CIRIA C609 **London, 2004**

Sustainable drainage systems

Hydraulic, structural and water quality advice

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sharing knowledge ▪ building best practice

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Summary

This technical report summarises current knowledge on the appropriate approach to the successful design and construction of sustainable drainage systems (SUDS).

The book provides an improved understanding of the hydrological, hydraulic, structural, water quality and ecological issues of various SUDS features based on the information currently available in the UK and overseas.

Sustainable drainage systems. Hydraulic, structural and water quality advice

Wilson, S; Bray, R; Cooper, P

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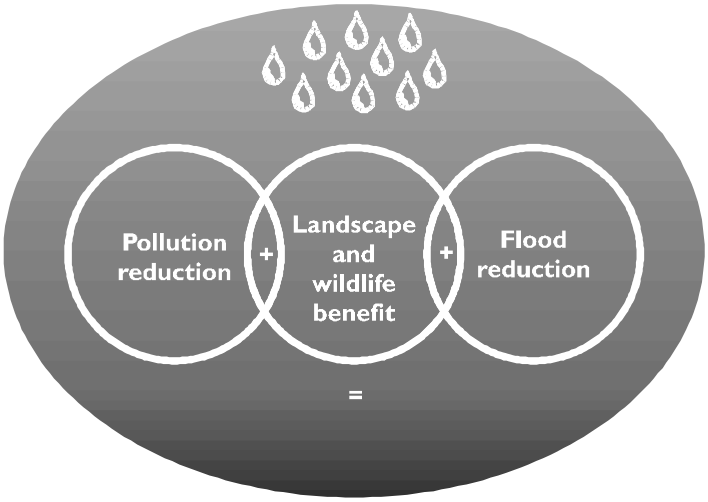
Sustainable drainage systems (SUDS)

The SUDS concept is to mimic, as closely as possible, natural drainage of a site in order to minimise the impact that urban development has on flooding and pollution of rivers, streams and other water bodies. The use of a variety of techniques within the management train allows the SUDS concept to be applied to all sites. The techniques utilising vegetative features to treat pollution and slow down or reduce flows can enhance the landscape and provide wildlife habitat.



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Glossary

Adsorption – The adherence of gas, vapour or dissolved matter to the surface of solids.

Aquifer – Layer of rock or soil that holds or transmits water.

Asphalt – European standard description of all mixtures of mineral aggregates bound with bituminous materials used in the construction and maintenance of paved surfaces.

Asphalt concrete – New European standard description of materials previously known as macadams and Marshall asphalt.

Attenuation – Reduction of peak flow and increase of the duration of a flow event.

Balancing pond – A pond designed to attenuate flows by storing runoff during the peak flow and releasing it at a controlled rate during and after the storm. The pond always contains water. Also known as wet detention pond.

Base – European standard description of the lowest bound layer of an asphalt pavement; known in UK as roadbase.

Base flow – The sustained flow in a channel or system because of subsurface infiltration.

Basin – A ground depression acting as a flow control or water treatment structure that is normally dry and has a proper outfall, but designed to detain stormwater temporarily (see **Detention basin**).

Binder course – European standard description of an asphalt pavement's second layer; known in UK as basecourse.

Biodegradation – Decomposition of organic matter by micro-organisms and other living things.

Bioretention area – A depressed landscaping area that is allowed to collect runoff so it percolates through the soil below the area into an underdrain, thus promoting pollutant removal.

Bitumen – A hydrocarbon binder. A virtually involatile adhesive material derived from crude petroleum that is used to coat mineral aggregate for use in construction and maintenance of paved surfaces.

Block paving – Pre-cast concrete or clay brick sized flexible modular paving system.

Capping layer – Layer of unbound aggregate of lower quality than sub-base, used to improve performance of foundation soils before laying the sub-base and to protect subgrade from damage by construction traffic.

Carriageway – The part of the road used to carry vehicular traffic.

Catchment – The area contributing surface water flow to a point on a drainage or river system. Can be divided into sub-catchments.

CBR value – California Bearing Ratio. An empirical measure of the stiffness and strength of soils, used in road pavement design.

Construction Quality Assurance (CQA) – A documented management system designed to provide adequate confidence that items or services meet contractual requirements and will perform adequately in service. CQA usually includes inspection and testing of installed components and it records the results.

Continuously graded – A soil or aggregate with a balanced range of particle sizes with significant proportions of all fractions from the maximum nominal size down.

Control structure – Structure to control the volume or rate of flow of water through or over it.

Controlled waters – Waters defined and protected under the Water Resources Act 1991. Any relevant territorial waters that extend seaward for three miles from the baselines, any coastal waters that extend inland from those baselines to the limit of the highest tide or the freshwater limit of any river or watercourse, any enclosed dock that adjoins coastal waters, inland freshwaters, including rivers, watercourses, and ponds and lakes with discharges and ground waters (waters contained in underground strata). For the full definition refer to the Water Resources Act 1991.

Conveyance – Movement of water from one location to another.

Denitrification – A microbial process that reduces nitrate to nitrite and nitrite to nitrogen gas.

Design criteria – A set of standards agreed by the developer, planners and regulators that the proposed system should satisfy.

Detention basin – A vegetated depression that is normally dry except following storm events constructed to store water temporarily to attenuate flows. May allow infiltration of water to the ground.

Diffuse pollution – Pollution arising from land-use activities (urban and rural) that are dispersed across a catchment or sub-catchment and which do not arise as a process effluent, municipal sewage effluent or an effluent discharge from farm buildings.

Elastic modulus – Also known as Young's Modulus or stiffness modulus; the ratio of stress divided by strain for a particular material.

Eutrophication – Water pollution caused by excessive plant nutrients that results in reduced oxygen levels. The nutrients are powerful stimulants to algal growth which in turn use up oxygen in water. The excessive growth, or "blooms", of algae promoted by these phosphates change the water quality in lakes and ponds, and can kill fish.

Evapotranspiration – The process by which the Earth's surface or soil loses moisture by evaporation of water and its uptake and then transpiration from plants.

Extended detention basin – A detention basin where the runoff is stored beyond the time normally required for attenuation. This provides extra time for natural processes to remove some of the pollutants in the water.

Filter drain – A linear drain consisting of a trench filled with a permeable material, often with a perforated pipe in the trench's base to assist drainage and store and conduct water, but it may also be designed to permit infiltration.

Filter strip – A vegetated area of gently sloping ground designed to drain water evenly off impermeable areas and filter out silt and other particulates.

Filtration – The act of removing sediment or other particles from a fluid by passing it through a filter.

Fines – Small soil particles less than 63 micron in size.

First flush – The initial runoff from a site/catchment following the start of a rainfall event. As runoff travels over a catchment it will collect or dissolve pollutants and the "first flush" portion of the flow may be the most contaminated as a result. This is especially true for intense storms and in small or more uniform catchments. In larger or more complex catchments, pollution wash-off may contaminate runoff throughout a rainfall event.

Floodplain – Land adjacent to a watercourse that would be subject to repeated flooding under natural conditions. See the Environment Agency's *Policy and practice for the protection of groundwater* (EA, 1998b) for a fuller definition.

Flow control device – A device used to manage the movement of surface water into and out of an attenuation facility, for example weirs.

Footway – Areas for pedestrians at the side of the carriageway.

Geocellular structure – A plastic box structure used in the ground often to attenuate runoff.

Geogrid – Plastic grid structure used to increase strength of soils or aggregates.

Geomembrane – An impermeable plastic sheet, typically manufactured from polypropylene, high-density polyethylene or other geosynthetic material.

Geotextile – A plastic fabric that is permeable.

Green roof – A roof on whose surface plants can grow. The vegetated surface provides a degree of retention, attenuation and treatment of rainwater, and promotes evapotranspiration.

Groundwater – Water that has percolated into the ground; it includes water in both the unsaturated zone and the water table.

Groundwater protection zone (source protection zone) – Areas that influence water supply boreholes where groundwater must be protected from pollution. These are defined by reference to travel times of pollutants within the groundwater. See the Environment Agency's *Policy and practice for the protection of groundwater* (EA, 1998b) for specific details.

Gully – Opening in the road pavement, usually covered by metal grates, which allows water to enter conventional drainage systems.

Highway drain – A conduit draining the highway. For highways maintainable at the public expense it is vested in the highway authority.

Hydrograph – A graph illustrating changes in the rate of flow from a catchment over time.

Hydrology – The study of the waters of the Earth, their occurrence, circulation and distribution, their chemical and physical properties and their reaction with the environment including their relation to living things.

Impermeable – Does not allow water to pass through it.

Impermeable surface – An artificial non-porous surface that generates a surface water runoff after rainfall.

Infiltration (to a sewer) – The entry of groundwater to a sewer.

Infiltration (to the ground) – The passage of surface water into the ground.

Infiltration basin – A dry basin designed to promote infiltration of surface water to the ground.

Infiltration device – A device designed to aid infiltration of surface water into the ground.

Infiltration trench – A trench, usually filled with permeable granular material, designed to promote infiltration of surface water to the ground.

Integrated management practice – The concept of integrating SUDS into the design of a development from the feasibility stage so that the development is designed to achieve the best SUDS layout.

Interflow – Shallow infiltration to the soil, from where it may infiltrate vertically to an aquifer, move horizontally to a watercourse or be stored and subsequently evaporated.

Initial rainfall loss – The amount of rain that falls on a surface before water begins to flow off the surface.

Lagoon – A pond designed for the settlement of suspended solids.

Pathogen – An organism that causes disease.

Micropool – Pool at the outlet to a pond or wetland that is permanently wet and improves the pollutant removal of the system.

Pavement – Technical name for the road or car park surface and underlying structure, usually asphalt, concrete or blockpaving. Note that the path next to the road for pedestrians (colloquially known as "pavement") is formally called the footway.

Percentage runoff – The proportion of rainfall that runs off a surface. See also **Runoff**.

Permeability – A measure of the ease with which a fluid can flow through a porous medium. It depends on the physical properties of the medium, for example grain size, porosity and pore shape.

Permeable surface – A surface formed of material that is itself impervious to water but, by virtue of voids formed through the surface, allows infiltration of water to the sub-base through the pattern of voids, for example concrete block paving.

Pervious surface – A surface that allows inflow of rainwater into the underlying construction or soil.

Piped system – Conduits generally located below ground to conduct water to a suitable location for treatment and/or disposal.

Pollution – A change in the physical, chemical, radiological or biological quality of a resource (air, water or land) caused by man or man's activities that is injurious to existing, intended or potential uses of the resource.

Pond – Permanently wet basin designed to retain stormwater and permit settlement of suspended solids and biological removal of pollutants.

Porosity – The percentage of the bulk volume of a rock or soil occupied by voids, whether isolated or connected.

Porous asphalt – An asphalt material used to make pavement layers pervious, with open voids to allow water to pass through (previously known as pervious macadam).

Porous surface – A surface that infiltrates water to the sub-base across the entire surface of the material forming the surface, for example grass and gravel surfaces, porous concrete and porous asphalt.

Prevention – Site design and management to stop or reduce the pollution of impermeable surfaces and reduce the volume of runoff by reducing impermeable areas.

Proper outfall – An outfall to a watercourse, public sewer and in some instances an adopted highway drain. Under current legislation and case law, having a proper outfall is a prerequisite for defining a sewer.

Public sewer – A sewer that is vested and maintained by the sewerage undertaker.

Rainfall event – A single occurrence of rainfall before and after which there is a dry period that is sufficient to allow its effect on the drainage system to be defined.

Rainwater use system – A system that collects rainwater from where it falls rather than allowing it to drain away, and includes water that is collected within the boundaries of a property, from roofs and surrounding surfaces.

Retention pond – A pond where runoff is detained for a sufficient time to allow settlement and possibly biological treatment of some pollutants.

Return period – The occurance frequency of an event. A 100-year storm refers to the storm that occurs on average once every 100 years. In other words, its annual probability of exceedance is 1 per cent (1/100). A 500-year storm is the storm expected to occur once every 500 years, or has an annual probability of exceedance equal to 0.2 per cent (1/500).

Road pavement – The load-bearing structure of a road (note that the path at the side of a road, commonly referred to as a "pavement", is properly called the footway).

Runoff – Water flow over the ground surface to the drainage system. This occurs if the ground is impermeable or saturated, or if rainfall is particularly intense.

Runoff coefficient – A measure of the amount of rainfall converted to runoff.

Sewer – A pipe or channel with a proper outfall that takes domestic foul and/or surface water from buildings and associated paths and hardstandings from two or more curtilages.

Sewerage undertaker – An organisation with the legal duty to provide sewerage services in an area, including disposal of surface water from roofs and yards of premises. In England and Wales these services are provided by water companies, in Scotland by water authorities and in Northern Ireland by the Water Service of the Department of the Environment, NI.

Sewers for adoption – A guide agreed between sewerage undertakers and developers (through the House Builders Federation) specifying the standards to which private sewers need to be constructed to facilitate adoption.

Sewers for Scotland – Technically the same as *Sewers for adoption*, but varying in legal detail.

Single-size grading (single-size material) – The majority of the soil or aggregate particles are of one nominal size, although there may be small proportions of other sizes.

Soakaway – A subsurface structure into which surface water is conveyed to allow infiltration into the ground.

Source control – The control of runoff at or near its source.

Storm – An occurrence of rainfall, snow or hail.

Stormwater hotspot – Stormwater hotspots are defined in the USA as areas where land use or activities may generate highly contaminated runoff, or where groundwater is an important resource for drinking water abstraction.

Sub-base – The unbound layer of aggregate used immediately below the bound layers. It is laid on the soil (or capping layer) to provide a stable foundation for construction of the road pavement.

Sub-catchment – A division of a catchment, allowing runoff management as near to the source as is reasonable.

Subgrade – The soils onto which the road pavement is constructed.

SUDS – Sustainable drainage systems or sustainable (urban) drainage systems. A sequence of management practices and control structures designed to drain surface water in a more sustainable fashion than some conventional techniques (may also be referred to as SuDS).

Surface course – European standard description of the top layer of an asphalt pavement currently known in UK as wearing course.

Surface water management train – The management of runoff in stages as it drains from a site.

Suspended solids – Undissolved particles in a liquid.

Swale – A shallow vegetated channel designed to conduct and retain water, but may also permit infiltration; the vegetation filters particulate matter.

Time of entry – Time taken for rainwater to reach an inlet into the drainage system after hitting the ground.

Treatment – Improvement of the quality of water by physical, chemical and/or biological means.

Treatment volume – The proportion of total runoff from impermeable areas captured and treated to remove pollutants.

Turbidity - Reduced transparency of a liquid caused by the presence of undissolved matter.

Type 1 sub-base – Specification for the most commonly used sub-base material in conventional pavements, from the *Specification for highway works* (Highways Agency *et al*, 1998a).

Void ratio – The ratio of open air space to solid particles in a soil or aggregate.

Watercourse – Any natural or artificial channel that conveys surface and/or ground water.

Weep garden – Bioretention system built into a terrace on a sloping site, where the water is allowed to seep out of the face of the retaining wall that forms the terrace.

Wetland – A pond that has a high proportion of emergent vegetation in relation to open water.

Abbreviations

A_d	total area to be drained, including any adjacent impermeable area
A_b	base area of infiltration system below pervious pavement
A_I	area of adjacent impermeable surface draining on to pervious surface
A_p	area of pervious pavement
AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ADAS	Agricultural Development and Advisory Service
AGS	Association of Geotechnical and Geo-environmental Specialists
AOS	apparent opening size
ASTM	American Society for Testing of Materials
BAP	biodiversity action plan
BMP	best management practice
BOD	biochemical oxygen demand
BSI	British Standards Institution
BRE	Building Research Establishment
C	shape factor
CBM	cement-bound material
CBR	Californian Bearing Ratio
CDM	Construction (Design and Management) Regulations 1984
CEN	Comité Européen de Normalisation (European Committee for Standardisation)
CESMM3	Civil Engineering Standard Method of Measurement, third edition
CIWEM	Chartered Institution for Water and Environmental Management
CMA	calcium magnesium acetate
COD	chemical oxygen demand
COPA	Control of Pollution Act 1974
CQA	construction quality assurance
CSO	combined sewer overflow
D	rainstorm duration
DBM	dense bitumen macadam
DEFRA	Department of the Environment, Food and Rural Affairs (UK)
DMRB	*Design manual for roads and bridges* (the Highways Agency, Scottish Executive Development Department, the National Assembly for Wales and the Department for Regional Development Northern Ireland)
DNAPL	dense non-aqueous-phase liquid
DTLR	Department for Transport, Local Government and the Regions (UK)
D_s	effective particle size diameter
D_{10}	soil particle size such that 10 per cent of the sample consists of particles having a smaller nominal diameter
D_{15}	soil particle size such that 15 per cent of the sample consists of particles having a smaller nominal diameter
D_{50}	soil particle size such that 50 per cent of the sample consists of particles having a smaller nominal diameter
D_{85}	soil particle size such that 85 per cent of the sample consists of particles having a smaller nominal diameter
e	void ratio of aggregate
E	Young's Modulus
EA	Environment Agency (England and Wales)
EMC	event mean concentration
EPA	Environmental Protection Agency (USA)
EQS	environmental quality standard

FEH	*Flood estimation handbook*, produced by Institute of Hydrology
FHWA	Federal Highway Administration
FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.
G_s	specific gravity of soil or aggregate particles
h	Thickness of aggregate or other storage medium below pervious pavement
h_{max}	maximum depth of water that will occur in the storage medium
i	rainfall intensity
IMP	integrated management practice
IOH	Institute of Hydrology (now Centre for Ecology and Hydrology)
IRL	initial runoff loss
k	coefficient of permeability
LNAPL	light non-aqueous-phase liquids
MSA	motorway service area
MTBE	methyl tert butyl ether
NSWG	National SUDS Working Group
n	porosity of soil or aggregate
O_{95}	apparent opening size
PAH	polycyclic aromatic hydrocarbons
PPG 3	Planning Policy Guidance 3 *Housing*
PPG 25	Planning Policy Guidance 25 *Development and flood risk*
Q	flow through outlet from storage below pavement
q	infiltration coefficient
r	rainfall ratio
SEPA	Scottish Environment Protection Agency
SNIFFER	Scotland and Northern Ireland Forum for Environmental Research
SSSI	site of special scientific interest
SUDS	sustainable drainage systems
T	return period for storm event
TON	total oxidised nitrogen
TPH	total petroleum hydrocarbons
TRL	Transport Research Laboratory (formerly Transport and Road Research Laboratory,TRRL, and Road Research Laboratory, RRL)
TSS	total suspended solids
USEPA	United States Environmental Protection Agency
V	maximum storage volume for water below pervious pavement
V_t	treatment volume
VOC	volatile organic compound
γ_d	dry unit weight of soil or aggregate
γ_w	unit weight of water
μ	viscosity
ν	Poisson's ratio
WQO	water quality objective
WQS	water quality standard

Foreword

This publication is intended for use by clients, landscape architects, consulting engineers, local authorities, architects, highway authorities, environmental regulators, planners, sewerage undertakers, contractors, developers and other organisations involved in the provision or maintenance of surface water drainage to new and existing developments. It discusses the critical issues that must be considered when designing, constructing and maintaining SUDS schemes to effectively manage rainwater runoff from development sites.

The first part of the book includes general information relevant to all SUDS techniques. The second part contains detailed discussions about the design and performance of each technique.

To help the reader navigate the book, two flow charts are provided on the following pages (the SUDS information guide and the SUDS design process). The first identifies where information is located within the document, based on typical questions that a reader may want answered. The second identifies those sections of the book that are relevant to the various stages of the SUDS design process.

