use of infiltration basins in preference to soakaways, infiltration trenches and/or other landscape features – this premise is based on the anticipated construction costs and ease of implementation. However given the space limitations associated with most residential properties in the Meanwood catchment, and the fact that infiltration basins require a larger surface area than soakaways of equivalent capacity, it is considered that soakaways would constitute the cheapest and the easiest to implement of these source control technologies.

Soakaways (Meanwood)

Potential roofed area to which soakaways may be applied = ***3.022 ha***

Roofed area disconnected = ***3.022 ha***

7.4.3.2 Source control – Local disposal

The flowchart procedure recommends that local disposal is the next most viable form of retrofit source-control SUDS after infiltration-based devices. In the context of the Meanwood catchment, the only viable form of local disposal would be to divert roof runoff (via infiltration trenches) to existing land drains, which serve the green-field sites adjacent to the catchment. These land drains run close to a number of residential properties (see Figure 7.15) – and so it may therefore be feasible to redirect runoff from these roofs into these existing drainage facilities, without the need for extensive new conveyance systems (e.g. swale networks). However, it should be noted that pursuing this course of action might lead to the overloading of the existing land drainage network – this would need to be established by more thorough

investigations/analysis. It is envisaged that such calculations would be conducted at the detailed stage of the design process – depending upon whether the preliminary phase indicates that such SUDS proposals are viable, and worth further consideration.

It should be noted that this proposal would only apply to 86 roofs that have already been identified as being appropriate for soakaways. Table 6.15 indicates that the use of infiltration trenches would be significantly more expensive than the use of soakaways – this option is therefore not pursued any further.

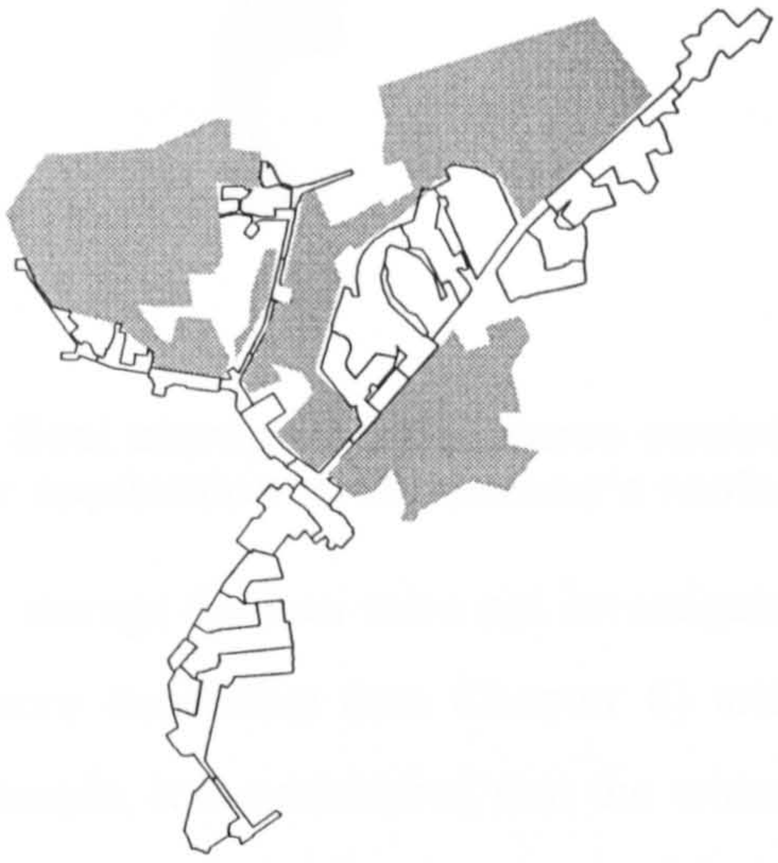


Figure 7.15 Adjacent fields/green land served by existing land drainage network

Infiltration trenches (Meanwood)

*Potential roofed area to which infiltration trenches may be applied = **0.473 ha***

*Roofed area disconnected = **0 ha***

Note: soakaway option considered to be cheaper (see Chapter 6)

7.4.3.3 Source control – Storage options

The flowchart procedure recommends storage devices as the third most viable form of retrofit source-control SUDS, after infiltration-based devices and local disposal schemes.

It was considered that the most viable opportunities for adopting storage-based source controls for Meanwood's roofed area would be the use of water butts in conjunction with those roofs not ear-marked for infiltration devices (see Figure 7.16). Retrofitting water butts to those roofs already deemed as appropriate for infiltration devices was not considered – since it had been established that these infiltration devices were capable of draining the critical design storm event.

Figure 7.16 Best storage-based source control opportunities for application to Meanwood's roofed area

Other source control SUDS storage devices were not investigated because it was envisaged that they would prove to be more expensive (see Chapter 6) and difficult to implement in the Meanwood context. For example, it is considered that the widespread application of residential ponds would be difficult to promote in relation to the Meanwood catchment, due to space limitations in most of the catchments residential properties, and possible safety fears (e.g. from families with young children).

Local storage (Meanwood)

*Potential roofed area to which water butts may be applied = **3.973 ha***

Assuming water butts are applied to all roofs not served by infiltration devices

7.4.3.4 Source control – Reuse options

Reuse-based source control schemes were not explored for use in conjunction with Meanwood's residential roofed area because they were considered to be prohibitively expensive and/or difficult to implement, and because all suitable roofs have already been earmarked for more preferential SUDS devices.

Reuse technologies (Meanwood)

*Potential roofed and paved areas to which reuse technologies may be applied = **0 ha***

Cost constraints are considered to restrict the use of reuse technologies

7.4.3.5 Conveyance

The second sub-section of the residential roofs flow-chart explores the viability of applying conveyance systems to those roofed surfaces for which source controls were not considered viable.

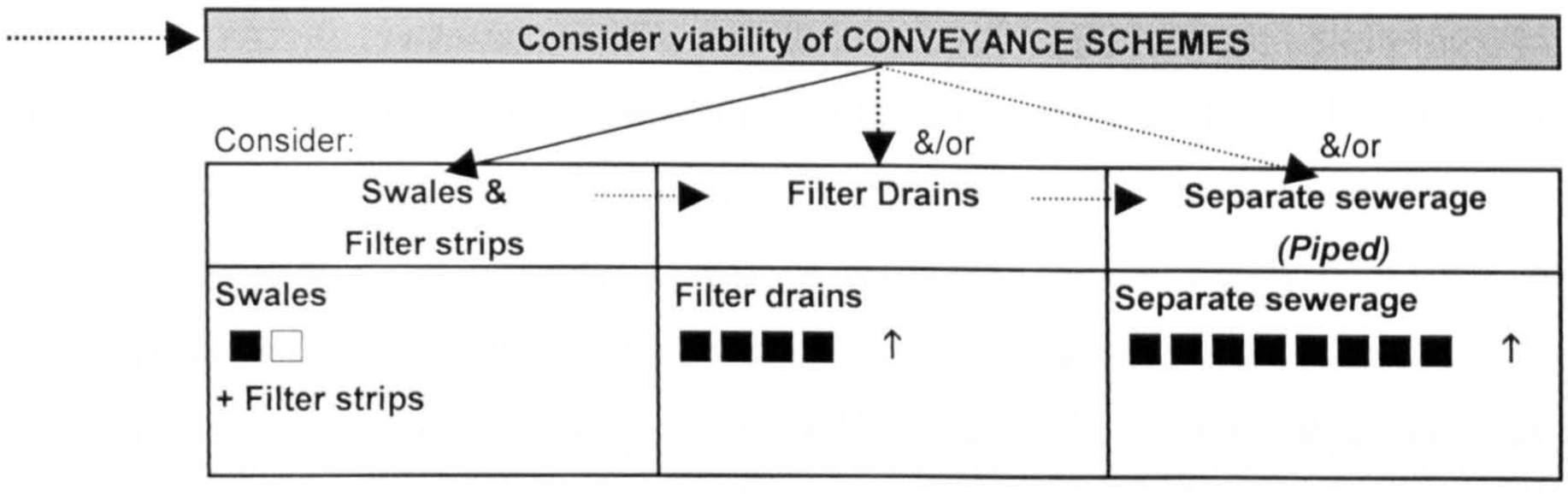


Figure 7.17 Outline of flowchart methodology (Part 2) – Meanwood

The process of assessing the viability of conveyance schemes was sub-divided into separate assessments of the three alternative conveyance options: swales, filter (French) drains or conventional separate sewerage.

Conveyance methods were only considered for use in conjunction with those roofs not already earmarked for infiltration devices or local disposal techniques (i.e. those roofs located within the sandstone region). It should be noted that the same roofs earmarked for conveyance schemes, were also considered appropriate for water butts. However, it was considered unlikely that water butts, alone, would be adequate to deal with peak runoff from a peak 10-year storm.

The only constraint listed within the flow-chart methodology, which was practically considered as limiting the application of retrofit swales to the Meanwood catchment was the issue of available space. This is reflected by the fact that swales were only considered viable for application within Meanwood's existing grass roadside verges (See Figure 7.18). Other locations were not considered due to their significant additional associated costs (e.g. the construction of a retrofit swale would be significantly higher for an existing paved site than for an existing grass verge).

Filter (French) drains and conventional separate sewerage were both considered prohibitively expensive and difficult to implement.