Part I

Chapter 1 (Introduction) introduces the concepts of SUDS and discusses the background to the development of a concept that deals with the management of surface water runoff. It identifies the relationship between this book and publications from CIRIA and other organisations.

Chapter 2 (SUDS concepts) identifies the management train concept, discusses how to integrate SUDS into site design and introduces the different techniques available. It gives information on the use of SUDS on brownfield sites (or sites where natural contamination is present). It also looks at the use of SUDS in conjunction with rainwater harvesting schemes.

Chapter 3 (Stormwater pollution) deals with stormwater pollutants that are either discharged to watercourses and sewers or infiltrated into the ground from SUDS schemes. It looks at the mechanisms and processes that occur within SUDS to improve water quality. This section also identifies applicable legislation and the issues that must be addressed to avoid causing pollution of either surface or groundwater. It describes how different combinations of techniques can be assessed to give the optimum efficiency for the management train.

Chapter 4 (Rainfall and runoff) is concerned with the assessment of greenfield runoff rates and runoff from developed sites. It identifies the criteria that should be considered when designing SUDS. This approach requires consideration of runoff from events with a range of annual probabilities (or return periods) and also requires careful consideration of overland flow routes during events that exceed the design criteria of the system (also known as flood routeing).

Chapter 5 (General SUDS design) discusses the general design issues that relate to all SUDS features, including the make-up of design teams, guidance on the choice of techniques to meet site-specific constraints and design information. It also explains how SUDS may be designed to maximise environmental benefits and to meet the required health and safety standards.

Chapter 6 (Construction of SUDS) includes information on the education of site staff and how the construction programme may need to be changed to allow for the SUDS. It recommends an independent inspection regime during construction.

Chapter 7 (Management) provides information on the maintenance regimes required.

Chapter 8 (Economics of SUDS) discusses the factors that should be included in any cost analysis of SUDS.

Part 2

Chapter 9 (Technical data for SUDS techniques) offers an in-depth discussion of the performance for each individual SUDS technique and provides best practice guidance for the design, construction and operation of SUDS.

Appendix 1 includes a decision matrix and flow chart to assist in selecting SUDS techniques.

Appendix 2 provides design examples.

Appendix 3 is a design information checklist.

Appendix 4 provides case studies (for further case studies see the CIRIA website, <www.ciria.org>).

Appendix 5 discusses the planting for SUDS.

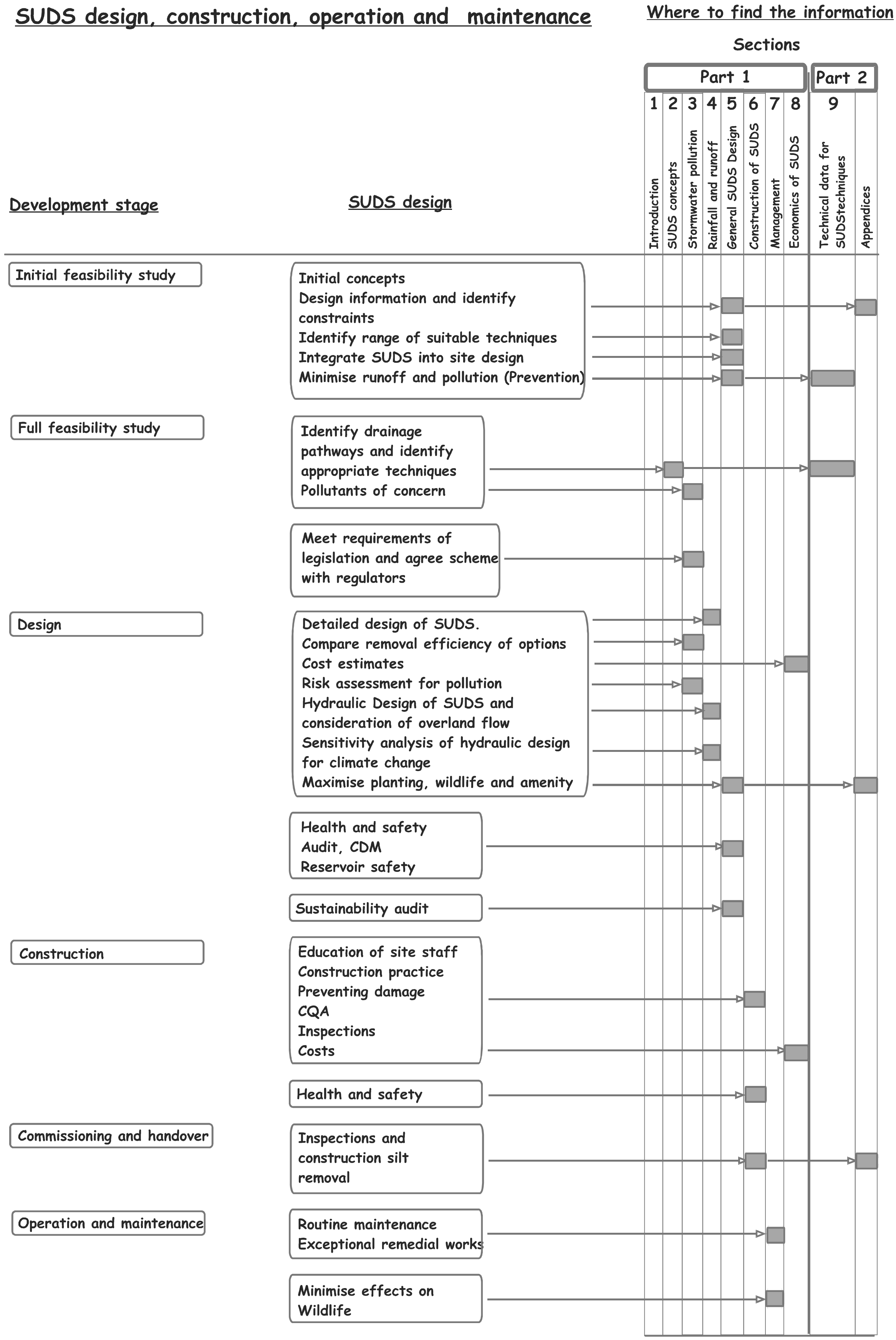
Appendix 6 gives a design accreditation checklist.

Appendix 7 gives a construction inspection checklist.

SUDS information guide

What information are you looking for?		Part 1: 1 Introduction	Part 1: 2 SUDS concepts	Part 1: 3 Stormwater pollution	Part 1: 4 Rainfall and runoff	Part 1: 5 General SUDS Design	Part 1: 6 Construction of SUDS	Part 1: 7 Management	Part 1: 8 Economics of SUDS	Part 2: 9 Technical data for SUDS techniques	Part 2: References	Part 2: Appendices
What are SUDS?		■	■									
Why use SUDS?		■										
Available techniques						■						
Constraints on the use of Techniques	A. General B. Detailed information for each technique		A							B		B
Make up of design teams						■						
Responsibilities for complying with environmental legislation				■								
Pollutant removal - comparison of techniques				■								
How do SUDS remove pollutants?	A. General B. Detailed information for each technique			A						B		
How do SUDS reduce runoff rate and volume?					■							
Estimation of runoff volumes for different design criteria					■							
Modelling SUDS					■							
Health and safety						■						
Designing SUDS for wildlife						■						
What are the routine maintenance and remedial work requirements?	A. General B. Detailed information for each technique							A		B		
How much will it cost to construct or maintain SUDS?									■			
Design details and recommendations										■		
Where can I find other information on SUDS?		■									■	■
What is different about building SUDS?							■					

SUDS design, construction, operation and maintenance



Part 1
General issues

What does this part include?

General introduction to the concept of sustainable drainage systems (SUDS) and a description of the techniques available (Chapter 1).

A discussion of how SUDS might be used on brownfield sites (Section 2.6).

General information on pollutant removal and the different mechanisms that occur with SUDS techniques (Chapter 3).

A discussion of the environmental legislation that affects SUDS designers, builders, operators and owners (Section 3.2).

General information on the assessment and modelling of rainfall and runoff for SUDS techniques (Chapter 4).

Description of how site-specific constraints affect the choice of techniques (Section 5.2).

A discussion of the design information required for SUDS (Section 5.4).

Information on how to maximise the wildlife benefits of SUDS (Section 5.6).

General issues relating to the construction of SUDS (Chapter 6).

General issues relating to the maintenance of SUDS (Chapter 7).

Information on the costs associated with SUDS schemes (Chapter 8).

1 Introduction

This chapter provides information for all readers of this technical report.

It describes the purpose and scope of the book and, for those readers not familiar with sustainable drainage systems (SUDS), gives a general introduction. The chapter also describes the important concepts and benefits that may be gained by using the techniques.

It provides other sources of information on SUDS techniques.

1.1 WHAT ARE SUSTAINABLE DRAINAGE SYSTEMS?

Sustainable drainage systems (SUDS) are increasingly being used to mitigate the flows and pollution from runoff. The philosophy of SUDS is to replicate as closely as possible the natural drainage from a site before development and to treat runoff to remove pollutants, so reducing the impact on receiving watercourses. This requires a reduction in the rate and volume of runoff from developments, combined with treatment to remove pollutants as close to the source as possible. They can also provide other environmental benefits such as wildlife habitat, improved aesthetics or community resource (Figure 1.1).

Figure 1.1 *SUDS*

SUDS permit a very flexible approach to be taken to drainage, and the techniques available range from soakaways to large-scale detention basins. The individual techniques are used in series in a management train designed to meet the site-specific constraints (Section 2.1). The techniques are not new, and many have been successfully used both in the UK and worldwide for at least 20 years, especially in the USA where they are known as best management practices (BMPs). A wealth of knowledge about their performance has been developed, particularly in the USA and mainland Europe. Over the past five years, a comprehensive SUDS research and monitoring programme has been undertaken in the UK, in Scotland in particular, which is beginning to yield a lot of performance data on systems in the UK climate.

Some common misconceptions about SUDS and what they comprise include:

- SUDS is the use of soakaways
- SUDS cannot be used on clay soils
- SUDS is the use of ponds and wetlands
- SUDS is storing rainwater on site and allowing it to flow out at a restricted rate
- SUDS does not include pipes.

None of these statements is entirely correct. The SUDS approach to drainage involves controlling the runoff from development sites so that it mimics greenfield runoff and maintains the natural drainage patterns, as far as possible. SUDS should also enhance the local environment.

To achieve this, a treatment or management train is required (Section 2.2) that comprises one or more techniques. These may or may not include soakaways, ponds and wetlands or pipes. The management train may also include techniques such as good site management to prevent pollution. Several SUDS techniques will be needed to reduce the volume of runoff and treat pollution.

A drainage set-up that does not provide a management train to meet all three criteria of quality, quantity and amenity may not be a sustainable drainage system in the strictest sense, although on some sites specific factors it may be that one criterion is more prominent than the others. A SUDS approach to drainage can and should be applied to all sites, although site constraints may limit the potential for a truly sustainable solution (Section 5.5).

Sustainable drainage systems may also incorporate storage for water reuse. (The permanent storage volume will generally be additional to any storage volume required to control runoff rates, unless a continuous rate of use can be guaranteed.) Further information on the design of systems for rainwater reuse can be found in CIRIA publication C539 (Leggett *et al*, 2001).

1.2 BENEFITS OF SUDS

It is widely accepted that the use of SUDS, as opposed to conventional drainage systems, generates several benefits (Martin *et al*, 2000a, 2000b and 2001). Appropriately designed, constructed and maintained SUDS can mitigate many of the adverse effects of urban stormwater runoff on the environment.

1. Lowering peak flows to watercourses or sewers, thereby reducing the risk of flooding downstream.
2. Reducing volumes and frequency of water flowing directly from developed sites to watercourses or sewers, to replicate natural land drainage and reduce flood risk.
3. Improving water quality over conventional surface water sewers by removing pollutants from sources such as cleaning activities (vehicles, windows), wear from tyres, oil leaks from vehicles or atmospheric fallout from combustion (in rural areas this can include runoff from fields where fertilisers and biocides are used).
4. Improving amenity through the provision of features such as wildlife habitat.
5. Reducing the number of times that combined sewer overflows (CSOs) operate and discharge polluted water to watercourses.
6. Replicating natural drainage patterns so that changes to base flows are minimised.
7. Finally, by increasing base flow to watercourses (through slow release of water).

The UK Government has recognised the benefits in relation to flooding, in PPG 25, *Development and flood risk* (DTLR, 2001).

Imaginative site design allows SUDS to be incorporated into almost any development, provided the risk of watercourse or groundwater contamination can be managed to acceptable levels. There is no reason why SUDS cannot be incorporated into urban developments where space is restricted. To achieve this, the SUDS design should be integrated into the site layout at the feasibility stage (Goransson, 1997 and Piel *et al*, 1999). Allocating space for SUDS was not a problem on Scottish developments owing to the production of innovative solutions for cramped sites (Jefferies, 2000). In these situations it is helpful to use SUDS features such as proprietary modular treatment systems and green roofs, or to implement rainwater harvesting. It should be remembered that public open space can be used for storing runoff in extreme storm events.

One aspect of SUDS that has received little attention in the UK is the "pond premium" (USEPA, 1995 and Schueler, 2000m). Evidence from the USA has shown there is a price premium on waterfront properties where SUDS ponds are incorporated into new developments. The premium in the USA is greatest for houses, flats or offices overlooking a well-designed and well-maintained pond or wetland with an area greater than 0.4 ha. This effect was also observed at a development in Scotland (McKissock *et al*, 1999) although the economic benefits experienced in the US were greater. There are other economic benefits from integrating SUDS into the overall site design, such as reduced construction costs (New Jersey Department of Environmental Protection, 2000), especially where impervious areas are reduced.

In the broader planning of the urban landscape, the use of SUDS for water storage for reuse may help with the maintenance of plants, trees and shrubs. The use of stored rainwater, which is often less acidic (and cheaper) than treated mains water, is another benefit available through the appropriate use of SUDS, with the potential to reduce demand for potable water.

Maintenance requirements for SUDS are no more onerous (and often less so) than those for conventional drainage, but they are different (Section 7.2). This should not prevent the selection of SUDS, as the other advantages in flood control, water reuse and groundwater recharge may have greater benefits, both locally and more widely in the environment.

1.3 BACKGROUND TO PROJECT

Organisations including DEFRA, Environment Agency, SEPA and Environment Heritage Services (Northern Ireland) widely promote SUDS as a more sustainable alternative to traditional drainage schemes. There has been a growth in the number of SUDS schemes implemented since 1995, especially in Scotland, where nearly 4000 systems have been installed. Nonetheless, for many involved in site development there is scope for increased knowledge about the technical detail of SUDS, including the available techniques and, in particular, the hydraulic, structural and water quality issues that need to be considered during their design life (including the life-span itself). To date there has been no wide-scale implementation of the management train, one of the key concepts of SUDS, so the valuable amenity benefits SUDS could deliver have not been fully realised.

CIRIA and other organisations in the UK have produced general design guidance for SUDS systems, but consultation with a wide range of stakeholders, including clients, designers and contractors, has identified the need for more detailed design guidance.

This book and its associated research project address this by providing more detailed information than has been previously available for the individual SUDS techniques, drawn from UK and international sources. This should encourage even wider uptake of SUDS and ensure greater consistency in design in the UK as a whole.

1.4 PURPOSE AND SCOPE OF THIS BOOK

This technical guide informs readers about the appropriate approach to take for the successful design and construction of SUDS. Using the best available information, it also aims to improve readers' understanding of the hydraulic, structural and water quality performance issues of SUDS techniques and components. The current level of knowledge relating to some of the design and performance issues varies, and in some cases rigorous analysis is not possible. This is true in other areas of engineering and should not be a barrier to the use of SUDS. Where necessary, conservative assumptions and judgement based on observed performance can be used to produce a successful design.

The book provides sufficient design information to enable both specifiers and constructors of SUDS to adopt a more scientifically-based approach to the design of a stormwater treatment or management train. SUDS management trains designed in accordance with this publication should:

- deal with stormwater by helping to maintain runoff rates and volumes from developments at or close to pre-development levels
- minimise the risk of pollution to controlled waters
- provide improved public amenity
- be appropriate for the site.

This book is not intended be a detailed guide to the hydraulic or structural design of drainage systems. Only those aspects of hydraulic and structural design directly affected by the use of SUDS are discussed. Where necessary, reference is made to other publications describing design methods that can be applied to SUDS.

The book does not cover the design of sustainable drainage schemes for major highways under the control of the Highways Agency. The Highways Agency in England and Wales does not recognise the term "sustainable drainage system" and refers to a range of sustainable highways drainage practices, including vegetative treatment. It does not allow the use of pervious pavements for source control on major roads (Pratt *et al*, 2002). Readers should refer to the *Design manual for roads and bridges* (Highways Agency *et al*, 2001) for design advice for SUDS for major roads controlled by the Highways Agency. This does not preclude the use of SUDS on other highways.

In Scotland the use of SUDS on highways is an accepted drainage technique.

1.5 SOURCES OF INFORMATION

The book has been compiled from information gained from a worldwide literature review covering all aspects of SUDS. Where possible, UK data has been used, in particular drawing on the wealth of monitoring that has been undertaken in Scotland. The literature search revealed a strong weighting towards the USA, where monitoring and assessment of SUDS techniques has been carried out for more than 15 years.

To obtain the widest possible range of opinions, views have been sought from a diverse range of consultants, contractors and manufacturers/distributors.

The research has been reviewed and agreed by a dedicated steering group comprising experienced individuals from a diverse range of disciplines.

1.6 ASSOCIATED PUBLICATIONS

This book provides independent best practice guidance on the development of a more scientific approach to the design, construction and maintenance of SUDS techniques and components. It forms part of a suite of CIRIA publications relating to the design and construction of SUDS. Published titles are listed below, by date of publication.

- *Design of flood storage reservoirs*, Book 14 (Hall *et al*, 1993). A design guide that can be applied to SUDS ponds.
- *Control of pollution from highway drainage discharges*, Report 142 (Luker and Montague, 1994). Information on the water quality of highway runoff.
- *Infiltration drainage, manual of good practice*, Report 156 (Bettess, 1996). Provides a method of rainfall estimation and a design method for infiltration below pervious pavements.
- *Review of the design and management of constructed wetlands*, Report 180 (Nuttall *et al*, 1997). Design information for wetlands for water treatment.
- *Sustainable urban drainage systems – design manual for Scotland and Northern Ireland*, publication C521 (Martin *et al*, 2000a). Describes best practice in Scotland and Northern Ireland, and sets out the technical and planning considerations for designing drainage systems for surface water inspired by natural processes.
- *Sustainable urban drainage systems – design manual for England and Wales*, publication C522 (Martin *et al*, 2000b). Technical and planning considerations for designing drainage systems for surface water inspired by natural processes, with guidance adapted for the geophysical conditions, planning and environment and legal system of England and Wales.
- *Sustainable urban drainage systems – best practice manual*, publication C523 (Martin *et al*, 2001c). Covers the wider aspects of best practice in sustainable drainage systems. Addresses the legislative issues surrounding SUDS and ways in which organisations may work together in employing drainage systems based on natural processes.
- *Source control using constructed pervious surfaces*, publication C582 (Pratt *et al*, 2002). Technical review of existing information on pervious surfaces, which discusses the hydraulic, structural and water quality issues.
- *Model agreements for sustainable water management systems. Model agreements for SUDS*, publication C625 (Shaffer *et al*, 2004). Basic advice on the use and development of model operation and maintenance agreements for SUDS alongside simple guidance on their incorporation in developments.

Further information on the publications and general information about SUDS is provided on the CIRIA website, <www.ciria.org>, together with additional case studies.