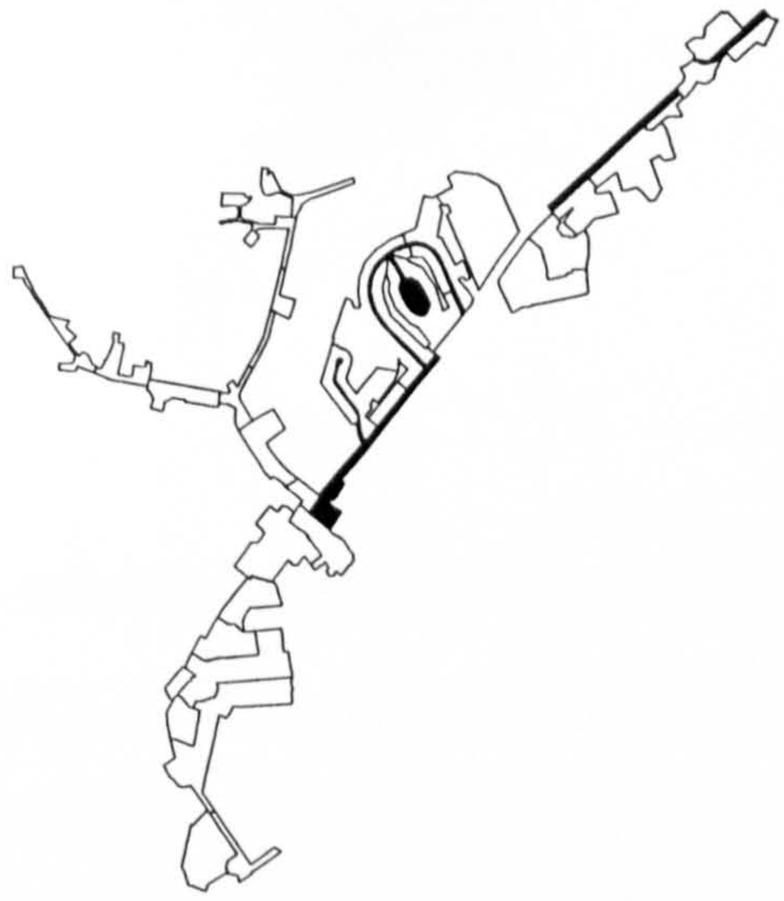


Figure 7.18 Viable locations for retrofit swales

7.4.3.6 Offsite controls

The third sub-section of the 'residential roofs' flow-chart explores the viability of off-site facilities (See Figure 7.19). However, the first issue that must be addressed is whether conveyance systems are viable – this is reflected by the conditional link between the 'conveyance' sub-section and the 'off-site controls' sub-section.

The viability of off-site controls should be addressed by the separate assessment of each of the functional SUDS sub-groups (i.e. infiltration devices, disposal devices, storage devices and reuse devices). It is worth noting that these are the same groupings that are explored in the 'source controls' sub-section.

The flowchart recommends that infiltration facilities are the most preferred form of retrofit off-site control SUDS approach. Preliminary calculations were conducted that indicated there was sufficient land, with appropriate properties (e.g. soil conditions, water table level, etc), located downstream of the viable swale network (highlighted in the previous Section) to support the use of any of the infiltration technologies presented in the flow-chart methodology. These preliminary calculations also indicated that any one of these infiltration technologies that could be constructed in the available space would adequately drain the feeder imperious area (i.e. the impervious area considered to be connected to the swale network) for the 10 year critical design storm. However the investigations undertaken in Chapter 6 indicated that infiltration basins were the cheapest of these three infiltration technologies.

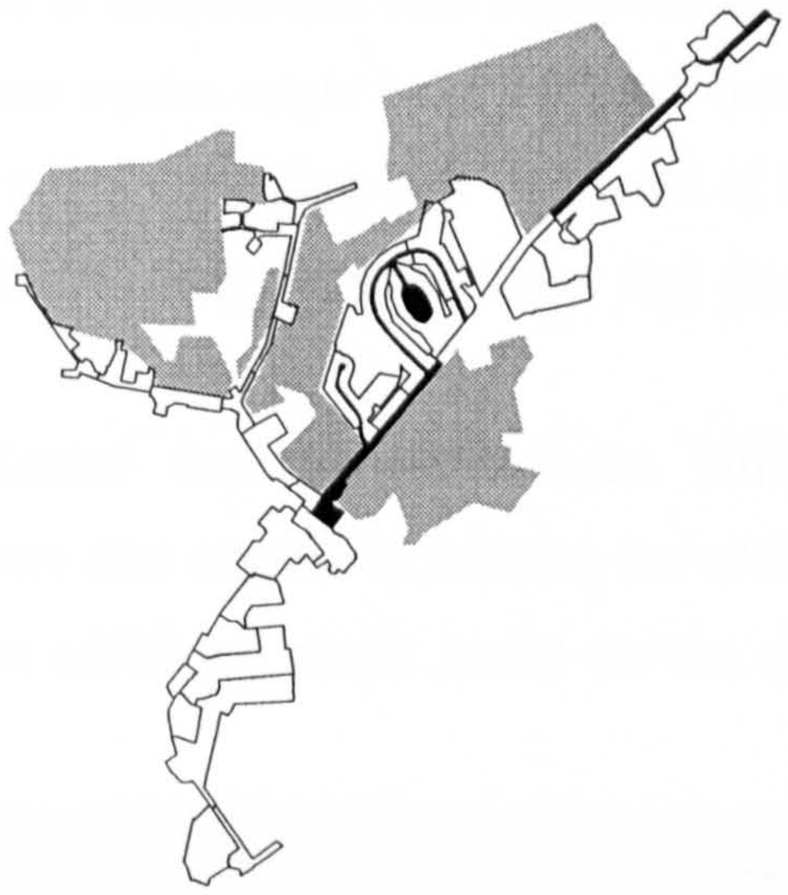


Figure 7.19 Viable locations for off-site controls

No other viable locations were identified within the Meanwood catchment for additional off-site facilities (i.e. the only viable locations for off-site facilities were those already ear-marked for infiltration schemes). Therefore, no further off-site SUDS strategies were considered – since preliminary calculations had indicated that infiltration devices were capable of draining all the feeder area for the critical design storm event.

This proposal may be applied to **1.90 ha** of roofed area. However, all but **0.375 ha** of this area has already been identified as being appropriate for the use of soakaways. Table 6.15 demonstrates that soakaways are a more cost effective than infiltration basins (the cheapest of the three off-site technologies considered).

Off-site controls (Meanwood)

*Potential roofed area for disconnection using (infiltration basin) offsite controls = **1.90 ha***

*Roofed area for disconnection = **0.375 ha***

(see Appendix 7A for further details)

7.4.4 Roads and other paved areas

It was considered that the application of retrofit SUDS techniques to roads and other paved areas would not be viable with respect to the Meanwood catchment. This reflects the fact that additional treatment facilities are required for retrofit SUDS that serve roads and other heavily trafficked paved areas, and that the inclusion of such facilities would be prohibitively expensive for an 'easy pickings' type design approach.

Source controls (Meanwood)

*Potential paved area to which local storage may be applied = **0 ha***

Space constraints are considered to restrict the use of storage facilities for paved areas

However, it may be viable to connect those roads that are adjacent to the proposed swale network for roof-water runoff (see Chapter 4). This relates to the fact that a swale network had already been advocated for use in conjunction with Meanwoods roofs, and that infiltration of paved runoff conveyed via these swales might be considered viable. The low traffic/pollution characteristics of these roads might mean that only one level of treatment would be required prior to infiltration, and the SUDS design manual states that this might be considered to be provided by swales.

Preliminary calculations indicated that the downstream infiltration devices highlighted previously (Section 7.4.3.6) were also capable of draining the additional feeder area (including both upstream roofs and these additional paved areas) for the critical 10 year design storm event.

Off-site controls (Meanwood)

*Potential paved area for disconnection using offsite controls = **2.886 ha***

*Paved area disconnected = **2.886 ha***

7.4.5 Combined proposal

It is considered that the most cost-effective method of combining these recommended retrofit SUDS options would be to undertake the disconnection of ***3.022 ha*** of roofed area using the soakaways option, and the disconnection of a further ***0.375 ha*** of roofed area and ***2.886 ha*** of paved area using the *swales-based* off-site (infiltration basin) proposal. These options give a

combined disconnection of ***3.397 ha (or 46%)*** of roofed area and ***2.886 ha (or 31%)*** of paved area (or ***6.283 ha*** of impervious area). These proposals are summarised in Table 7.3.

There is additional scope to retrofit water butts to the remaining ***3.973 ha*** of roofed area *(i.e. =7.370 ha -3.397 ha)* contained in this catchment, which were not served by infiltration devices.

Table 7.3 Summary of Combined SUDS proposal for Meanwood catchment

Section		Potential area for the application of specific infiltration SUDS technology (ha)	Adopted area for the application of specific infiltration SUDS technology (ha)	Running total of adopted area for the application of infiltration SUDS technologies (ha)	Running total of adopted area for the application of specific storage SUDS technology (ha)
7.4.1	**Institutional roofs**	0	-	**0**	-
7.4.2	**Car-parks**	0	-	**0**	-
7.4.3	**Residential roofs**				
7.4.3.1	Infiltration	3.022	3.022	3.022	-
7.4.3.2	Local disposal	0.473	-	3.022	-
7.4.3.3	Storage	-	-	3.022	3.973
7.4.3.4	Reuse	0	-	3.022	3.973
7.4.3.5	Conveyance/offsite	1.9	0.375	**3.397**	**3.973**
7.4.4	**Roads**				
	Source controls	0	-	3.397	3.973
	Conveyance/offsite	2.886	2.886	**6.283**	**3.973**
	TOTAL			**6.283**	**3.973**

The construction costs associated with undertaking these combined proposals are presented in Table 7.4. This Table presents total costs both including, and excluding, the costs associated with the supplementary use of water butts. See Appendix 7A for further details on the derivation of these costs.

It is evident that under this proposal **54%** of roofs and **69%** of paved areas would remain connected to the Meanwood catchment. This data was subsequently used to extrapolate a corresponding flood volume for the critical (M10-60s) design storm using Table 5.3, and the methodology outlined in Chapter 5. This approach yielded an estimated flood volume of 414 m^3 for the 'excluding water butts' proposal. The extrapolation approach could not be used to estimate a flood volume for the 'including water butts' proposal – as the methodology was developed for infiltration-based (not combined storage and infiltration) proposals. This would have required a more detailed level of modelling (using HydroWorks), than considered appropriate for the preliminary stage of the design process.