2 SUDS concepts

This chapter should be read by those who are not familiar with the concepts of SUDS techniques and by designers who want more detailed information on the choice of techniques and their use on brownfield sites.

It stresses the importance of the management train and explains how SUDS can be integrated into site design. It provides general guidance on the site-specific constraints that affect the selection of each technique. It also includes a discussion on specific issues and on retrofitting SUDS to existing sites.

2.1 INTEGRATION AND PLANNING

Successful SUDS design requires the drainage to be carefully integrated into the site while taking account of the original greenfield drainage patterns (Section 4.3.1). Integration is the most effective way to achieve the desired objectives of SUDS use. SUDS designs that integrate the features into the overall site design generally result in smaller, more cost-effective solutions (Minnesota Metropolitan Council, 2001). The philosophy that "prevention is better than cure" is appropriate to SUDS. If SUDS is considered only as a bolt-on to a conventional site design, the results are often unnecessarily large and costly, as shown in Figure 2.1.

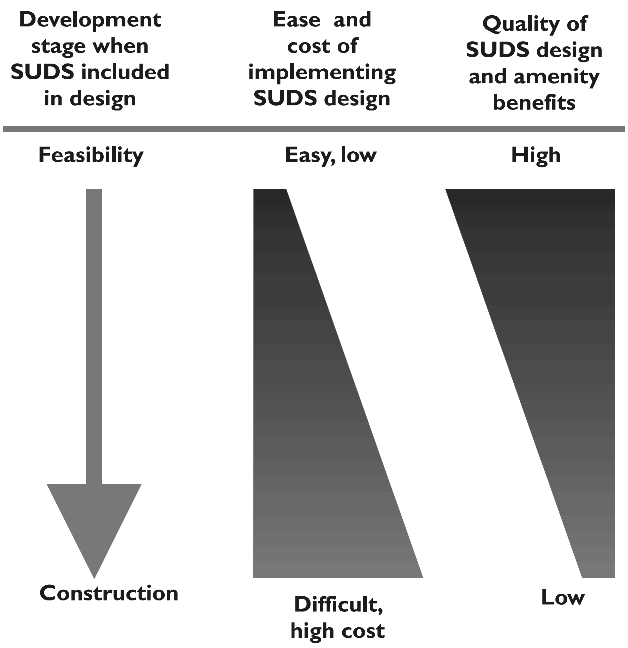


Figure 2.1 *Cost of environmental control versus point of implementation*

To help incorporate SUDS into the initial site design, the following factors should be taken into account.

- Street design can be used to reduce impervious surfaces. Site layout can minimise the length of roads and keep the width to the absolute minimum consistent with achieving safe traffic movement. The edge of streets can be constructed using pervious surfaces to minimise runoff. Cul-de-sac turning areas can be given the minimum practicable radius and hammerheads should be used in preference to circular areas to minimise imperviousness.

- Raised kerbs and gutters should be avoided wherever possible, as they amplify stormwater volume and velocity (Minnesota Metropolitan Council, 2001). Roads without raised kerbs and gutters tend to be less expensive, but the edges should be detailed so that water is collected in a SUDS feature and does not flow back into the road construction and weaken it.

- Reinforced grass can be used for overspill car parking areas and parking space dimensions minimised. Again, kerbs and gutters can be avoided.

- The landscaped areas associated with roads and car parks can be placed so that they act as filter strips, swales, bioretention areas or other SUDS features.

- The site layout and levels can be designed to follow the existing topography as far as possible. This helps preserve natural hydrology and drainage pathways on the site and assists with overland flood routes (Atlanta Regional Commission, 2001).

2.2 THE IMPORTANCE OF THE MANAGEMENT TRAIN CONCEPT

The concept of the stormwater management train is described in CIRIA C521 and C522 (Martin *et al*, 2000a and 2000b). This concept is fundamental to designing a successful SUDS scheme and addresses the quality and quantity of runoff at all stages of a drainage system. It uses drainage techniques in series to improve the quality and quantity of runoff incrementally, by reducing pollution, flow rates and volumes.

The management train provides a hierarchy of techniques, which are listed below in order of preference.

1. **Prevention** – the use of good site design and housekeeping measures on individual sites to prevent runoff and pollution (for example, sweeping to remove surface dust from car parks), and rainwater reuse/harvesting.
2. **Source control** – control of runoff at or very near its source (through the use of pervious pavements or green roofs, for example).
3. **Site control** – management of water from several subcatchments (by routeing water from building roofs and car parks to one large soakaway or infiltration basin for the whole site, for example).
4. **Regional control** – management of runoff from several sites, typically in a detention pond or wetland.

The management train is summarised in Figure 2.2. Techniques that are higher in the hierarchy are preferred to those further down, so that prevention and source control should always be considered before site or regional controls. Water **should be conveyed elsewhere only if it cannot be dealt with on site**, for example because of lack of space. Conveyance between individual parts of the management train should also be considered.

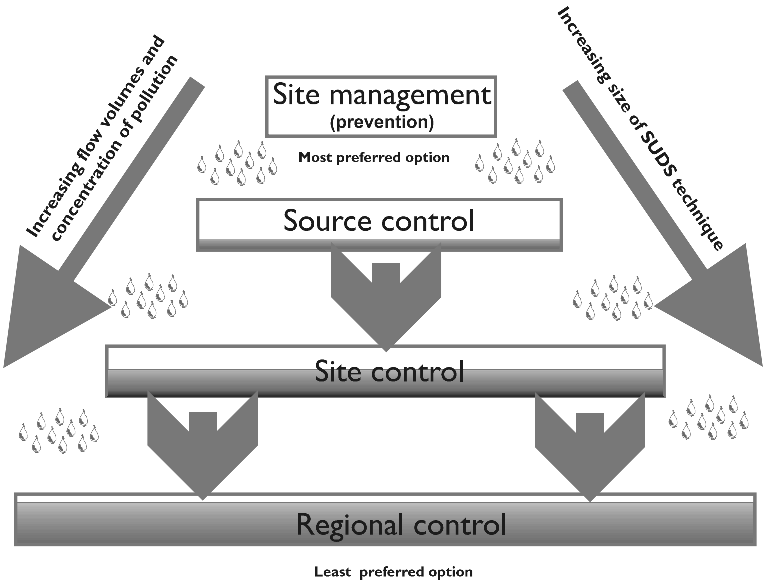


Figure 2.2 *The management train*

Dealing with runoff at source should generally be more effective, since volumes should be lower and pollutants will not be concentrated in the stormwater stream. The concept is enshrined in the Building Regulations, Part H (DTLR, 2002), which states that infiltration of runoff is preferred over discharge to watercourses. Discharge to sewers should be used only when no other option is available.

Before treatment, it vital for the SUDS techniques employed to be able to remove gross silt or sediment loads, so as to ensure the long-term effectiveness of all techniques.

All SUDS designs should clearly demonstrate that a stormwater management train is provided (Sustainable Drainage Associates, 2002). The treatment system should comprise a series of features that complement each other (for example, filter strips and infiltration trenches). The more techniques used in a system, the better the performance is likely to be. The use of more than one technique reduces the risk of system failure. The response of the management train to runoff in excess of the design event also needs to be considered. Overland flow routes (or flood routes) need to be designed to avoid causing flooding to buildings (see Section 4.3.4).

The design of a SUDS scheme should recognise that several features may be required to achieve different objectives. For example, a swale may be used to control pollution and attenuate some runoff flows, but a detention pond may be required to control the flows from more extreme events. The relative contribution each technique can make to water quality, volume or flow reduction and improved amenity is provided in Appendix 1.

2.2.1 Site management

In the USA great emphasis is placed on site management tools or good housekeeping procedures that are used to limit or prevent runoff and pollution. These include:

- the frequent sweeping of impervious surfaces with disposal to licensed landfill
- the minimising of application rates of de-icing products and use of alternative techniques (for example, wet gritting to reduce total chloride load) or alternative products such as calcium magnesium acetate (CMA), which has been shown to decrease sodium levels in runoff (Minnesota Metropolitan Council, 2001).

- careful choice and minimisation of fertilisers, herbicides and fungicides applied to landscaped areas
- management of construction sites to limit soil erosion and the volume of sediment in runoff – see CIRIA C532 (Masters-Williams, 2001)
- ensuring adequate procedures and equipment exist for prompt treatment of spillage of materials using dry rather than wet techniques
- limiting the potential for runoff to come into contact with pollutants (for example, by keeping stored chemicals inside buildings or bunds)
- educating the public to reduce the volume of fertiliser and weedkiller applied to lawns and to reduce runoff from car washing into the surface water system.

An essential part of the use of these procedural approaches is the education and training of site owners, occupiers and maintenance staff. Further information is provided in Section 5.4 and Section 7.2. The use of independently monitored environmental management systems that comply with ISO 14001, *Environmental management systems – specification with guidance for use* will also be useful to increase confidence that procedures will be followed. The Environment Agency and Scottish Environment Protection Agency also produce a series of Pollution Prevention Guidelines that recommend good practice to prevent pollution of controlled waters.

2.2.2 Source control

Source control (also known as best management practices) is the preferred option in any SUDS scheme and should be the first to be considered. This is because controlling runoff at source should result in relatively small catchment areas where the volume of runoff and pollution are not concentrated into the surface water stream, thereby reducing the consequence of failure.

It is important to try to reduce site runoff at source, where possible, by the use of infiltration and planting to encourage evapotranspiration. Source control techniques include pervious pavements, swales, bioretention areas, green roofs, filter drains and infiltration devices (Figure 2.3). Rainwater harvesting can also provide a valuable method of reducing the volume of runoff from a site.

2.2.3 Conveyance

Water should only be conveyed elsewhere if it cannot be dealt with at source. Methods of conveyance include swales, pipes and filter drains (Figure 2.3).

2.2.4 Site control

Where source control is not feasible, or additional control of runoff is required, then site control measures can be used. In this case, the runoff from several sub-catchments within a site are amalgamated and dealt with in features such as ponds, basins or wetlands. Care should be taken when using site control, as the effect of concentrating runoff increases volumes and can increase pollutant concentrations. Thus the consequence of failure is likely to be greater with site than source control.

2.2.5 Regional control

Regional control is similar to site control, but the overall catchment tends to be larger as it deals with water from several sites and the same site control techniques are used (Figure 2.3). Regional control features should not be used on their own without some form of source control provided within individual developments.

2.3 QUALITY, QUANTITY AND AMENITY

As discussed in Section 1.1, a SUDS scheme should include provisions to control volume and rate of runoff from a site, remove pollution and provide some public amenity benefit such as open space or wildlife habitat. Any scheme that does not provide these is not fully consistent with the SUDS philosophy, although a scheme that provides some, but not all, of these benefits may be the most sustainable solution in certain cases. To maximise benefits it is particularly important to ensure that the amenity value is integrated into the overall design from an early stage (Everard and Street, 2002). Guidance on provision of amenity and wildlife is provided in Section 5.7.

2.4. COMMON SUDS TECHNIQUES

A wide range of SUDS techniques can be used to provide a stormwater management or treatment train. The most common techniques fit into the following categories: those with a primary use of pre-treatment, conveyance, source, site or regional controls (Figure 2.3). Many of the techniques are used in more than one category and several may be considered useful for pre-treatment and conveyance of runoff.

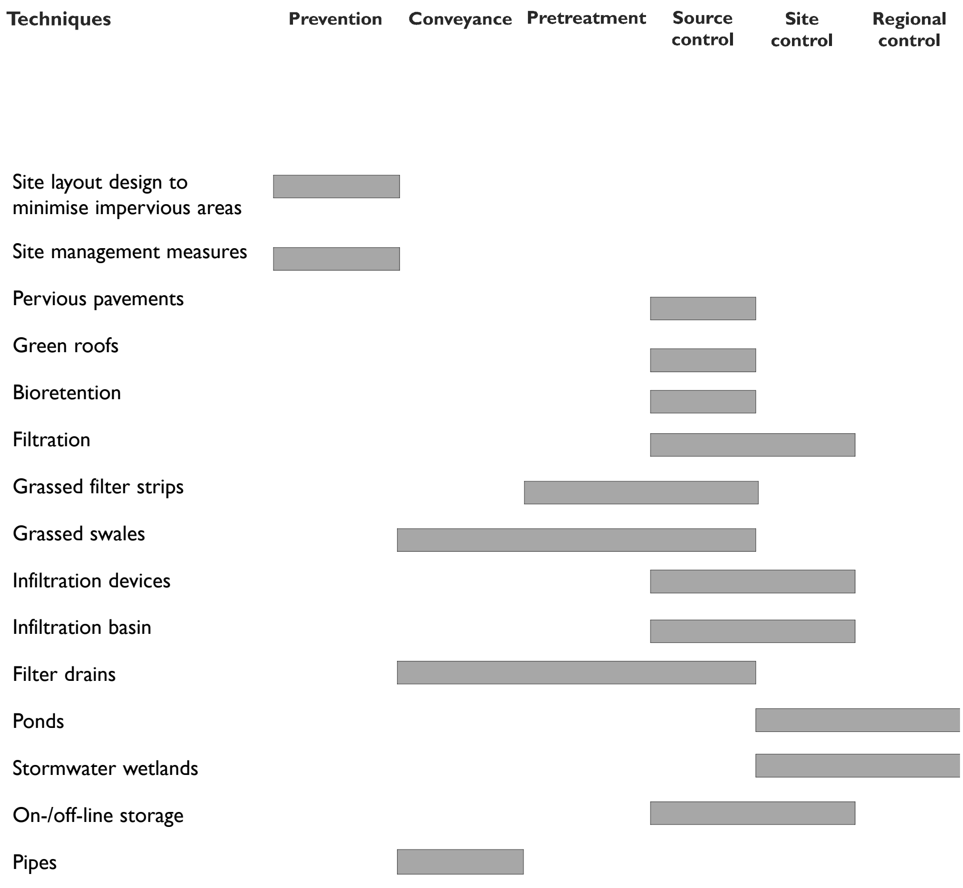


Figure 2.3 *Common SUDS techniques*

Each technique has particular capabilities with respect to water quality treatment, attenuation and reduction of volumes, so a series of features is usually required to meet all the design criteria. Further information on the choice of techniques to meet the design criteria is provided in Section 5.5. The use of SUDS is a rapidly developing area and new proprietary techniques are being developed constantly. The above list is not exhaustive, therefore, and new techniques should be judged on their merit.

2.5 RETROFITTING

SUDS techniques can be retrofitted to existing sites to reduce the risk of flooding in receiving waters or to reduce pollutant loadings in runoff. It is often easier to retrofit an individual technique, rather than provide a management train. An example of retrofitting is provided in CIRIA C582 (Pratt *et al*, 2002) where a pervious surface and a filter drain were installed along one edge of a residential street in Powells Creek, Australia. This improved the water quality in the stream receiving the runoff. Retrofit schemes have also been installed in Japan to improve river quality and reduce the number of sewer overflow operations (Koyama and Fujita, 1990).

The six methods of retrofitting SUDS to sites used in the USA (Claytor, 2000) are listed below.

1. Retrofit older existing stormwater management facilities (for example, changing a detention pond into a constructed wetland by deepening and changing the outlet structure is a particularly effective method of retrofit). The implications of changing water levels should be fully considered (for example, whether an altered pond will fall under the requirements of the Reservoirs Act).
2. Construct new facilities at the upstream end of road culverts, subject to obtaining the necessary agreements and approvals. This may be achieved by providing a control structure and a micro pool, although the provision of these should not cause flooding elsewhere and must be approved by all appropriate authorities. This approach may be difficult in the UK.
3. Construct new facilities at the end of drainage systems (such as off-line sand filters, storage systems or bioretention areas).
4. Provide small-scale amendments in open channels (for example, widen ditches and provide bioretention or check dams to slow down flow and promote sedimentation).
5. Construct on-site measures at the edges of large parking areas by removing or slotting the kerbs to allow water to flow into grassed landscaped areas that will act as filter strips and bioretention areas (New Jersey Department of Environmental Protection, 2000).
6. Construct new stormwater practices within highway boundaries.

One further method is the replacement of impervious surfaces with pervious surfacing. It is important to consider the need for and objectives of retrofitting SUDS, as they may not be appropriate in some cases. All the constraints on a site should be understood before undertaking a retrofit design (for example, the location of all buried services should be known so that conflicts can be designed out).

Conventional SUDS design usually follows a pre-determined design criteria, but for retrofit the design process works in reverse. Starting with a set of existing site constraints, the designer should determine the best stormwater control or treatment obtainable, even though this may not fully comply with current design standards (New Jersey Department of Environmental Protection, 2000).

The key to the successful design of retrofit SUDS is balancing the needs of pollutant removal and watercourse protection while limiting the impacts of the new installation on adjacent structures and occupiers.

The following factors should be considered (Claytor, 2000):

- avoid relocating existing utilities
- minimise impact on existing wetland and forest
- maintain existing floodplain levels
- comply with reservoir safety
- avoid causing maintenance nuisance situations.

The opportunity to retrofit is likely to be limited to situations where sites are being refurbished or where the existing drainage system has failed and requires replacement.

A case study of a retrofit system to a UK school is provided in Appendix 4. The retrofit was installed during construction of an extension to reduce the cost of installing drainage for the scheme.

2.6 SUDS ON BROWNFIELD SITES

The main consideration for SUDS on brownfield sites is whether ground contamination is present (note that not all brownfield sites are contaminated). Implementing a SUDS scheme should not be difficult if care is taken in the design to avoid mobilising pollution into the surface water or groundwater. Indeed, the use of shallow SUDS should limit the need for the deeper and oversized excavations and lining commonly associated with conventional drainage on contaminated sites. The use of piped systems can also provide sub-surface off-site pollution pathways, via the trench backfill, that may be removed by the use of SUDS.

Each contaminated site is different and contamination may vary from slight to gross, so each site should be assessed on its own merits (City of Portland Environmental Services, 2002). Where SUDS are used on contaminated sites, it is essential to seek the advice of an experienced geo-environmental specialist (as defined by the AGS) who is familiar with contaminated land and groundwater risk assessment.

The need for a comprehensive site investigation and hydrogeological assessment is of the utmost importance on contaminated sites. The site investigation should include a desk study and the determination of both total and leachable concentrations of soil contaminants together with the concentrations of groundwater contaminants. The site investigation should be designed to satisfy the predicted requirements of the SUDS, that is, it should be undertaken after the conceptual design has been prepared so that, for example, infiltration tests can be carried out in the location of infiltration devices. More information can be obtained from BS 5930:1999, CIRIA C552 (Rudland *et al*, 2001) and CIRIA Special Publication 103 (Harris *et al*, 1995).

On contaminated sites the following factors need to be addressed.

1 Prevent mobilisation of contamination and transportation to receiving waters, especially by infiltration from shallow features such as swales or pervious surfaces. Water cannot be allowed to percolate through soils if they contain contaminants in a form that can be leached out. If such soils are present, then infiltration may still be used if it occurs below the base of the contaminated soils. The problem may also be solved by removing contaminated soil from around an infiltration trench or soakaway. Contaminated soil may be removed from below and around the sides of the infiltration zone to a minimum radius of 2 m (see Figure 2.4), but each site will require its own assessment.