Table 7.4 Derivation of total construction costs for joint proposal for Meanwood catchment

Item/ *Description*	**Paved Area Disconnected (ha)**	**Roofed Area Disconnected (ha)**	**Cost (£)**
Soakaways *To all roofs in sandstone region*	-	3.0221 ha	£209,767 [(1)]
Swales – Paved area *Disconnection of all paved areas adjacent to swales (Option B)*	2.886 ha	-	£298,746[(2)]
Swales – non-sandstone roofs *Disconnection of 62 non-sandstone roofs served by swales (Option A) (see Appendix 7A)*	-	0.3749 ha	£8,962 [(3)]
Water butts *The use of water butts for 3.973 ha of roofs not served by infiltration devices*	-	-	£79,460 [(4)]
Total (excluding water butts)			**£517,475**
Total (including water butts)			**£596,935**

[(1)] From Table 6.11
[(2)] From Table 6.15
[(3)] £8,962 = Cost of connecting an individual property: £144.55 (Table 6.12) x No. of properties (62)
[(4)] £79,460 = Cost of providing a 0.3m^3 water butt per 50m^2 of roofed area for the 3.973ha of Meanwood's roofs not served by infiltration devices. Assuming cost of water butt = £100 (Table 6.1)

This proposal represents the best use of retrofit SUDS technologies that was considered to be practically achievable given the Meanwood catchment constraints highlighted by this thesis. Figure 7.20 compares the level of SUDS coverage achieved by this proposal with that considered feasible by Walker's (2000:b) best case Meanwood SUDS proposal (the *100% SUDS proposal*). The Walker (2000:b) *100% SUDS proposal* is described in Chapter 5.