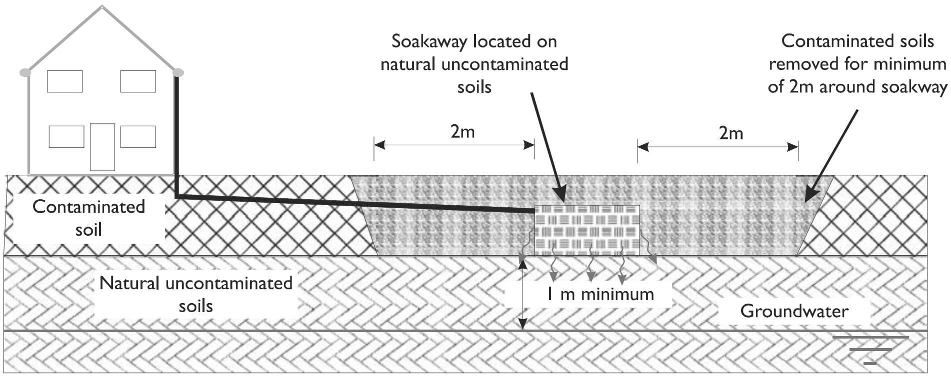


Figure 2.4 *Example installation of an infiltration system on a contaminated site*

2 Prevent flow of contaminated groundwater into the SUDS. Any SUDS element into which groundwater can flow should be lined with a membrane or constructed with its base at least 1 m above the highest estimated groundwater level.

3 Use features that minimise the need for excavation and disposal of contaminated soils, which is expensive, especially in the south-east of England. These costs are likely to increase in the future as landfill space becomes scarcer. Shallow SUDS features such as pervious pavements, swales and bioretention areas can minimise excavations and disposal costs, lowering costs considerably.

4 Many brownfield sites are only marginally contaminated and the contamination is in a non-leachable form. On such sites the presence of slight contamination should not pose a significant risk to groundwater when SUDS are used. A risk assessment should be used to identify whether the risks are acceptable.

Prevention of surface or groundwater contamination during construction is especially important and runoff from exposed contaminated soils should not be allowed to enter the SUDS scheme. (For further information on preventing runoff from construction operations damaging the SUDS see Section 6.4.)

Some contaminants, such as arsenic, occur naturally and are present in many greenfield sites in the UK. The risks posed by the presence of natural contaminants require careful consideration. Evaluation should be undertaken by a geo-environmental engineer familiar with risk-management techniques applied to contaminated sites. The risk posed by using SUDS on such sites can be managed by mimicking the natural drainage patterns and avoiding the use of devices that concentrate infiltration in a small area. In this respect, the use of pervious surfaces that infiltrate water over a wide area would be preferred to soakaways.

2.7 SUDS AND RAINWATER HARVESTING

Rainwater from roofs and hard surfaces such as car parks can be stored and reused (or "harvested"). The collected water can be used for non-potable purposes, such as watering gardens or flushing toilets. Rainwater may not require disinfection or physical/biological treatment to allow it to be stored and reused. Such systems can be used to reduce the volume of runoff, even where other SUDS devices may be considered unsuitable and can be regarded as a prevention technique (Section 2.2).

Typically, the stored water is held in off-line storage tanks and the permanent storage volume required for reuse is provided in addition to the volume required to attenuate stormwater flows, unless a continuous rate of use can be guaranteed. More information is provided in CIRIA C539 (Leggett *et al*, 2001).

3 Stormwater pollution

This chapter should be read by those who require information on the type of pollution that occurs in runoff from urban surfaces, the sources of such pollution and its effects on streams, rivers or other surface waters.

The following pages describe how rainfall washes pollution off surfaces such as roads and car parks and the mechanisms in SUDS techniques that work to clean the pollution.

Detailed information is provided on levels of pollution that occur and guidance is given on risk assessment for SUDS. The section examines how the management train can be designed to achieve efficient removal of pollutants using a combination of techniques.

It discusses the environmental legislation with which clients, owners, operators, designers and contractors must comply if they are to avoid incurring liabilities or committing an offence.

3.1 POLLUTION AND FIRST FLUSH CONCEPT

3.1.1 Sources of pollution in runoff

Impermeable surfaces collect pollutants from a wide variety of sources including cleaning activities (vehicles, bins, windows), wear from car tyres, deposition from vehicle exhausts, vehicle oil leaks, general atmospheric deposition, from maintenance of landscape areas and as a result of illegal disposal of chemicals and oils. Several authors have identified the significant sources of pollution in urban runoff. The main source of information specific to the UK is a CIWEM report (D'Arcy *et al*, 2000), although there is useful information in other references (Novotny and Olem, 1994; Luker and Montague, 1994; Novotny, 1995 and Pitt *et al*, 1996). The pollution that occurs due to runoff from impermeable surfaces is known as diffuse non-point pollution. Diffuse pollution is defined as follows (D'Arcy *et al*, 2000):

> *pollution arising from land-use activities (urban and rural) that are dispersed across a catchment, or sub-catchment, and do not arise as a process effluent, municipal sewage effluent, or an effluent discharge from farm buildings.*

It includes the following characteristics:

- discharges enter receiving waters at intermittent intervals and the levels of pollution are variable; both are dependent on meteorological events (rainfall in the case of drainage systems)
- the pollution is generated over a wide area and transported overland to receiving waters
- the source is very difficult to monitor at the point of origin
- individual sources may be minor but collectively they are significant
- there may be a time lapse between the onset of pollution and the manifestation of adverse effects.

Non-point sources of pollution can be characterised as not entering receiving waters at any specific identifiable location.

The most important pollutants from diffuse sources are suspended solids, nutrients and toxic compounds including oil and heavy metals. The types of pollutants and their sources are summarised in Table 3.1. The precise concentrations that may occur are related to land use, geographic location and traffic volumes (see Section 3.1.3).

Table 3.1 *Sources of pollution on impermeable surfaces*

Source	Typical pollutants	Comments
Atmospheric deposition	Phosphorous Nitrogen Heavy metals (lead, cadmium, copper, nickel, zinc)	Industrial activities, traffic air pollution and agricultural activities all contribute to atmospheric pollution. This is deposited as particulates on surfaces. Rain also absorbs pollutants from the atmosphere
Traffic – exhausts	Hydrocarbons MTBE Cadmium Platinum Palladium Rhodium	Vehicle emissions include polycyclic aromatic hydrocarbons (PAH) and unburnt fuel and particles from catalytic converters
Traffic – wear and corrosion	Sediment Heavy metals (lead, chromium, copper nickel and zinc)	Abrasion of tyres and corrosion of vehicles deposits pollutants on to the road or car parking surfaces
Traffic – leaks and spillages	Hydrocarbons Phosphates Heavy metals Glycols Alcohols	Engines leak oil and spillages occur when refuelling. Lubricating oil can contain phosphates and metals that are present in performance additives. Accidental spillages of fuel or oil may occur, but in practice this is more likely in specific locations such as filling stations. Leakage and spillage of hydraulic fluids and de-icing fluids also occurs from vehicles during maintenance.
Roofs – atmospheric deposition, bird droppings, corrosion and vegetation (eg moss)	Heavy metals (copper, lead and zinc), bacteria, organic matter (BOD)	Roof water is often regarded as clean. It can however, contain significant concentrations of heavy metals resulting from atmospheric deposition, the corrosion of metal roofing or from other coatings such as tar (Schueler, 2000c and Thomas, 1994).
Litter/animal faeces	Bacteria (for example faecal coli-form) Viruses Phosphorous Nitrogen	Litter deposits can contain items such as drinks cans, paper, food, cigarettes, animal excreta, plastic and glass. Some of this will break down and cause pollutants to be washed off urban surfaces. Dead animals in roads decompose and release pollutants including bacteria. Pets leave faeces that wash into the drainage system
Vegetation/ landscape maintenance	Phosphorous Nitrogen Herbicides Insecticides Fungicides Organic matter (BOD)	Fallen leaves and grass cuttings can fall on to impervious surfaces and cause pollution of runoff. Herbicides and pesticides used for weed and pest control in landscaped areas such as gardens, parks, recreation areas and golf courses can be a major source of pollution
Soil erosion	Sediment Phosphorous Nitrogen Herbicides Insecticides Fungicides	Runoff from poorly detailed landscaped or other areas can wash on to impervious surfaces and cause pollution of runoff

Table 3.1 *Sources of pollution on impermeable surfaces* (continued)

Source	Typical pollutants	Comments
De-icing activities	Sediment Chloride Sulphate Heavy metals (iron, nickel, lead and zinc) Cyanide phosphate	De-icing salt is commonly used for de-icing roads and car parks in the UK. Rock salt for this purpose comprises predominantly sodium chloride (91 per cent) and insoluble residue (9 per cent), although the composition will vary depending on the source (Luker and Montague, 1994) De-icing salt can include cyanide (commonly as sodium ferrocyanide) as an anti-caking agent and corrosion inhibitor, and phosphate additives to control corrosion and prevent caking, but the use of these is being reduced because of the environmental implications. It can also include heavy metals Urea and ethylene glycol may also be used in some limited situations. Urea can cause pollution by ammonia and can seriously affect copper items leading to secondary copper pollution
Cleaning activities	Sediment Phosphorous Nitrogen Detergents	Washing vehicles, windows or bins, or pressure-washing yards, leads to silt, organic matter and detergents entering the surface water drainage (for example, on private driveways)
Wrong sewer connections	Bacteria Detergents	Wrong connections of foul sewers to surface water sewers where separate sewers exist
Illegal disposal of chemicals and oil into sewers	Hydrocarbons Various chemicals	Illegal disposal of used engine oils or other chemicals can occur in a range of situations from small-scale domestic events to large-scale industrial scenarios

3.1.2 Pollutants of concern

Each pollutant affects the environment in different ways and has different transport mechanisms and fates. These are summarised in Table 3.2 along with typical removal mechanisms that occur in SUDS.

Table 3.2 *Effects, transport and fate of pollutants*

Pollutant	Environmental effects	Transport mechanisms	Removal mechanisms (fate) in SUDS
Nutrients Phosphorous Nitrogen	Algal growth, eutrophication and reduced clarity. Results in fish kill	Dissolved in water or attached to sediment	Sedimentation, biological removal, denitrification, precipitation
Sediments Total suspended solids (TSS)	Increased turbidity, lower dissolved oxygen levels, smothering of aquatic habitat	Carried within water	Sedimentation, filtration
Pathogens Bacteria Viruses	Human health risks via drinking water supplies, bathing and other recreational pursuits	Carried with water or attached to sediment	Attack by soil microflora, sunlight, filtration, adsorption (although viruses will still be infectious until they are killed – Novotny and Olem, 1994), reduced length of survival in dry warm soils (Novotny and Olem, 1994)

Table 3.2 *Effects, transport and fate of pollutants* (continued)

Pollutant	Environmental effects	Transport mechanisms	Removal mechanisms (fate) in SUDS
Hydrocarbons Total petroleum hydrocarbons Polycyclic aromatic hydrocarbons Volatile organic compounds (VOCs) MTBE	Causes toxicity of water, bio accumulates in aquatic species. Reduces oxygen levels in water	Predominantly attached to sediment (70% – Mitchell *et al*, 2001). VOCs and MTBE readily dissolve in water	Sedimentation, filtration, adsorption, biodegradation (time can vary from days to years depending on technique), volatilisation (VOCs and MTBE)
Metals Lead Copper Cadmium Mercury Zinc Chromium Aluminium	Causes toxicity of water, bio-accumulates in aquatic species. Can result in fish kill	The majority of metals in runoff are attached to sediment (Pitt *et al*, 1996) although some are dissolved. Zinc in runoff is predominantly soluble form whereas lead is predominantly attached to sediment (Novotny, 1995)	Sedimentation, adsorption, filtration
Pesticides	Causes toxicity of water, bioaccumulates in aquatic species. Algal growth, eutrophication. Can result in fish kill	Dissolved in water or attached to sediment	Biodegradation, biological processes, adsorption, volatilisation
Other			
Chlorides	Cause toxicity of water	Dissolved in water	Prevention (chlorides do not adsorb to soils, cannot be filtered as they are dissolved and are hard to remove – Pitt *et al*, 1996)
Cyanide	Cause toxicity of water	Dissolved in water or attached to sediment	Under acidic conditions, in the presence of strong sunlight, sodium ferrocyanide is known to break down, generating toxic cyanide forms, including hydrogen cyanide. Most cyanide in surface water will form hydrogen cyanide and evaporate (Mangold, 2000)
Litter	Visual impact and threat to wildlife	Deposited in SUDS technique directly, carried along by water or wind-blown	Trapping using outlet guards, removal during routine maintenance
Organic matter BOD	The BOD of organic wastes (eg plant and grass cuttings, farm slurries) removes dissolved oxygen in receiving waters. Results in death of aquatic life. Nutrients are also associated with organic waste	Carried in water	Filtration, sedimentation, biodegradation

Pollutants are transported from impermeable areas to receiving waters either by surface flow and flow through pipes or via sub-surface paths where runoff is infiltrated and eventually reaches the groundwater table.

Surface flow is characterised by relatively high velocities and horizontal flow, which keeps pollutants entrained in the runoff. Sub-surface flow in the unsaturated zone is mostly vertical but with occasional horizontal flows, and it follows a potentially complicated pathway through the soil or rock via fissures and permeable zones. When it reaches the groundwater, the flow becomes sub-horizontal in the direction of groundwater flow. Subsurface flow is slow compared with surface flows, which maximise the opportunity for filtration of sediment and adsorption of pollution (Figure 3.1).

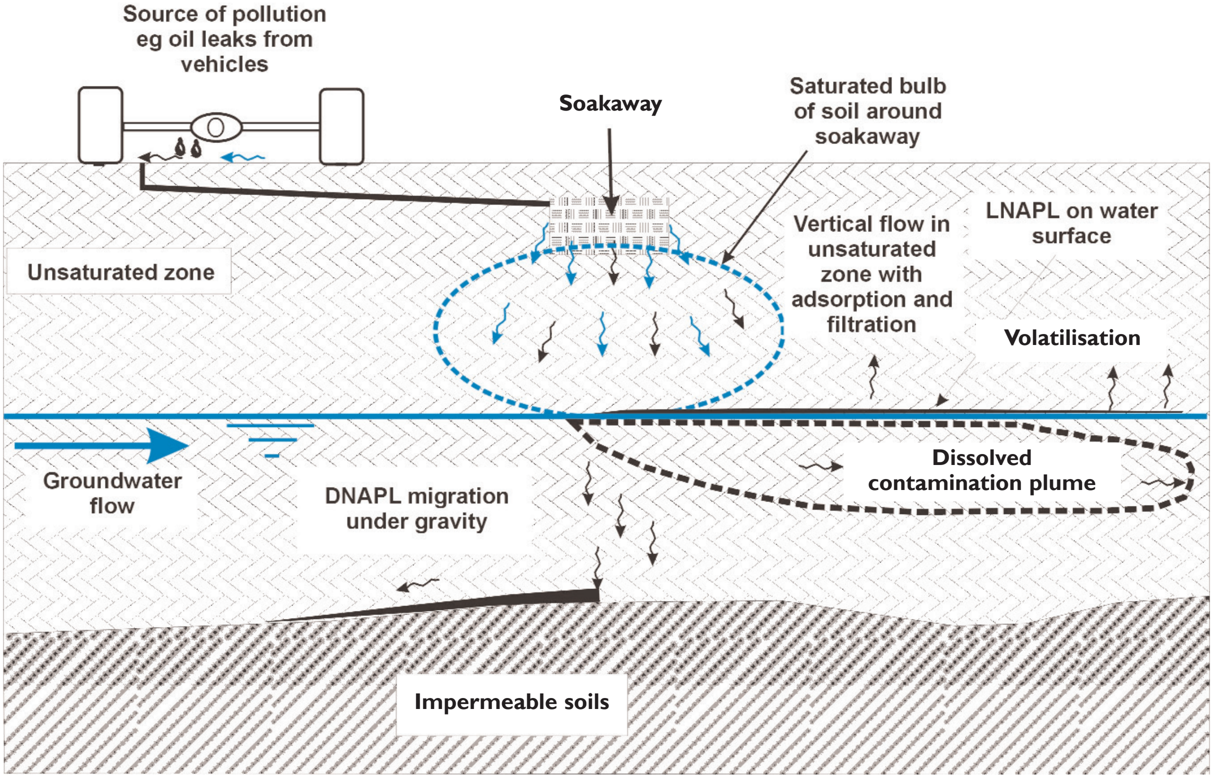


Figure 3.1 *Sub-surface pollutant transport*

Up to 70 per cent of hydrocarbon pollution, 90 per cent of lead, 70 per cent of copper and 56 per cent of cadmium are associated with sediment in the runoff from a rural road. Several studies have found that the pollution is predominantly attached to the fine sediment (less than 63 m) (Highways Agency *et al*, 1998b). Sedimentation is, therefore, the most common removal technique that occurs in SUDS (Pitt *et al*, 1996).

3.1.3 Pollutant build-up and concentrations

The pollutants that occur in runoff originate from a variety of sources (Section 3.1.1). Their concentration in runoff is highly variable and depends on many factors including location, traffic volumes, length of dry period before a rainfall event, frequency of street sweeping and the nature of the surface from which runoff is generated.

Leeds University has undertaken a comprehensive study of pollutant build-up (Mitchell *et al*, 2001) and this provides more data on the types and sources of pollution in runoff in the UK. Event-mean concentrations for a range of pollutants and land uses are included in a further Leeds University report (Mitchell, 2001) and shown in Table 3.3.

Table 3.3 *Recommended mean EMC values for North European screening applications (Mitchell, 2001)*

Pollutant (mg/l unless stated)	Land use category	Mean [1]	First quartile [1]	Third quartile [1]
Suspended solids (TSS)	Urban open	126.3	57.0	279.8
	Industrial/commercial	50.4	18.1	140.4
	Residential	85.1	37.6	192.5
	Motorways	194.5	110.1	343.5
	Other main roads	**156.9**	**62.2**	396.3
Biochemical oxygen demand (BOD)	Urban open	7.9	3.5	18.2
	Industrial/commercial	9.9	5.9	16.7
	Residential	8.5	5.1	14.1
	Main roads	23.9	17.5	32.6
Chemical oxygen demand (COD)	Urban open	36.0	20.0	64.6
	Industrial/commercial	**146.2**	**121.3**	**176.1**
	Residential	80.0	53.2	120.4
	Main roads	**136.5**	**89.1**	**209.2**
Cadmium (μg/l)	All urban	2.2	1.3	3.7
Chromium (μg/l)	All urban	7.3	3.5	15.0
Copper (μg/l)	Urban open	**27.9**	**19.8**	**39.2**
	Developed urban	51.1	22.3	117.1
	Main roads	80.3	43.2	149.5
Iron	All urban	3.0	1.4	6.3
Lead [2] (μg/l)	Urban open	60.6	28.8	127.4
	Industrial/commercial	132.6	55.8	315.4
	Residential	140.5	91.6	215.5
	Motorways	330.1	197.7	551.1
	Other main roads	201.0	107.7	375.0
Mercury (μg/l)	All urban	0.27	0.10	0.74
Nickel (μg/l)	Urban open	**14.8**	**10.2**	**21.6**
	Developed urban	30.4	18.2	50.6
Zinc (μg/l)	Urban open	203.0	102.0	403.9
	Industrial/commercial	188.6	84.7	420.2
	Residential	296.9	192.8	457.2
	Motorways	417.3	284.0	613.3
	Other main roads	253.1	97.7	655.5
Total phosphorous	Urban open	0.22	0.08	0.58
	Industrial/commercial	0.30	0.16	0.54
	Residential	0.41	0.24	0.72
	Motorways	0.28	0.15	0.52
	Other main roads	0.34	0.17	0.67
Soluble phosphorous	Urban open	**0.056**	**0.018**	**0.174**
	Industrial/commercial	0.156	0.070	0.345
	Residential	0.198	0.109	0.359
	Main roads	**0.178**	**0.101**	**0.313**
Total nitrogen	Urban open	1.7	0.86	3.3
	Industrial/commercial	1.5	0.89	2.6
	Residential	2.9	1.7	4.7
	Main roads	2.4	1.5	3.7
Total K nitrogen	Urban open	1.2	0.73	2.0
	Industrial/commercial	1.5	1.1	2.2
	Residential	2.4	1.5	3.7
	Main roads	1.6	2.8	0.47
NO_{2+3}	Urban open	**0.84**	**0.43**	**1.7**
	Industrial/commercial	0.6	0.40	0.92
	Residential	0.98	0.50	1.9
	Main roads	0.81	0.63	1.0
NH_4- N	Urban open	**0.10**	**0.10**	**0.10**
	Developed urban	0.56	0.30	1.1
Oil and grease	Urban open	0.60	0.60	0.60
	Developed urban	4.24	1.2	14.9

Notes

1 Values in bold have a sample size of less than 10 and should be treated cautiously.

2 Due to reduction of lead in petrol, use of first quartile is recommended.

An alternative method of calculating the pollutant load in runoff is given in CIRIA Report 142 (Luker and Montague, 1994). This is based on calculating pollutant build-up between rainfall events then estimating the volume washed off. Report 142 provides typical pollutant build-up rates for roads in the UK, which are reproduced in Table 3.4. They cover a limited range of pollutants and are only applicable to UK roads.

Table 3.4 *Typical pollutant build-up rates (Luker and Montague, 1994)*

	(kg/ha/y)						
Traffic flow (AADT)	**Total solids**	**COD (kg O_2)**	**NH_4 - N**	**Total copper**	**Soluble copper**	**Total zinc**	**Soluble zinc**
Less than 5000	2500	250	4.0	0.4	0.2	0.4	0.2
5000 to 15 000	5000	400	4.0	0.7	0.3	1.0	0.5
15 000 to 30 000	7000	550	4.0	1.0	0.4	2.0	1.0
Greater than 30 000	10 000	700	4.0	3.0	1.2	5.0	2.5

The likely concentration of a pollutant in runoff can be estimated using appropriate rainfall data and assumptions regarding the preceding dry period. The dilution of the pollutant in the receiving water is then assessed and compared with the permitted EQS to assess if the self-purifying capacity of the receiving water is exceeded. A worked example is provided in Appendix 2.

In both cases, the pollutant load from rainfall runoff is calculated and loads from base flow are ignored. For most development sites the base flow will be small and can be ignored (Hall *et al*, 1993), although large low-density residential developments can develop significant base flows. The techniques discussed can only provide an estimate of pollutant loads and the values obtained should not be considered absolute.

It has been demonstrated that 95 per cent of pollution on impermeable urban ground surfaces such as roads and car parks accumulate within 600 mm of the kerb (Mitchell *et al*, 2001). Thus kerb height can affect the level of pollutant build-up at the edge of an impermeable surface (associated with fine sediment). The effects of kerb height on sediment build-up is shown in Figure 3.2, which demonstrates that the absence of kerbs and gutters from SUDS schemes is beneficial in reducing the pollutant loads the system will have to handle.

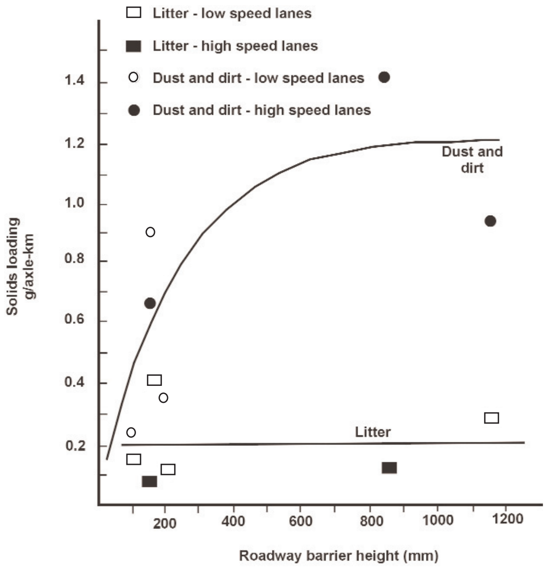


Figure 3.2 *Effect of kerb height on particle loading of street surface (Novotny and Olem, 1994)*

More detailed information on specific pollutants for a wider variety of land uses is provided by CIWEM (D'Arcy *et al*, 2000) in a report on diffuse pollution impacts. It also includes information on modelling of pollution in runoff. Selected data from this study are provided in Table 3.5.

In most cases the annual pollutant load from runoff is more important than the concentration discharged at any one time (Highways Agency *et al*, 1998b). The exception to this will be accidental spillages (see Section 7.2.4).

Runoff from roofs is often assumed to be clean, but research from the USA and Europe has found it contains high levels of metals. The pollution in most cases is caused by atmospheric deposition (Thomas, 1994), although deterioration of the metal roofs that are typically used in industrial and commercial developments can add metals to the pollutant load.

The predominant types of roofing used in both domestic and commercial buildings vary between countries, and pollution data from other countries should not be used unless the roof system under consideration is similar. In the United Kingdom, conventional pitch roofs in housing may be constructed from concrete, clay or slate and pose a relatively low risk of adding to the atmospheric pollution load through degradation of materials. Flat or low-pitch roofs on commercial and industrial buildings are constructed from plastic-coated steel, aluminium, galvanised metal, copper and bituminous products. Corrosion of some of these systems can add to the pollutant load from roofs (Schueler, 2000c).

Data on pollution of roof runoff in the UK for TSS is provided in Table 3.5.

Table 3.5 *Concentrations of selected pollutants for various land uses (D'Arcy et al, 2000)*

	TSS loading (kg/ha/y)		TSS concentrations (mg/l)		Hydrocarbon loading (kg/ha/y)		Total hydrocarbon concentrations (mg/l)		PAH concentrations (µg/l)	
	Median	**Range**	**EMC**	**Range**	**Median**	**Range**	**EMC**	**Range**	**EMC**	**Range**
General urban runoff	—	—	—	—	6.4	2.5 to 13.1	3.7	1.8–43.0	0.01	0.007–18.2
Highways	502	121–723	250	28–1178	—	—	28	2.5–13.1	3.7	0.01–20
Commercial	865	50–840	280	230–1894	—	6	1.95	0.04–5.71	0.05	0.01–0.35
Light industrial and engineering	210	242–1369	158	1–3920	—	140	35.2	1.03–58.4	—	—
Residential	—	—	—	—	—	1.8	—	—	—	0.01
Low-density	200	60–340	100	—	—	—	1.7	0.67–25.9	—	—
Medium-density	322	97–547	187	112–1104	—	—	5.1	0.89–45	—	—
High-density	434	133–755	250	—	—	—			—	—
Car parking areas	440	124–762	—	—	—	—	—	—	—	—
Roof runoff	—	12–216	—	12–216	—	—	—	—	—	—
Open space/ parks	346	80–588	—	—	—	—	—	—	—	—
Construction sites	67 415	22 000–84 000	—	—	—	—	—	—	—	—
Gully pot liquor	—	—	—	15–840	—	—	—	—	—	—

Pollution in runoff is partly dissolved and partly associated with sediment. An estimate of the ratio of dissolved heavy metals to those associated with sediment is provided in Table 3.6. This information can be important when considering the effectiveness of various features since those that rely on filtration will have only a limited effect on dissolved pollutants. A combination of features may be required to remove dissolved pollution and that associated with sediment.

Table 3.6 *Heavy metal fractions in runoff (Hall et al, 1993)*

Pollutant	Dissolved %	Solid-associated %
Copper	30	70
Lead	10	90
Zinc	40	60
Calcium	75	25

3.1.4 First flush

Rainfall washes pollution that has accumulated on impervious surfaces into the drainage system. The level of pollution for any rainfall event depends on factors including the type of site (industrial areas will generally have higher levels of pollution), the length of time since the last rainfall event (antecedent conditions) and the duration and intensity of the rainfall itself.

Studies have shown that frequently occurring storms produce the majority of surface runoff from developed sites and consequently generate most of the pollution (Roesner, 1999). For less frequent events on small catchments, the rainfall that runs off an impervious area in the early stages of a storm is more polluted than that which runs off later, because of the cleaning effect of a storm (Martin *et al*, 2000a and 2000b). This is known as the first flush. It is more obvious on small catchments with a large proportion of impervious area, which will be typical of many locations where SUDS will be used.

The first flush phenomenon is not always observed for several reasons (New South Wales EPA, 2002).

1 On large catchments the initial runoff from the farthest part of the catchment may not reach the outlet until some time after the storm has started. The outlet may therefore receive consecutive first flushes from different parts of the catchment so that the pollutant load at the outlet remains relatively constant throughout the storm event. This is an important consideration when designing SUDS features for large sites or regional controls.

2 Pollutants may not be very mobile. Oil and grease is not easy to remove from impervious surfaces.

3 Vegetated surfaces are not easily cleansed by rainfall, so catchments with large pervious areas generally do not show a pronounced first-flush effect.

4 Some pollutant sources may be continuous during a rainfall event. For example, erosion of soil from landscaping areas may give a continuous flow of sediment.

Further information on the volume of runoff that needs to be captured and treated to remove the majority of pollution is provided in Section 4.3.2.

Studies in Florida found that as the catchment area increases above 40 ha the annual pollutant load contained in the first flush drops to below 80 per cent (Livingstone, 1986). The first flush effects also diminished as the percentage of impermeable area in the catchment decreased

In this regard, sloping roof surfaces contribute most to the volume of the first discharges within the drainage system, but the later contributions from paved surfaces deliver the highest pollution contribution (Figure 3.3).

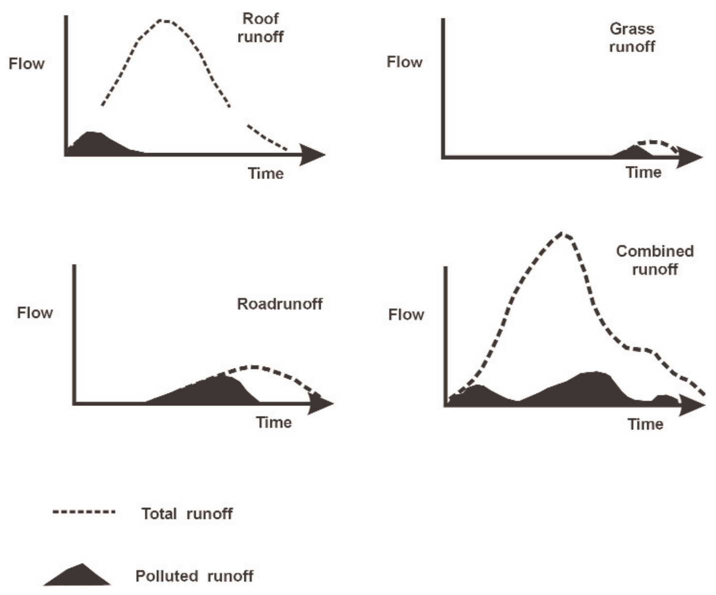


Figure 3.3 *Contribution of flow and pollution from urban surfaces (WS Atkins Consultants, 2001)*

3.2 POLLUTION AND WATER QUALITY LEGISLATION

If correctly designed and maintaned, SUDS should give lower concentrations of pollutants at the outlet than a conventional system, and hydrocarbons should have been degraded, unlike in conventional drains. Oil separators used on conventional drains do not stop dissolved contaminants or those adsorbed to very fine sediments entering controlled waters (defined in Box 3.1).

Nevertheless, if SUDS are incorrectly designed, constructed or maintained, they have the same potential to cause pollution of controlled waters as conventional drainage. They must comply with current environmental legislation and failure to ensure this is a criminal offence. The implications of inadequate installation are potentially serious, therefore, and courts can impose large fines or even prison sentences for individuals or companies. Designers, contractors, maintainers, owners and operators should familiarise themselves with the relevant legislation.

Sustainable drainage systems will generally discharge water in one of three ways. The Building Regulations Approved Document H (DTLR, 2002) lists the discharge options in order of priority.

1. Infiltration to the ground via a soakaway or other system (which will ultimately reach groundwater).
2. Discharge to a watercourse or other surface water.
3. Discharge to a sewer.

In Scotland, the Scottish Executive Technical Standards for compliance with the Building Standards (Scotland) Regulations, 1990, as amended, go further to promote the use of SUDS and stipulate that:

> *...a drainage system must be capable of discharging surface water:*
>
> *a* *by suitable SUDS techniques, including a soakaway; or*
>
> *b* *to a public sewer provided under the Sewerage (Scotland) Act 1968; or*
>
> *c* *to a suitable outfall that will minimise the risk of environmental pollution; or*
>
> *d* *where it is rainwater from a* building, *to a storage container with an overflow discharging in accordance with sub-clause a, b or c.*
>
> Technical Standards Part M: Drainage and sanitary facilities. 6th Amend (Scottish Executive, 2002)

The requirements for the use of a SUDS scheme are met where suitable SUDS features are provided in accordance with CIRIA C521 *Sustainable urban drainage systems – design manual for Scotland and Northern Ireland* (Martin *et al*, 2000a). This will also meet the requirements to minimise the risk of environmental pollution.

In most cases, discharge to a soakaway, watercourse or other surface water is likely to involve controlled waters (defined in Box 3.1). A surface water sewer is likely eventually to discharge to controlled waters. In some cases, surface water drainage systems may discharge to a foul or combined sewer that will eventually discharge to a treatment works. All will be covered by legislation that must be considered in relation to pollution of controlled waters, and in some cases discharge consents will be required.

The legislation is complex and continually evolving, particularly in response to European Union directives. It is important, therefore, to consult the Environment Agency, Scottish Environmental Protection Agency or the Department of the Environment in Northern Ireland at the feasibility stage of any proposals to confirm their requirements for discharges and pollution prevention.

3.2.1 England and Wales

It is essential that any drainage system, including SUDS, complies with the relevant environmental legislation (summarised in Box 3.1).

The Environment Agency regulates pollution of controlled waters through the issue of various permits. Those most relevant to surface water drainage are discharge consents issued under the Water Resources Act 1991. The consents usually specify limits for individual parameters. Any discharge of pollutants must be authorised by the Agency. A person is not guilty of an offence if the discharge has received consent from the Environment Agency and it meets the standards set in the consent.

For a SUDS discharge, the level of regulation applied by the Environment Agency will be proportionate to the risk of contamination of that discharge (National SUDS Working Group, 2003). In summary:

- if the SUDS discharge is uncontaminated surface water, then a discharge consent will not be required
- where the runoff into the SUDS is likely to contain high concentrations of pollutants and/or the SUDS runoff requires treatment before it can be discharged to a controlled water, then it will require a discharge consent.

Where the level of risk lies between the two extremes the Environment Agency will require the developer to undertake an appropriate risk assessment of the SUDS to identify potential sources of pollution, potential migration or transport pathways and the severity of the impact on receiving waters. The assessment should also consider the risks associated with accidental spillages. The Environment Agency should be consulted at an early stage to agree the nature and scope of the risk assessment.

Where discharge is to a foul sewer, a discharge consent will be required from the owner of the sewer (normally the water company).

The legislation aims to protect aquifers from discharge of pollutants, particularly substances in Lists I and II. In addition, environmental regulators have policies for the protection of groundwater quality (Environment Agency, 1998a). In England and Wales, the Environment Agency has defined groundwater source protection zones around public water supply boreholes, to ensure the installation and operation of appropriate pollution control measures to prevent contamination (Box 3.3). In association with the EA policy, criteria on the use of infiltration techniques with conventional drainage from various land uses have been developed (Box 3.4).

Further information is provided in the framework document prepared by the National SUDS Working Group (National SUDS Working Group, 2003).

Box 3.1 *Summary of environmental legislation applicable to SUDS*

England and Wales

The Water Resources Act 1991 (WRA 1991) and the Groundwater Regulations 1998, provide the main body of control relating to the prevention and control of water pollution in England and Wales. Other statutes contain provisions that relate to control and prevention of pollution or the maintenance of water quality standards. These include:

- The Salmon and Freshwater Fisheries Act 1975
- The Environmental Protection Act 1990
- The Land Drainage Act 1991
- The Environment Act 1995.

Controlled waters are defined in the WRA 1991 as:

- inland fresh waters – rivers, streams, lakes, ponds and canals
- groundwaters – all water contained in underground soils and rocks
- coastal waters – all estuarine waters up to the fresh water limits of rivers and streams.

The Groundwater Regulations require that List I substances are prevented from entering groundwater and List II substances must be controlled to prevent groundwater pollution. This applies to both direct (to the water table) and indirect (after percolation through the ground) discharges. The Groundwater Regulations define groundwater as all water below the surface of the ground that is in the saturation zone.

- List I includes substances such as cadmium, mineral oils and hydrocarbons and many pesticides that may be found in runoff
- List II includes substances such as heavy metals and MTBE that may be found in runoff.

Under Section 85 of the Water Resources Act, it is an offence to cause, or knowingly permit, the entry into controlled waters, either directly or via a drain or sewer, of:

- poisonous, noxious or polluting matter
- solid waste matter
- matter, other than trade or sewage effluent, via a drain or sewer pipe, if it has been prohibited by the Environment Agency
- trade or sewage effluent
- matter likely to impede the flow
- effluent through a pipe into the sea outside the seaward limit of controlled waters.

All discharges to watercourses from industry, agriculture, local authorities and water company sewage works require a discharge consent under the Water Resources Act. The Environment Agency does not normally require a consent for stormwater discharges (although this policy may change) and it controls them through the planning system via conditions attached to planning applications. The Environment Agency is a statutory consultee under the Town and Country Planning Act 1990, and will advise the planning authority on drainage and environmental protection issues. It is important not to compromise the water quality objectives or water quality standards set for receiving waters by the Environment Agency (see Section 3.3).

The Environment Agency can, however, impose a prohibition order on any discharge under the Water Resources Act if pollution happens or is likely to occur. In locations such as stormwater hotspots (Box 3.2) the surface water runoff may be contaminated and considered an industrial discharge by the Environment Agency. In such cases, discharge consents may be applied to specify limits for individual prescribed substances. The Environment Agency can use a Groundwater Regulations Notice to prohibit or control activities that may lead to the discharge of List I and List II substances.

Under the Water Industry Act 1991, consents to discharge to foul sewers may be required if the sewer owner allows surface water to drain into it. The consent limits will be set by the sewer owner so that they can comply with discharge limits set by the Environment Agency for the downstream treatment works.

Section 100 of the Highways Act 1980, allows highway authorities to install drains, and discharges do not require consent for either surface or groundwater. This does not remove the need to comply with environmental standards, because the Environment Agency can impose a prohibition order under the Water Resources Act if pollution occurs or is likely to occur.

Scotland

SEPA policy is to promote SUDS schemes and encourage their design to be undertaken in accordance with the CIRIA design manual for Scotland and Northern Ireland (Martin *et al*, 2000a).

The main legislation relating to the prevention and control of water pollution in Scotland is:

- The Control of Pollution Act 1974, as amended by the Environment Act 1995
- The Groundwater Regulations 1998
- Water Environment and Water Services (Scotland) Act 2003.

Controlled waters in Scotland are defined in the Control of Pollution Act and the definition is similar to that for England and Wales. The definition of the water environment in the Water Environment and Water Services (Scotland) Act 2003 is also similar to that for controlled waters. The Groundwater Regulations also apply in Scotland: List I substances must be prevented from entering groundwater and List II substances must be controlled to prevent groundwater pollution.