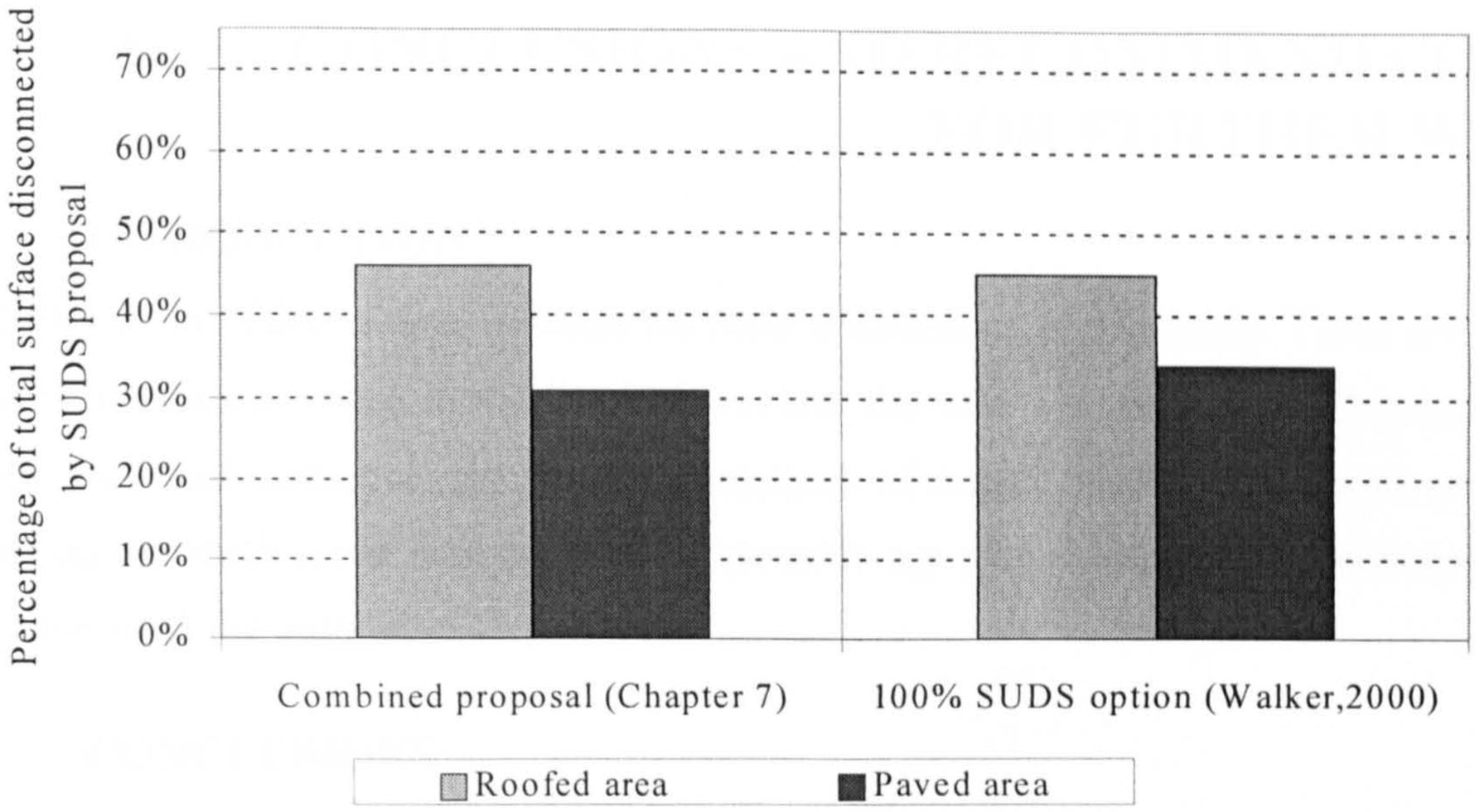


Figure 7.20 Disconnection rates achieved by use of combined proposal (Chapter 7) and Walker's 100% SUDS proposal (2000:b)

The combined proposal, compiled using the flowchart methodology, achieved the disconnection of ***3.397 ha*** *(or 46%)* of roofed area and ***2.886 ha*** *(or 31%)* of paved area, whilst Walker's (2000:b) *100% SUDS proposal* achieved the disconnection of ***3.35 ha*** *(or 45%)* of roofed area and ***3.16*** *(or 34%)* of paved areas. The high level of agreement between these two proposals may be considered to provide added confidence in the decision-making methodology. The flowchart approach appears to have effectively mirrored the design process of an experienced SUDS design engineer, in identifying viable locations for retrofit SUDS technologies within the Meanwood catchment.

It is relevant to highlight some of the differences between this approach and the development of SUDS-based proposals for Meanwood that was presented in Chapters 4 to 6. The initial designs presented in previous Chapters were developed without reference to the urban surface types hierarchy. This implies that no account was taken of the logistical advantages of disconnecting institutional buildings, or of the pollution risks associated with runoff from paved areas. Use of the framework explicitly addresses these issues. The prioritisation of infiltration over storage-based schemes was evident in both approaches, but only in Chapter 7 was it feasible to develop a realistic multiple-technology SUDS-based scheme.

The following Chapter seeks to summarise the research undertaken in this thesis, draw a number of conclusions and highlight the potential for further work.

8. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

8.1. INTRODUCTION

The first section of this chapter presents the main conclusions of this thesis. These are grouped into conclusions that relate to the literature review, the case studies, and the development of specific tools and methodologies for the assessment of retrofit SUDS. Section 5.3 presents a discussion, in which some limitations of the research are acknowledged and recommendations for further work are outlined.

8.2. CONCLUSIONS

8.2.1. Literature Review

1. Urban areas in the UK are typically served by combined sewer systems. These systems often experience flooding and/or excessive CSO discharge problems during storms. Conventional approaches to this problem typically focus on engineered solutions, such as the incorporation of additional underground storage. It may be argued that this approach is neither sustainable (either in the sense of being 'close-to-nature' or from the perspective of providing a long-term solution) nor economically effective. However, the approach is supported by procedural guidelines (UPM manual, SRM and WaPUG Guide) and by well-established modelling approaches, which are required to demonstrate compliance with the relevant regulators. Information on costs is also widely available.
2. At the same time, the advantages of using 'more-sustainable' approaches in the design of stormwater management controls are widely recognised in the context of new developments. Although the UK has been comparatively slow in adopting such measures, there is considerable international evidence of the effective use of SUDS (Sustainable Urban Drainage Systems) and BMPs (Best Management Practices). UK-based guidance on the design of SUDS technologies is available (CIRIA Reports C521, C522 and C523, 2000), but this largely relates to their application to new developments.
3. Some preliminary feasibility studies have been reported that seem to indicate that the use Yof retrofit SUDS might be feasible in many urban contexts (Balmforth and Bailey, 1985; Attanasio *et al.*, 1994; Hermann and Hasse, 1997). It was also evident that several issues would need to be addressed before retrofit SUDS might be routinely considered as (part of) a drainage rehabilitation option for UK applications. The key obstacles to the broader implementation of retrofit SUDS were identified as:
   - Lack of design guidelines (i.e. that address issues relating specifically to retrofit);
   - Uncertainty associated with the costs of construction, operation and maintenance;

- Legal issues and ownership/operational responsibilities.

The thesis focused on the development of tools/methodologies aimed at addressing the first two obstacles highlighted above. It was felt that legal issues relating to planning, ownership and operation, although clearly important, were beyond the scope of the present research.

8.2.2. Case Studies

1. This thesis has reviewed a number of previous investigations that sought to evaluate the merits of applying retrofit SUDS systems for the remediation of urban drainage problems (Icke *et al.*, 1999; Herrmann and Hasse, 1997; Attanasio, Hemphill. and Lee, 1994; Balmforth and Bailey, 1985). The studies conducted by Herrmann & Hasse (1997) and Balmforth & Bailey (1985) indicated that roof-water based retrofit SUDS were economically viable as a sewer rehabilitation methodology. Attanasio *et al.* (1994) demonstrated that the use of retrofit SUDS was economically viable in conjunction with conventional techniques as part of an integrated programme of sewer rehabilitation works in an American context. Similar schemes have been shown to be valid, and subsequently adopted for a number of other North American cities. These North American experiences run contrary to the prevailing view within the United Kingdom, which assumes that SUDS are only viable for new development applications. The British perspective would seem to be supported by the results of the catchment X study (Chapter 2), which rejected the use of retrofit SUDS in terms of performance. No further UK studies were found within the public domain. This illustrated the need for a more detailed analysis of the impacts of retrofit SUDS with respect to problem UK catchments.
2. Retrofit SUDS were investigated in relation to two UK case study catchments. These catchments were selected because they exhibited typical UK problem characteristics (i.e. excessive CSO discharges and hydraulic capacity problems). Both case studies related to areas in the city of Leeds, in the North of England. Industrial collaborators provided all relevant catchment data and the hydraulic models corresponding to the present status of the networks. The two case studies were examined at different levels. Preliminary analysis into the hydraulic feasibility and cost-effectiveness of using retrofit SUDS to address excess CSO spills were undertaken with respect to the Gipton catchment. The Meanwood catchment was utilised for the development of more detailed tools and methodologies for retrofit SUDS evaluation.
3. The Gipton catchment, which comprised four sub-catchments each with an unsatisfactory CSO, had a total area of 297.8 ha. Housing types ranged from semi-detached to terraced properties, with a small number of retail and institutional buildings. The catchment geology varied from sandstone (permeable) to mudstone (impermeable). Modest slopes, reasonable garden sizes, some grassed verges, some institutional buildings and some open space meant that reasonably widespread use of SUDS was

feasible. The main techniques in the proposed SUDS schemes were garden soakaways, with some swales conveying stormwater into existing watercourses or land drainage networks. The main findings from the Gipton study (as outlined in Chapter 3) were as follows:

- Although SUDS-based approaches could not entirely eliminate the CSO-related discharge problems, they could provide cost-effective improvements, and would be useful components of a hybrid (part SUDS/part conventional rehabilitation) proposal;
- The disconnection of institutional buildings enabled large areas to be disconnected cheaply, and was seen to be an important factor in the attractiveness of the SUDS-based proposals;
- Conventional urban drainage models were identified as being appropriate tools for simulating the hydraulic performance of retrofit SUDS schemes. However, this required the development of novel modelling techniques (as described in part 3. of the following section).

8.2.3. Tools and Methodologies

1. The literature review and the Gipton case study highlighted the complexity of the retrofit SUDS design and evaluation process, and confirmed the need for specific design, hydraulic modelling, costing and evaluation guidance. The second case study (Meanwood) was employed to develop, and subsequently illustrate, those design, modelling, cost and evaluation tools.
2. Chapter 4 outlined the main **design** issues to affect those SUDS technologies judged to be widely applicable in the retrofit context. These were grouped in terms of geology, urban landcape, building regulations etc. Although the hydraulic performance and constructional detail of retrofit SUDS will generally mirror SUDS for new developments, there are unique, additional design factors that affect the viability of retrofit SUDS. These factors, including, for example garden size and whether or not road verges are grassed, were compiled into a unique checklist of design issues for retrofit SUDS. A fundamental distinction between infiltration- and storage-based SUDS was made.
3. Chapter 5 evaluated **hydraulic** modelling approaches for use in conjunction with conventional urban drainage hydraulic modelling software. Two approaches were identified: area disconnection was used to represent infiltration-based SUDS, whilst the initial losses parameter was adjusted to account for storage-based SUDS.
4. Chapter 6 reflected the fact that cost is an inescapable consideration in the evaluation of drainage rehabilitation options, and presented relevant **costing** data. The costing methodologies acknowledged the need to include connection and conveyance costs for

off-site technologies. Unit costs, as well as representative scheme costs have been derived. The latter enabled the comparative costs of alternative SUDS technologies to be assessed. Of the technologies considered, basins and soakaways were found to represent comparatively cheap options when compared with ponds, infiltration trenches, and porous pavements.

5. The newly-developed tools were applied to the Meanwood catchment in Chapters 4, 5 and 6. The catchment's sewer network contains four sites that exhibit unsatisfactory surcharging / flooding problems. The Meanwood catchment serves a total contributory area of 55.ha, and is largely residential (containing semi-detached and terraced housing) with some public buildings and retail outlets. There is also a significant amount of grassed and wooded areas in the catchment's upstream reaches. The geology varies from sandstone (permeable) to mudstone and Stanningley rock (impermeable). The catchment's key characteristics (geology, slopes, garden sizes, availability of green spaces) mean that the widespread use of SUDS was considered a feasible option. Various SUDS-based rehabilitation options for Meanwood were presented. A distinction was made between *optimum* scenarios, i.e. the level of disconnection that might be achieved given only geological (permeability) constraints, and *best-case* single-technology implementation scenarios. Where appropriate, the hydraulic performance and cost of each scenario was also presented. As with Gipton it was found that SUDS alone would not fully address Meanwood's rehabilitation requirements, although SUDS solutions might usefully be combined with conventional components to produce a cost-effective proposal.
6. In Chapter 7 the design and cost constraints were employed in the development of a **decision-support framework** for retrofit SUDS. The framework is presented as a set of decision flowcharts. The approach is based around four key decision-making hierarchies that relate to:
   - The **Type of urban surface** to which the SUDS device is to be applied;
   - The **Surface water management train** concept – i.e. whether the SUDS device is intended for use as a source control, conveyance structure or an off-site control;
   - The **Mode of operation** by which the SUDS device manages stormwater runoff;
   - The **Costs** associated with the SUDS device.
7. An appraisal of the framework's potential role within sewerage rehabilitation procedures in the UK was also presented. It is believed that the flowcharts would be a useful tool in developing potential schemes. Similarly, the design checklist, hydraulic modelling protocols and costing methodologies that have been presented could contribute to the development of detailed schemes and their evaluation. In practice, schemes that include SUDS devices are likely to incorporate more that one type of