The Water Environment and Water Services (Scotland) Act 2003, transposes the Water Framework Directive into Scottish national law and provides a framework to assess, protect and enhance the water environment in Scotland. It prohibits unauthorised polluting discharges to the water environment (although SUDS are excluded from the definition of water environment since they are designed to remove pollution). The way in which the legislation will be applied is still being determined; SEPA should be consulted for up-to-date advice.

Northern Ireland

Regulation of water quality issues in Northern Ireland is the responsibility of the Environment and Heritage Service, which is an agency of the Department of the Environment in Northern Ireland. The main legislation relating to protection of controlled waters in Northern Ireland is:

- Water Act (Northern Ireland) 1972
- Groundwater Regulations (Northern Ireland) 1998
- Water (Northern Ireland) Order 1999 (when fully implemented this will replace the Water Act (Northern Ireland) 1972).

The Environment and Heritage Service promotes and regulates the conservation of water resources and the cleanliness of water in waterways and underground strata in accordance with the Water Act (Northern Ireland) 1972.

"Underground strata" is defined as "strata subjacent to the surface of any land: any reference to water contained in any underground strata is a reference to water so contained" (but excluding public sewers, pipes, reservoirs and tanks).

Waterways include any river, stream, watercourse, inland water (whether natural or artificial), or tidal waters and any channel or passage of whatever kind (whether natural or artificial) through which water flows (but excluding public sewers and drains).

The Groundwater Regulations (Northern Ireland) 1998, require that List I substances must be prevented from entering groundwater and List II substances must be controlled to prevent pollution of groundwater.

3.2.2 Scotland

In Scotland, the policy relating to the use of sustainable drainage techniques is provided in Scottish Environment Protection Agency Policy No 1 (SEPA, 1996) and Policy No 15 (SEPA, 2001). These criteria not only define when infiltration may be used, but indicate when pre-treatment of waters may be required (details will be discussed at the planning stage of a development). It is an offence to cause or knowingly permit pollution as defined in the Control of Pollution Act (COPA) 1974 (as amended).

COPA allows SEPA to consent to discharges to controlled waters in three categories.

1. Trade effluent.
2. Sewage effluent.
3. Matter other than trade or sewage effluent (surface water discharges are regarded as other matter).

Discharges of other matter to controlled waters do not require consent unless SEPA serves a prohibition notice. The notice may require a discharger to apply for consent or be conditional. Discharges of surface water runoff do not automatically require consent from SEPA, although runoff from stormwater hotspots may do (Box 3.2). Planning Advice Note 61 (Scottish Executive, 2001) states:

> *...it is not the intention of SEPA to prohibit discharges, but to give them powers to regulate the discharge through a consent, if it is considered necessary in a particular case. It is anticipated that SEPA will use its discretionary powers at the design stage by issuing a conditional prohibition notice on the developer, specifying that final drainage arrangements should be in accordance with the drainage design agreed during pre-application discussions.*

Discharges of other matter to land are not subject to SEPA's statutory control. Even if a consent to discharge is unlikely to be required, SEPA should nevertheless be made aware of the drainage proposals.

The Water Environment and Water Services (Scotland) Act 2003, provides for the replacement of the Control of Pollution Act in Scotland (it is an enabling Act that will allow new regulations to be drawn up by the Scottish Executive to replace COPA). The Act transposes the European Community's Water Framework Directive (Section 3.2.4) into Scottish law and provides a framework for the basin-wide assessment, protection and enhancement of the water environment. The definition of "water environment" is similar to controlled waters in the Water Resources Act in England and Wales. The Act prohibits the pollution of surface or groundwater unless it is authorised.

Box 3.1 gives more detail on Scottish environmental legislation as it applies to SUDS.

Box 3.2 *Stormwater hotspots*

Stormwater hotspots are defined in the USA (Maryland Department of the Environment, 2000) as areas where:

- land use or activities can potentially generate highly contaminated runoff, or
- groundwater is an important resource for drinking water abstraction.

Such areas are defined by three factors.

1 Groundwater resource value

In areas such as groundwater inner source protection zones, infiltration may not be appropriate. Outflow may have to be to watercourses or to surface water sewers with sufficient levels of treatment.

2 Use of site

Locations include:

- fuel stations
- hazardous or toxic materials storage or handling areas
- vehicle or equipment maintenance areas.

Infiltration should not normally be used in these locations unless a full assessment of the risks and consequences of both general day-to-day and major spillage has been undertaken. A system should be used with mechanisms for treating the runoff and closing the outlet from the SUDS system provided.

Such sites can also be subdivided into separate catchments so that low-risk areas can be drained via infiltration. For example, supermarkets can put pervious surfaces below car parks but construct loading bays or other higher-risk areas with conventional surfacing and drainage with separators.

3 Ground conditions

On sites where contaminated soils are present, infiltration should not be used if it is likely to cause leaching of contaminants. Where ground contamination is minor and not mobile, infiltration may be possible if a risk assessment identifies that risks to groundwater are acceptable.

To define a zone, one has to know how the groundwater behaves in that area and understand well construction, water levels and groundwater/surface water interactions. This information is used to create a conceptual model that acts as a clear, concise statement on the groundwater setting. The choice of zone definition technique is based on:

- the quality of data available and the degree of understanding of the groundwater setting
- the operational importance of the source concerned.

Once a model has been applied and calibrated, protection zones are defined based on the best estimate of the parameter values.

Inner Zone 1 is defined by a 50-day travel time from any point below the water table to the source and, additionally, as a minimum 50 m radius from the source. It is based principally on biological decay criteria and designed to protect against the transmission of toxic chemicals and water-borne disease.

Outer Zone 2 is defined by the 400-day travel time or 25 per cent of the source catchment area, whichever is larger. The travel time is derived from consideration of the minimum time required to provide delay, dilution and attenuation of slowly degrading pollutants.

Source Catchment Zone 3 is defined as the area needed to support the protected yield from long-term groundwater recharge (effective rainfall). In areas where the aquifer is confined beneath impermeable strata, the source catchment may be located some distance from the abstraction.

Zone shapes

Many factors control the shape and size of zones such as:

- groundwater abstraction rate
- recharge (direct and indirect)
- aquifer permeability (hydraulic conductivity)
- effective porosity (specific yield)
- aquifer thickness
- hydraulic gradient and direction of groundwater flow.

Inner protection zones are generally simple in geometry and tend to be circular in form, reflecting the "cone of depression" around an abstraction borehole. The key factors in defining the geometry of source catchment zones are recharge, the form of the groundwater surface and the catchment boundary conditions. Zone shapes can vary from the very simple to the complex. Outer protection zones are generally intermediate in shape between inner and source catchment zones.

The main use of groundwater protection zones is to signal that within specified areas, should certain activities take place, there is likely to be a particular risk posed to the quality or quantity of water obtained. When used in conjunction with the Pollution Prevention Guidelines they are primarily a screening tool to be used with caution when assessing specific activities. They can help to target pollution prevention measures more effectively to the areas of greatest risk. Many regulatory bodies, including the Agency, have influence over land use. It is important they are aware not only of the issues of concern that could influence groundwater quality, but also of the areas that are at greatest risk. The definition of zones around boreholes provides a readily comprehensible tool for regulators, landowners and developers alike. The zones are an attempt to explain the likely regulatory response in particular areas to make the decision-making process more open and transparent for the wider community.

3.2.3 Northern Ireland

The Environment and Heritage Service policy in relation to infiltration drainage is described in the *Policy and practice for the protection of groundwater in Northern Ireland* (Department of the Environment Northern Ireland, 2001). This is similar to the Environment Agency policy and includes information on source protection zones and groundwater vulnerability. It states: "Disposal of surface drainage water to underground strata should have due regard to the contamination risk posed to groundwater".

Discharges of surface water runoff to watercourses do not automatically require a discharge consent. However, as in the rest of the UK, prohibition notices can be issued if considered necessary. Environmental legislation relating to SUDS in Northern Ireland is discussed in more detail in Box 3.1.

The Environment Agency policy in relation to infiltration drainage is given in the *Policy and practice for the protection of groundwater* (Environment Agency, 1998b). This is based on the concept of groundwater vulnerability, which is simply defined as a measure of the ease with which unacceptable effects on groundwater resources can occur. It describes aquifer protection in terms of both source and resource protection. The vulnerability depends on site-specific factors such as geology, depth of unsaturated zone and location of abstraction wells. The table below shows the Environment Agency's likely response in relation to various activities involving a conventional drainage system, based on the application of the policies (from the *Policy and practice for the protection of groundwater*, Environment Agency, 1998b).

	Source protection		
Activity	**I Inner zone**	**II Outer zone**	**III Catchment zone**
Roof drainage	No objection (R5) providing for sole use of roof drainage	No objection (R5)	No objection (R5)
Impermeable areas			
– public/amenity	Not acceptable (R1)	Acceptable (R4)	Acceptable (R4)
– large car parks	Not acceptable (R1)	Acceptable (R3/4) with separator	Acceptable (R4) with separator
– lorry parks	Not acceptable (R1)	Presumption against (R2)	Acceptable (R3/4) with separator
– garage forecourts	Not acceptable (R1)	Presumption against (R2)	Acceptable (R4) with separator
– major roads	Not acceptable (R1)	Presumption against (R2) Acceptable only in exceptional circumstances	Acceptable only if investigation favourable and with adequate precautions (R4)
Industrial sites	Not acceptable (R1)	Presumption against (R2)	Acceptable only if investigation favourable and with adequate precautions (R3/4)

	Resource protection		
Activity	**Major aquifer**	**Minor aquifer**	**Non-aquifer**
Roof drainage	No objection (R5)	No objection (R5)	No objection (R5)
Impermeable areas			
– public/amenity	Acceptable (R4)	Acceptable (R4)	Acceptable (R4)
– large car parks	Acceptable (R4) with separator	Acceptable (R4) with separator	Acceptable (R4) with separator
– lorry parks	Acceptable (R4) with separator	Acceptable (R4) with separator	Acceptable (R4) with separator
– garage forecourts	Acceptable (R4) with separator	Acceptable (R4) with separator	Acceptable (R4) with separator
– major roads	Acceptable (R4) subject to investigation and with separator	Acceptable (R4) subject to investigation and with separator	Acceptable (R4) with separator
Industrial sites	Acceptable only if investigation favourable and with adequate precautions (R3/4)	Acceptable (R4) subject to investigation and with separator	Acceptable (R4) subject to investigation and with separator

R1 Prohibit/object in principle
R2 Presumption against
R3 Prohibition notice/consent to discharge
R4 No objection subject to standard conditions
R5 No objection

Note: A discharge consent will not be permitted for List I substances.

Groundwater pollution cannot be seen and is difficult to put right once it has occurred. Therefore the precautionary principle should be adopted when assessing risks to groundwater and deciding whether to use infiltration.

3.2.4 Water Framework Directive

The Water Framework Directive is an item of European legislation that will establish a strategic framework for managing the water environment. It is incorporated into UK law in England and Wales by the Water Environment (Water Framework Directive) (England and Wales) Regulations 2003 and the Water Environment (Water Framework Directive) (Northumbria River Basin District) Regulations 2003. (The separate legislation for Northumbria is required because the Regulations are based on river catchments, and this catchment covers both England and Scotland.) The Directive is incorporated in Scottich law by teh Water Environment and Water Services (Scotland Bill 2003, which promotes the use of SUDS in Scotland.

Quality and ecological objectives will be set for all groundwaters and surface waters within the European Community and the water quality will have to be managed to meet those objectives. The legislation requires discharges liable to cause pollution to be subject to some form of prior control or treatment approval. It applies to surface water discharges, including SUDS, but the Environment Agency, SEPA and the Department of the Environment in Northern Ireland have yet to decide on the precise regime to be adopted.

Designers of SUDS schemes should take into account the water quality of discharges and their impact on receving waters. A risk assessment should be undertaken to determine that the level of risk to surface water or groundwater is acceptable to the regulatory authorities (Section 3.3).

3.3 ENVIRONMENTAL RISK ASSESSMENT

Risk assessment can vary from a simple descriptive procedure (qualitative assessment) to a full mathematical model using complex equations to describe pollutant transport and behaviour together with statistical methods to quantify the likelihood of pollution occurring (quantitative assessment). Qualitative risk assessment may be all that is required (a source-pathway-target analysis). Mathematical modelling should be carried out only if necessary, for example, where a particularly sensitive receptor is at risk.

The first step in any risk assessment is to define a conceptual model for the site and the drainage system: a diagram showing the sources of pollution, likely pathways to receptors and the receptors (Figure 3.4).

A simple qualitative procedure is described in Figure 3.5 that may be used as an aid to assess the likely hazards, consequences and overall risk of pollution from SUDS. It is based on the risk assessment procedure described in CIRIA C582 (Pratt *et al*, 2002) and additional information is provided by the Highways Agency (Highways Agency *et al*, 1998b). The risk assessment should be undertaken by a professional with an understanding of pollutant transport and decay mechanisms that occur in SUDS features, and experience of modelling pollutant transport in the sub-surface. Also the risk of accidental spillages needs considering in addition to an assessment of the risks posed by routine discharges from drainage systems (Box 3.5).

Box 3.5 *Assessment of accidental spillages*

Vehicles are one of the most likely causes of accidental spillage. Vehicles carrying dangerous goods that pose a threat to human health and safety must be marked using the HAZCHEM classification system. This allows swift, appropriate action to be taken in the event of a spillage. Other substances, such as fruit juice or milk, do not pose a risk to human health and safety, but can cause environmental damage due to their high BOD. The Highways Agency provides further information on the risk of accidental spillages occurring on highways (Highways Agency *et al*, 2001) and recommends that the risk of accidental spillage affecting a watercourse or groundwater should be based on a 2 per cent annual probability (50-year return period) (1 per cent probability or 1 in 100-year return period for sensitive waters such as those used for abstraction, recreation or with a high ecological value).

The effects of an accidental spillage must be assessed and are dependent on factors including:

- emergency services response time
- distance from point of spillage to receiving waters
- sensitivity of receiving waters and level of dilution that will occur
- the nature of the spilled materials
- ability to contain spilled materials.

The need to assess the impact of outlet discharges from drainage systems (including piped systems) is clearly identified in British Standard BS EN 752-4:1998. Drainage discharges should not compromise the Environment Agency's WQO or WQS for the receiving waters (Hall *et al*, 1993). Water quality standards for various categories and uses of surface waters are quoted in Environment Agency R&D Report 20 (Environment Agency, 1999). A documented qualitative risk assessment of the impacts of a sustainable drainage system on the receiving waters should always be undertaken and the results communicated to the developers/owners (Figure 3.5). It should take account of the sensitivity of the receiving environment.

Contamination of runoff to sustainable drainage systems may vary from low levels of continuous contamination, such as droplets of oil from vehicles in car parks, to the sudden accidental spillage of a large quantity of pollutant on one occasion. It is important that all possible events are considered when determining the level of protection to be provided against groundwater or surface water contamination. There are some locations that have an unacceptably high risk of generating contaminated runoff or where the groundwater is an important resource. In the USA, the practice is to prevent infiltration in these "stormwater hotspots" unless the risks have been fully assessed and suitable treatment provided (Box 3.2).

A precautionary approach should be adopted when considering the risk of groundwater pollution owing to the difficulty and cost involved in remediation should it occur.

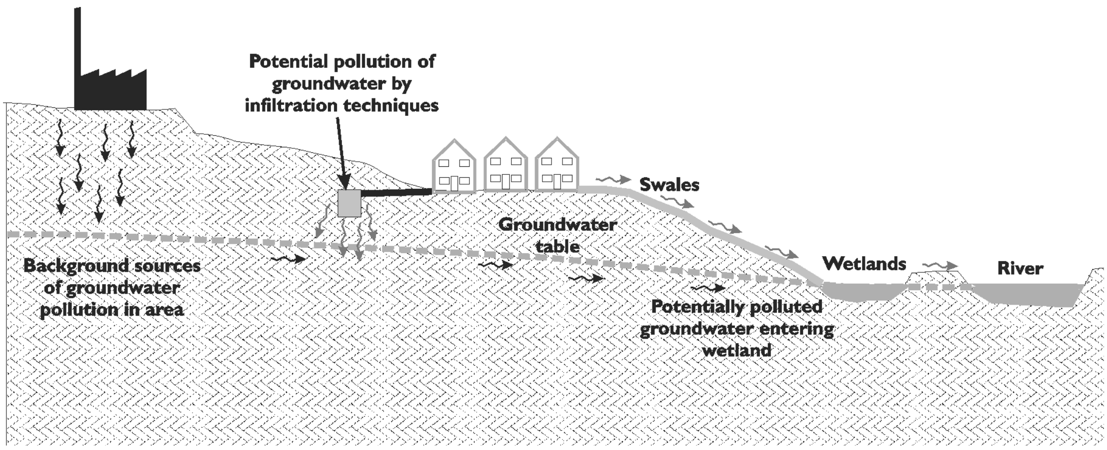


Figure 3.4 *Example of a conceptual model for a SUDS scheme*

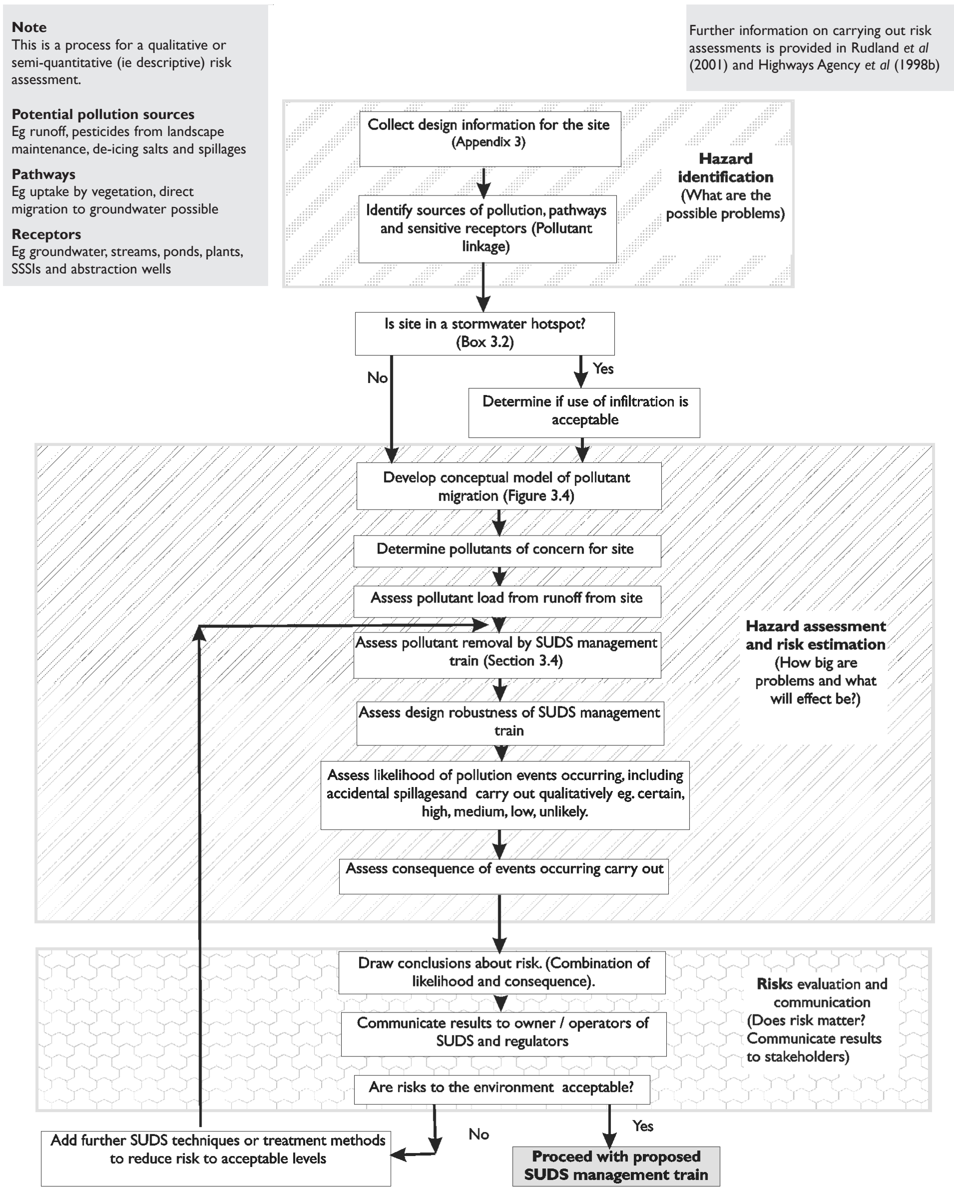


Figure 3.5 *Risk assessment for SUDS*

3.4 POLLUTANT REMOVAL

3.4.1 Mechanisms of removal in SUDS techniques

Sustainable drainage systems can be designed to provide various pollutant removal mechanisms that mitigate against the risks to controlled waters. These include:

- settlement and retention of solids (sedimentation)
- filtration and biofiltration
- adsorption of pollutants (in which pollutants attach or bind to soil surfaces), which depends on factors such as texture, soil or aggregate structure and moisture content. It also includes partition of pollutants that are dissolved by strongly held liquid layers or dissolved into polymer molecular structures
- biodegradation of organic pollutants such as petrol and diesel
- volatilisation of VOCs that are found in petrol, diesel and some pesticides
- precipitation
- uptake by plants
- nitrification.

Further information on the specific pollution removal mechanisms is provided in Box 3.6. The use of SUDS should also benefit water quality with the reduction in peak flows and total volumes to receiving waters. The reduced peak flow causes less of a short-term shock pollutant load to the receiving waters and allows increased dilution, which is usually an improvement over traditional systems where the first flush effect can be pronounced (see Section 3.1.4). The delay and treatment provided by SUDS can attenuate this effect and if the total volume of runoff is reduced, the overall pollutant load will be reduced.

Box 3.6 *Pollutant removal mechanisms in SUDS*

Sedimentation

Sedimentation is one of the main removal mechanisms in SUDS. Most pollution in runoff is attached to sediment particles (Section 3.2), so removal of sediment considerably lowers pollutant loads. Sedimentation is achieved by reducing flow velocities to a level at which the sediment particles fall out of suspension. Care has to be taken in design to minimise the risk of resuspension when extreme rainfall events occur.

Filtration and biofiltration

Pollutants that are conveyed in association with sediment may be filtered from the percolating waters. This may occur through trapping within the soil or aggregate matrix, on plants or on geotextile layers within the construction. The location of any filtration will depend upon the internal structure of the particular SUDS technique, for example whether a geotextile layer is near the surface or at the subgrade in a pervious surface.

Adsorption

Adsorption occurs when pollutants attach or bind to the surface of soil or aggregate particles. The actual process is complex but tends to be a combination of surface reactions grouped as sorption processes:

- adsorption – pollutants bind to surface of soil/aggregate
- cation exchange – attraction between cations and clay minerals
- chemisorption – solute is incorporated in the structure of a soil/aggregate
- absorption – the solute diffuses into the soil/aggregate/organic matter.

Realistically it is impossible to separate these processes in a SUDS technique.

Change in acidity of runoff can either increase or decrease the adsorption of pollutants by construction materials or soils. Eventually the materials will become saturated, so the treatment will stop. It is possible to estimate the maximum capacity of materials to adsorb contaminants using techniques adopted for design of contaminated water treatment plants (Muhammad *et al*, 1998 and US Army Corps of Engineers, 2001). The process is dependent on the precise combination and concentration of pollutants, and laboratory testing should be undertaken on a site-specific basis. The design life of the pavement in this respect can therefore be estimated.

Adsorption of pollutants increases the higher the organic and clay content (although the permeability of soil reduces with increasing clay content). The order of adsorption capacity of substrates, from strongest to weakest, is (Pitt *et al*, 1996):

1. Manganese oxides
2. Organic matter
3. Iron oxides
4. Clay minerals.

Some metals are also more easily adsorbed within the ground and the order of sorption affinity from strongest to weakest is as shown below (Pitt *et al, 1996*).

1. Lead
2. Copper
3. Nickel
4. Cobalt
5. Zinc
6. Cadmium
7. Iron
8. Manganese

The composition of substrate and combination of metals in the runoff will affect the overall sorbitive capacity of a SUDS technique.

Biodegradation

In addition to the physical and chemical processes possible on and within a SUDS technique, biological treatment may also occur. Microbial communities may be established within the ground, using the oxygen within the free-draining materials and the nutrients supplied with the inflows, to degrade organic pollutants such as oils and grease. The level of activity of such bioremediation will be affected by environmental conditions such as temperature and the supply of oxygen and nutrients. It also depends on the physical conditions within the ground such as the suitability of the materials for colonisation.

Volatilisation

Volatilisation comprises the transfer of a compound from solution in water to the soil atmosphere and then to the general atmosphere. The conversion to a gas or vapour is caused by heat, reducing pressure, chemical reaction or a combination of these processes. The rate of volatilisation of a compound is controlled by certain of its properties and those of the surrounding soil. The most important factors are the Henry's Law constant and the air flow above the ground surface, which removes the layer of saturated air in contact with the soil. They also include the concentration, the soil moisture content, temperature, rate of diffusion and the soil's sorptive characteristics with respect to the particular compound. In SUDS, volatilisation is primarily concerned with organic compounds in petroleum products and pesticides.

Precipitation

This process is the most common mechanism for removing soluble metals. Precipitation involves chemical reactions between pollutants and the soil or aggregate that transform dissolved constituents into a suspension of particles of insoluble precipitates. Metals are precipitated as hydroxides, sulfides, and carbonates, depending on which precipitants are present and the pH level. Precipitation can remove most metals (arsenic, cadmium, chromium III, copper, iron, lead, mercury, nickel, zinc) and many anionic species (phosphates, sulphates, fluorides).

Uptake by plants

In ponds and wetlands, uptake by plants is an important removal mechanism for nutrients (phosphorous and nitrogen). Metals can also be removed in this manner (although intermittent maintenance is required to remove the plants otherwise the metals will be returned to the water when the plants die). Plants also create suitable conditions for deposition of metals, for example as sulphides in the root zone.

Nitrification

Ammonia and ammonium ions can be oxidised by bacteria in the ground to form nitrate, which is a highly soluble form of nitrogen. Nitrate is readily used as a nutrient by plants.

3.4.2 Pollutant removal efficiency

There is a great deal of monitoring data for SUDS features, in particular from the Scottish SUDS Database, which is maintained by SEPA, SNIFFER and the University of Abertay (Wild *et al*, 2002), and from international sources such as the National Stormwater BMP Databases and the Center for Watershed Protection in the USA (<www.bmpdatabase.org> and Winer, 2000). The relative removal efficiency varies between features for different pollutants; in some cases, it also depends on the size of the structure (ponds, for example). It is apparent that many techniques have a wide range of reported pollutant removal efficiencies. When analysing quoted removal rates, bear in mind the following:

- some data have been collected using poorly designed techniques
- the performance of these techniques varies with season, rainfall pattern, inflow pollutant levels and maintenance frequency; for example, biodegradation of hydrocarbons slows down in winter. The presence of low efficiency values in some references demonstrates the variability of these natural systems and should not be taken as an indication that they are unreliable. The overall design of the management train should allow for the variable performance of any one individual element (see Section 2.4)
- the pollutant removal efficiency of SUDS techniques is far better than that of conventional drainage systems
- different methods of analysis

- there is a level of pollution below which the use of additional SUDS techniques will not be able to provide any additional improvement in water quality. These are known as irreducible concentrations. If inflow concentrations are already relatively low and close to the irreducible levels then the SUDS may not be able to provide any further significant pollutant removal. Monitoring may indicate very low or negative removal rates that will not be representative of performance when pollutant levels are higher (Winer, 2000).

In the USA, several stormwater design manuals quote quantified removal efficiencies for certain techniques. Values for the risk assessment of SUDS techniques have also been quoted (Highways Agency *et al*, 1998b and 2001).

Although climate and rainfall patterns affect the hydraulic performance of SUDS, they will have less influence on pollutant removal. Many mechanisms that remove pollutants should not be greatly affected (adsorption, filtration) although others (biodegradation, for example) may be slightly affected. Although the climate in the UK differs from that in the USA, where considerable information is available, it is valid to compare results in Scotland with Maryland (Macdonald and Jefferies, 2000b). It is reasonable, therefore, to compare results from various worldwide references and use similar values for the UK. The various methods of estimating pollutant removal used in monitoring studies are discussed in Box 3.7.

Box 3.7 *Methods of estimating pollutant removal*

Pollutant removal refers to the difference in pollution levels entering and leaving a SUDS scheme. The removal can be analysed by two basic methods (Winer, 2000).

1. Event mean concentration (EMC) efficiency. This averages the inflow and outflow pollutant concentration for all runoff events and does not take account of water volumes.

It is calculated on the following basis :

EMC efficiency (%) = 100 x (inlet average EMC – outlet average EMC)/inlet average EMC.

2. Mass load efficiency. This takes account of the volume of water entering the SUDS technique and allows for losses such as evaporation.

It is calculated on the following basis:

Mass load efficiency (%) = 100 x (sum of inlet pollution load – sum of outlet pollution load)/sum of inlet pollution load.

There are also variations of the basic methods. Although the method of analysis does affect the estimated pollutant removal for a site, other influences are likely to be far greater. Thus the use of removal efficiencies using both methods has been used to derive the values for Table 3.7.

Suggested values for pollutant removal are provided in Table 3.7 for use when comparing the effectiveness of various combinations of features to determine the optimum treatment train, and to assist in risk assessments. The values are applicable for systems that are designed, constructed and maintained in accordance with this publication, C609.

Caution!

The values in Table 3.7 may be used to assess the general relative performance of different designs or combinations of techniques in the treatment train so as to minimise the risk of pollution entering the receiving waters. It is important to note that the performance of SUDS is subject to the variables previously discussed and the values should not be considered or used as absolute values. They should be used as an aid to judgement when assessing the risks of system failure and to compare the relative performance between different combinations of systems.

Owing to variations that are inherent in rainfall, pollution deposition and treatment methods such as biodegradation, the actual efficiency at any time may fall below the quoted values. This emphasises the need for a treatment train to reduce dependence on any one technique and the need to consider design robustness (Table 3.9).

Table 3.7 *Estimates of pollutant removal capability for assessment of SUDS management trains*

Technique	Percentage removal of pollutants of concern [1 2 3]					
	Total suspended solids	Hydrocarbons	Total phosphorous	Total nitrogen	Faecal coli forms [5]	Heavy metals
Pervious pavements	60–95	70–90	50–80	65–80	— [6]	60–95
Green roofs [4]	60–95	—	—	—	—	60–90
Bioretention	50–80	50–80	50–60	40–50	—	50–90
Sand and organic filters	80–90	50–80	50–80	25–40	40–50	50–80
Grassed filter strips	50–85	70–90	10–20	10–20	—	25–40
Grassed swales (dry)	70–90	70–90	30–80	50–90	—	80–90
Grassed swales (wet)	60–80	70–90	25–35	30–40	—	40–70
Infiltration trench/ soakaway	70–80	—	60–80	25–60	60–90	60–90
Filter drains	50–85	30–70	—	—	—	50–80
Infiltration basin	45–75	—	60–70	55–60	—	85–90
Extended detention ponds	65–90	30–60	20–50	20–30	50–70	40–90
Wet ponds	75–90	30–60	30–50	30–50	50–70	50–80
Stormwater wetlands	80–90	50–80	30–40	30–60	50–70	50–60
On-/off-line storage	0	0	0	0	0	0
Oil separator	0–40	40–90	0–5	0–5	—	—
Modular treatment units	Product-specific	Product-specific	Product-specific	Product-specific	Product-specific	Product-specific

Notes

1 The performance of SUDS is subject to a number of variables and the values should not be considered or used as absolute values.

2 Summary based on design values provided in Atlanta Regional Commission (2001), Barrett (1998), New Jersey Department of Environmental Protection (2000), Highways Agency *et al* (1998b) and reviewed against mean values quoted by United States Environmental Protection Agency (1999a to 1999n) and median removal efficiency quoted by Center for Watershed Protection (Winer, 2000).

3 Stormwater pollution concentrations are dependent on various factors and the performance of the SUDS techniques will vary. For any one storm event the observed performance may not reach the specified level (it may also be exceeded). This can be allowed for in design.

4 Green roof values on basis that they will act in similar or better manner to pervious pavements.

5 Removal rate for faecal coli-form is based on no resident wildfowl population in ponds and wetlands.

— Insufficient data to quote removal rate.

More detailed information on the monitored performance of each technique is provided in Chapter 9.

To supplement removal efficiencies the Center for Watershed Protection (Winer, 2000) also provides a table of mean water quality concentrations recorded at the outlets to various SUDS techniques (Table 3.8). If the estimated outflow concentration approaches these levels then provision of additional features may not provide significant improvements in water quality. However, they may be required to give increased redundancy in the system, for example to give the required level of confidence that a SUDS scheme will continue to perform adequately if maintenance is not carried out.

Table 3.8 *Median pollutant concentrations for stormwater treatment practices (Winer, 2000).*

	Median effluent concentrations from SUDS techniques						
	TSS (mg/l)	**TP (mg/l)**	**OP (mg/l)**	**TN (mg/l)**	**NOx (mg/l)**	**Cu (?g/l)**	**Zn (?g/l)**
Stormwater dry ponds*	28	0.18	n/a	0.86	n/a	9.0	98
Stormwater wet ponds							
Wet extended detention ponds	14	0.11	0.03	1.0	0.08	4.5	26
Wet pond	18	0.12	0.03	1.5	0.3	6.0	30
Stormwater wetlands							
Shallow marsh	12	0.12	0.09*	1.7	0.9	4.5	30
Extended detention wetland*	29	0.27	n/a	1.6	0.84	n/a	n/a
Pond/wetland system	23	0.2	0.05*	1.7	0.31	7.0	28
Filtering practices							
Organic filter	12	0.1	0.5*	0.99*	0.6*	10*	22
Perimeter sand filter*	12	0.07	0.09	3.8	2.0	49	21
Surface sand filter*	38	0.13	n/a	1.8	n/a	2.9	23
Vertical sand filter*	74	0.14	0.04	1.3	0.6	5.5	20
Bioretention*	n/a	0.18	n/a	1.7	n/a	2.0	25
Infiltration practices							
Infiltration trench	n/a	0.63	0.01	3.8	0.09	n/a	n/a
Porous pavement	17	0.1	0.01	n/a	n/a	n/a	39
Open channels							
Ditch*	29	0.31	n/a	2.4	0.72	18	32
Grass channel*	15	0.14	0.09	n/a	0.07	10	60
Dry swale*	16	0.4	0.24	1.4	0.35	23	87
Wet swale*	8.2	0.13	0.08	0.96	31	13	39
Other							
Oil-grit separator*	48	0.41	0.05	1.9	0.2	13	170

Notes

* Data based on less than five sets of results.

3.4.2 Estimation of removal efficiency by the treatment train

There are often several combinations of techniques that can form a SUDS treatment train for any site. This section provides a framework to assist in choosing the combination that will provide the most effective pollutant removal. It is important to note that pollutant removal rates vary with inflow pollutant concentration and sediment size, and the efficiencies quoted in Table 3.7 are not cumulative. When techniques are placed in series in a treatment train the first technique will retain the pollution that can be most easily removed, leaving the more difficult pollution to be dealt with by the following technique. However, there is limited data that quantifies the reduction in performance (Barrett, 1998). A higher removal efficiency will occur for more heavily polluted runoff than for slightly polluted runoff.

The following method of estimating the pollution removal efficiency for a treatment train can be used to assess the comparative performance of different management train options (modified from the method described by the Atlanta Regional Commission, 2001).

Step 1 List techniques in the order they occur within the management train with their estimated pollutant removal efficiency from Table 3.7. Choose lower values where inflow concentrations are low or maintenance may not be carried out.

Step 2 For techniques that are located downstream of another technique use 50 per cent of the quoted removal efficiency (Atlanta Regional Commission, 2001).

Step 3 Use the following equation to estimate the total pollution removal efficiency for the treatment train.

Overall pollutant removal = (total pollutant load × control 1 removal efficiency) + (remaining pollutant load × control 2 removal efficiency) + (remaining pollutant load × control 3 removal efficiency) + …..for the other controls in series (3.1)

Step 4 Compare calculated outflow from each technique with the values in Table 3.8. These can be considered as limiting values of removal for each technique. If the outflow is close to these values then the use of further techniques is unlikely to give improved pollutant removal. However, additional techniques will give more redundancy in the system and thus reduce the risk of pollution occurring at the outfall.

An example of how the method can be applied is provided in Appendix 2.

Much of the pollution in runoff is attached to the finer sediments (known as total suspended solids,TSS). If the fine sediment is removed then a significant proportion of pollutants such as hydrocarbons and metals can also be removed. The box below describes a method of determining the removal of TSS (Barrett, 1998). This assumes optimum efficiency for each technique (that is, no reduction to allow for techniques being in series).

$$\text{Total removal efficiency for TSS} = [1-((1 - E_1) \times (1 - E_2) \times (1 - E_3) \times \ldots)] \times 100 \quad (3.2)$$

Where:

E_1 = TSS removal efficiency of first technique (as a decimal fraction)

E_2 = TSS removal efficiency of second technique (as a decimal fraction)

E_3 = TSS removal efficiency of third technique (as a decimal fraction)

3.4.3 Design robustness

Another consideration is the degree of confidence that can be placed in the performance of the chosen features, in terms of pollutant removal and control of water quantity. Each technique may be classified in terms of design technology robustness (Urbonas, 1997) as shown in Table 3.9. High design robustness means that the design is likely to perform as intended. A low robustness implies there may be uncertainties about how the technique will perform over time.

These criteria may be used to ensure that complementary techniques are provided in the stormwater management or treatment train to achieve the required degree of confidence in the performance of the overall system, based on the type of pollutants likely to be present and the sensitivity of the receiving waters. For example, where water from a car park discharges to a highly sensitive watercourse only two techniques may be required if they have a high design robustness, but three or more may be needed if each one only has a low design robustness. In this way any risk that may be associated with the use of SUDS can be managed.

Table 3.9 *Design robustness for SUDS techniques (amended from Urbonas, 1997)*

SUDS technique	Hydraulic design for flow and attenuation	Pollutant removal	
		Total suspended solids/solids	Dissolved pollutants
Pervious pavements	Moderate to high	High	Low to high
Green roofs	Moderate to high	High	Low to moderate
Filtration techniques (bioretention and sand and organic filters)	Low to moderate	Moderate to high	None to low
Grassed filter strips	Low to moderate	Low to moderate	None to low
Grassed swales	High	Low to moderate	None to low
Infiltration trench/soakaway	High	Moderate to high	Low to moderate
Filter drains	High	High	Moderate to high
Infiltration basin	Low to high	High	Moderate to high
Dry detention ponds	High	Moderate to high	None to low
Wet ponds	High	High	Low to moderate
Stormwater wetlands	Moderate to high	Moderate to high	Low to moderate
On-/off-line storage	High	None	None
Sediment trap	Low to moderate	Low	None
Oil separators	High	Low	None
Modular treatment units	Product-specific	Product-specific	Product-specific

4 Rainfall and runoff

This chapter begins with a general discussion on the adverse effects that development has on the runoff from a site and how SUDS can mitigate these effects.