technology, and it is envisaged that hybrid (part SUDS/part conventional) solutions may frequently represent cheap and effective alternatives.

8. In summary, the key conclusions of this research project have been:
   - The development of a novel database of construction costs for a number of retrofit SUDS technologies
   - The development of a decision-making tool for the design of retrofit SUDS, which addresses some of the deficiencies of the existing design guidelines.
   - The application of both of these novel tools to a real UK catchment (Meanwood).

8.3. DISCUSSION AND SUGGESTIONS FOR FURTHER WORK

The work described in this thesis addressed the potential utilisation of retrofit SUDS technologies in solving stormwater-related problems in existing urban catchments. These technologies are arguably 'more sustainable' and potentially cheaper than conventional drainage rehabilitation options. In the context of the current discussions on climate change, flooding and sustainability, it is clear that this is a timely and relevant topic for research. However, there are a number of limitations in the work that need to be appreciated and that should, ideally, be addressed in future research. These are discussed below:

1. **Verification of the hydraulic models and modelling strategies for SUDS.** The accuracy of the catchment models used in conjunction with this analysis is obviously an important issue. Amended models were used to represent the performance of each of the SUDS-based design proposals considered within this thesis. It was inevitable that, since these models represented proposals for future schemes, they were not, and could not have been, verified. Furthermore, the modelling techniques developed to represent the impacts associated with infiltration-based and storage-based SUDS have not been verified. The lack of extensive SUDS implementation in the UK makes validation against field data difficult. However, it may be feasible to undertake some verification work using data from outside of the UK.
2. **Performance comparisons.** The SUDS-based proposals were compared with the conventional options using conventional hydraulic criteria relating to spill frequency and flood/spill volume. The cost comparisons were restricted to construction costs alone. A broader investigation might have considered a range of other performance measures, including, for example environmental (water quality, ecological), aesthetic and social issues. Frameworks for assessing the comparative sustainability of scheme options exist (Ashley *et al.*, 2001), and might form the basis for future evaluations. SUDS-based schemes are likely to appear even more favourable once these intangible factors are incorporated into the decision-making process. Similarly, costings need to reflect whole-life costs that explicitly account for maintenance and replacement, and need to address catchment-wide implications of surface disconnection. Reduced sewer flows and reduced volumes to treatment may have important implications in some catchments, either for operational performance or cost or both.

3. **Limitations in the case studies.** It would be useful to extend the case studies to encompass a broader range of catchment types, in terms of location, geology, urban landscape, prevailing rainfall and sewer-related problems. This would enable some generalisations to be made with respect to the link between catchment characteristics and the viability of implementing retrofit SUDS.
4. **Universality.** The flow charts, and the methodologies that underpinned them, were principally developed for the UK context, and in the light of relevant UK legislation and planning/environmental policy. However, the relative costings, which were generated for the different technologies are likely to be fairly robust for non-UK applications. Similarly, the surface type and mechanism rankings and the treatment train concept are likely to have high levels of universality. Therefore further work could be undertaken to customise the UK-specific parts of the methodology, such as the design constraints that relate to UK Building Regulations and environmental policy, in order that it may be applied internationally.
5. **Secondary issues relating to SUDS implementation.** The methodology has attempted to account for secondary issues, such as institutional concerns about adoption, maintenance and safety. However, it should be acknowledged that many water/local authorities still perceive retrofit SUDS to represent a high-risk option, and may not be persuaded by the hydraulic and economic justifications alone.

The research presented in this thesis indicated that retrofit SUDS constituted economically viable rehabilitation strategies for two typical problem urban drainage catchments. The most realistic application for retrofit SUDS, under current UK conditions, is as part of integrated (conventional/retrofit SUDS) rehabilitation proposals. This integrated approach was shown to be cost effective for both case studies, and is also supported by international experience. However, it is recognised that there is reluctance in the UK's water sector to adopt retrofit SUDS. It is therefore hoped that the preliminary design, modelling and costing tools presented within this thesis may go some way to help to overcome this reluctance.

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APPENDICES

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