It identifies the design rainfall criteria that need to be applied to SUDS and provides detailed information on how they are assessed. The criteria that drainage designs should meet include water quality, prevention of river erosion, site flooding, river flooding and building protection.

The use of various methods of estimating greenfield runoff rates is discussed, together with the available rainfall data and the limitations of its use.

The design of drainage systems should also consider the water levels in the receiving waters and their effect on the performance of the systems (groundwater and river levels). The time to empty will also affect performance and the readiness of systems to accept the following storm.

Evaporation and snowmelt may require consideration in some parts of the UK, and guidance is provided in this chapter.

The need to undertake sensitivity analysis for climate change is also discussed.

4.1 URBAN HYDROLOGY

The hydrological cycle describes the movement of water within the closed system of circulation on earth. Water spends time circulating between the air, groundwater and surface water in rivers, lakes and oceans. It moves between the different phases by precipitation (rainfall), infiltration, surface flow and evaporation and transpiration. SUDS is concerned with the fate of rainfall when it hits the ground and includes consideration of precipitation, infiltration, surface flow and evaporation and transpiration. SUDS designers need to understand how these are changed from the natural situation by development.

When rainfall (or precipitation) falls on greenfield sites around 80–100 per cent can infiltrate to the ground, depending on the permeability of the soil, the slope and the degree of saturation of the soil from preceding rainfall events. The more permeable the soil and the lower the degree of saturation and slope, the more rainfall seeps into the ground. Some of this will be held at the surface and lost by evapotranspiration. Some will flow through the ground at shallow depth to recharge the groundwater table and the remainder will flow through the ground slowly to nearby watercourses (known as interflow).

When rainfall occurs faster than water can infiltrate into the ground it becomes surface runoff. On greenfield sites a relatively low percentage of rainfall flows on the surface to watercourses such as rivers or streams. A typical example is shown in Figure 4.1. The presence of grass and other vegetation slows down the surface flow to the watercourses.

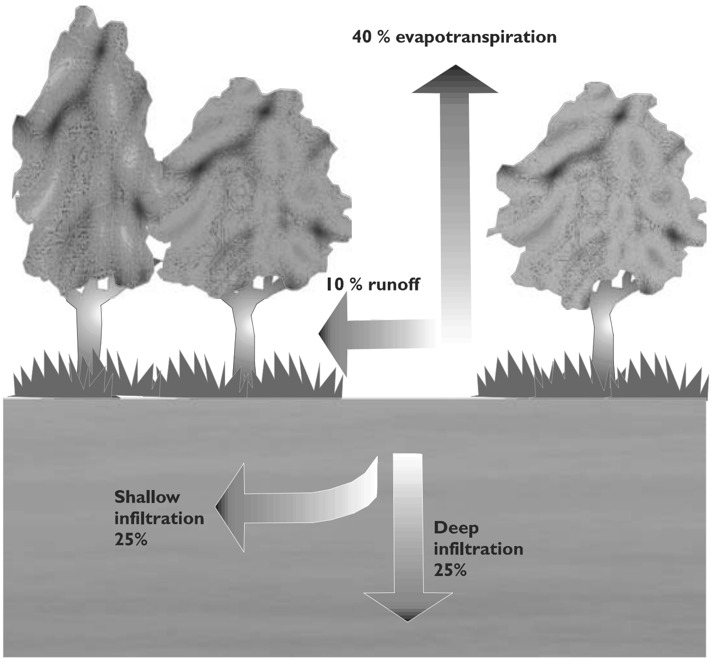


Figure 4.1 *Fate of rainfall on natural cover (Tourbier and Westmacott, 1981)*

When sites are developed and the amount of impervious surfaces increases (roofs and roads, for example) infiltration, evapotranspiration and the amount of vegetation are reduced. In the UK, experience suggests that the housing densities required by PPG 3 can lead to sites with 55–60 per cent impermeable area. As a result, the interflow, which slowly percolates to watercourses, and evaporation are reduced and surface runoff is increased by up to 90 per cent (Figure 4.2). The effects worsen with increasing proportions of impervious area. As the retarding and cleansing effects of surface vegetation are removed and there is less infiltration, the rate and volume of runoff to watercourses increases. This causes an increase in peak flows in the watercourse together with lower base flows. The frequency of peak flow events also increases after development.

The aim of SUDS is to return the post-development runoff, infiltration and evapotranspiration to as near natural conditions as possible, to minimise the adverse effects of urbanisation on the water environment.

4.2 FREQUENCY OF EVENTS

The concept of the return period was developed to convey the principle of risk in relation to the likelihood of a given event occurring. It can cause confusion, however, as many people believe that, following one 1 in 100-year event, there will be a 100-year gap before the next one takes place. This is not true, since the probability of this type of event occurring in any one year is always the same. For this reason, it is suggested that the term "return period" is *not* used to describe the risk of flood events occurring (Fleming, 2002). The design exceedance for a flood or rainfall event is quoted in this publication as an annual probability of exceedance or the probability of exceedance during the design life of a drainage system. A rainfall event with a 1 per cent annual probability of occurrence is therefore the same as an annual return period of 100 years.

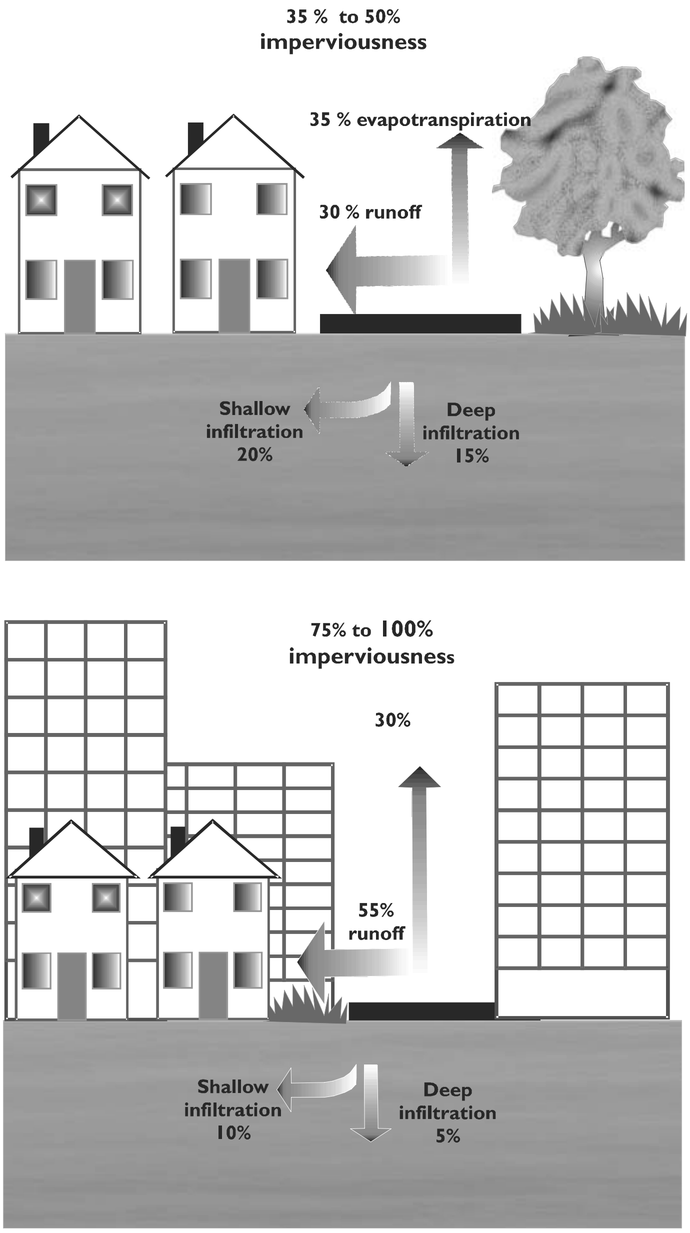


Figure 4.2 *Fate of rainfall on developed sites (Tourbier and Westmacott, 1981)*

Because this concept has not yet been widely adopted, the old terminology of return period is quoted in brackets after the annual probability.

The probability of a rainfall event occurring or being exceeded can be determined using the following equation (Butler and Davies, 2000).

$$P_r = 1 - [1 - (1/T)]^L \quad (4.1)$$

Where:

P_r = probability of event occurring or being exceeded within design life, L years (L= 1 for annual probability)

T = Return period (ie the rainfall event is exceeded, on average, once every T years)

L = design life (years).

Using the preceding equation, the annual probability of occurrence has been calculated for a range of return periods (Table 4.1). The table also includes the probability of a storm event occurring during 25-year and 100-year design lives.

Table 4.1 *Probability of a storm occurring*

Return period (years)	Annual probability of exceedance, %	Probability of exceedance during 25-year design life, %	Probability of exceedance during 100-year design life, %
2	50	100 (see below)	100 (see below)
5	20	100 (see below)	100 (see below)
10	10	93	100 (see below)
30	3.33	57	97
50	2	40	87
100	1	22	63
200	0.5	12	39

The figures in Table 4.1 have been rounded and where 100 per cent probability is recorded there is actually a very small chance that the event may occur within the design life. For example, the probability of a two-year return period event being exceeded within a 25-year design life is actually 99.9999970.

4.3 DESIGN RAINFALL CRITERIA

To design a SUDS correctly the different effects that can occur due to the increased runoff and pollution levels have to be considered. Stormwater or BMP design manuals in the USA require consideration of a treatment volume to reduce pollution. Many also specify other criteria to be taken into account when designing SUDS (Maryland Department of the Environment, 2000; Atlanta Regional Commission, 2001 and Washington State Department of Ecology, 2001). They require the analysis of SUDS systems under storm events ranging from the mean annual event up to annual probabilities of 1 per cent or lower (return periods of 1 in 100-year or greater). A similar approach has been proposed for the UK (Kellagher, 2004). It is recommended that SUDS should be sized to meet five criteria.

1. Meet pollutant removal targets and protect watercourse water quality (interception and treatment of the water quality volume). This is usually based on capturing 90 per cent of the average annual rainfall.
2. Maintain the natural regime and reduce channel erosion in downstream watercourses by controlling the peak runoff rate and volume from a site (attenuate the watercourse protection volume). Usually based on a storm with an annual probability of exceedance of 50 per cent (1 in 2-year return period).
3. Prevent site flooding by storing the site level of service volume, which is the current requirement in *Sewers for adoption* (WRc, 2001a) and *Sewers for Scotland* (WRc, 2001b). This is normally based on a storm with a 3.3 per cent annual probability of exceedance (1 in 30-year return period). However, BS EN 752-4:1998 gives different return periods for different types of development and locations.
4. Prevent overbank flooding of downstream watercourses by controlling the peak runoff rate and volume from a site (limit flows into the receiving watercourse). Often this is achieved with a design that ensures flows into the watercourse with an annual probability of exceedance of 1 per cent (1 in 100-year return) do not exceed greenfield rates. This does **not** mean the volumes have to be stored in the SUDS. It

can be achieved using overland flow routes and site flooding of selected areas, provided the areas are not affected by the 1 per cent (1 in 100-year) flooding from the receiving water.

5. Manage extreme flood flows in a controlled manner to downstream watercourses (building flood protection volume). Normally consider flood routeing of runoff from the storm with an annual probability of exceedance of 1 per cent (1 in 100-year storm). Building floor levels and site levels should be designed so that floor slabs are above the site or watercourse flood level with an annual probability of exceedance of 1 per cent (1 in 100-year return period) and so that safe emergency access is maintained. British insurers may require that buildings be protected against flooding with an annual probability of exceedance of 0.5 per cent in order to provide affordable insurance cover (Association of British Insurers, 2001). This also requires climate change to be taken into account (see Section 4.6).

Certain sites or particular situations may require a sixth criterion to be considered: catastrophic protection. This will normally be where flooding is likely to lead to loss of life or the destruction of property with an unusually high value.

Flow control and temporary storage of runoff is effective in reducing flooding where it occurs in response to short-duration rainfall events of high intensity. Research by HR Wallingford (Kellagher, 2004) has shown that it is unlikely to reduce flooding that results from long-duration rainfall events of low average intensities. In such situations it is desirable to reduce the volumes of runoff that discharge into watercourses. Therefore, source control using infiltration (where ground conditions permit) or other techniques that reduce the volume of runoff or provide long-term retention, such as pervious pavements or bioretention areas, should be considered before other features (Section 2.1).

Each of the criteria can be used in conjunction with the others to design a SUDS management train that addresses the overall impact of stormwater from a site. This will control the runoff from a whole range of rainfall events from the small and frequent, to the rare and large. The relative storage and/or treatment volumes required for each criteria are shown in Figure 4.3.

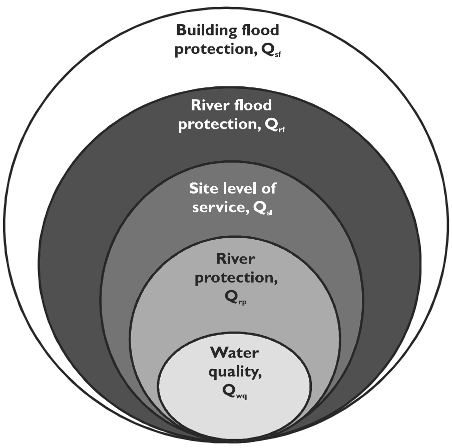


Figure 4.3 *Relative volumes for each design criterion (adapted from Atlanta Regional Commission, 2001). Note: not to any scale*

Not all sites will need to meet all the criteria, and is useful to arrange early consultation with the regulators (planning authority and Environment Agency) to set the design criteria. Should any be omitted, the reasons for doing so should be clearly documented in the SUDS design accreditation checklist (Section 5.3). Other considerations are the response of a SUDS system to runoff from events that exceed the design criteria and the overland flow routes that flood water will follow when the design capacity is exceeded.

Rainfall runoff for drainage design in the UK can be determined using the Wallingford Procedure, the *Flood estimation handbook* (FEH – Institute of Hydrology, 1999) or the simplified methods given in the Building Regulations and BS EN 752-4:1998.

The rainfall analysis provided in the *Flood studies report* (FSR) is based on data from 1941 to 1970. Volume 2 of the FEH has four times more data, based on more recent rainfall information from 1971 to 1990. The resulting rainfall depths using the FEH differ significantly from those obtained from the FSR, and in most cases are greater.

The FEH reports on a comparison of rainfall depths determined using the FSR and FEH methods for an annual probability of exceedance of 1 per cent (1 in 100-year return) and durations of one hour and one day. For one-day duration, similar results were obtained for most of the UK, except in upland areas where depths were up to 40 per cent greater using the FEH, and in Somerset, the East Midlands and south-east England where depths were 20–30 per cent greater using the FEH.

For the one-hour duration event the FEH showed a 30 per cent greater depth in western upland areas, the east Midlands and south-east England. It also indicated significant increases in some very localised areas (up to 60 per cent). The increase in rainfall depth using the FEH data was smaller for storms with increased probabilities of occurrence (shorter return periods).

Rainfall data in the Wallingford Procedure is based on the FSR. There is no reference to the FEH in *Sewers for adoption*, *Sewers for Scotland*, BS EN 752-4:1998, the Building Regulations or the Building Standards (Scotland) Regulations, and most conventional drainage is still designed on the basis of the Wallingford Procedure. Indeed, British Standard BS EN 752-4:1998 specifically refers to it. The data from either the FEH, the Wallingford Procedure, Building Regulations or BS EN 752-4:1998 may therefore be used for design of SUDS until updated guidance is provided. At the time of writing, the Environment Agency and SEPA recommend the use of the FEH, while other organisations have yet to declare a formal position.

Designers should be aware that in certain areas the Wallingford Procedure may underestimate rainfall depths and in these situations the rainfall data from the FEH will give a more accurate assessment. However, most SUDS are natural systems that operate within a design envelope and in practice natural variations in performance may make irrelevant any theoretical variations due to different methods of analysis.

4.3.1 Greenfield runoff rates and limiting discharges

A study by HR Wallingford (Kellagher, 2004) investigated the effectiveness of runoff storage for a range of limiting discharges. It analysed the design storage requirements for a site for rainfall events including those that occurred during periods of watercourse flooding. It also looked at the volume of runoff that entered the watercourse during the flood.

The report concluded that flow control devices need to limit additional flows from development sites to between 1 l/s/ha and 3 l/s/ha, otherwise the majority of runoff from a site is passed into watercourses during periods of flooding. This is because as discharge limits reduce, the critical duration increases and becomes closer to that of the watercourse.

The discharge limits and their method of assessment for a particular site should be agreed with the Environment Agency. In the absence of a detailed assessment, common values used for greenfield runoff rates vary between 5 l/s/ha and 7 l/s/ha. Care should be taken if applying these values, as they may not be applicable to all sites, since the runoff rate is dependent on factors that include soil type and site gradient. The application of these limits may be limited by the size of opening required in the flow control device, especially on small sites. The minimum size of opening in an orifice plate or vortex flow control to provide an acceptable risk of blockage is 75 mm, although some adopting authorities may insist on larger openings (for example, water authorities normally specify a minimum diameter of 150 mm).

One method of overcoming the problem has been the use of geocelluar boxes with known flow characteristics as conveyance systems. The attenuation of flow in the boxes has been used to remove any need for a flow control device and silt is prevented from entering the boxes with the use of geotextile filters. Other devices use 20 mm openings with filters in front to reduce the risk of blockage or proprietary devices that are designed to prevent blockage.

Several methods, of varying complexity, are available for assessing a site's greenfield runoff rate. The advantages and disadvantages of the most commonly used methods are set out in Box 4.1. Whichever method is used the assessment and resulting discharge limits should allow for the effect of land drainage flowing on to the site from upstream (which should be accommodated within the outflow from the site drainage system).

In practice, the Environment Agency normally requires that, for a range of annual flow rate probabilities up to and including the 1 per cent annual probability (1 in 100-year), the developed rate of runoff is no greater than the undeveloped rate of runoff. Volumes of runoff should also be reduced where possible.

This can be achieved in two ways. Ideally, there should be minimal discharge to receiving watercourses for rainfall depths up to 5 mm. Alternatively, the difference in runoff volume pre- and post-development for the 100-year 6-hour event (the additional runoff generated) should be disposed of by way of infiltration or, if this is not feasible because of the soil type, discharged from the site at flow rates below 2 l/s/ha. Where compliance to the 100-year volumetric criterion, as defined in Section 10.2, is not provided, the limiting discharge for the 30- and 100-year return periods will be constrained to the mean anual peak of runoff for the greenfield site (referred to as Q_{BAR} in IoH Report 124).

Establishing whether this requirement is being met demands an standard calculation method, consistent across the UK. By offering several techniques, covering a range of site sizes, the approach recognises the need for a method appropriate to the scale of any individual site (for example, a complex method may not be appropriate to an infill development of a few houses).

A range of views exists across the water industry regarding the most appropriate techniques for determining greenfield runoff rates. The methodology in Table 4.2 is taken from the guidance provided by the National SUDS Working Group (National SUDS Working Group, 2003) and may be used until updated information is provided. Whichever approach is adopted it should be agreed with the Environment Agency.

The choice of method of assessing greenfield runoff is important because the results will have a significant impact on the storage volumes required on a site. Careful consideration of the implications of using a particular technique is required.

Flood studies report (National Environment Research Council, 1975)
This has been superseded by the *Flood estimation handbook* (Institute for Hydrology, 1999). Although the growth curves may still be used with other, simpler techniques.

ADAS Report 345 (1982)
This technique was developed to determine the size of land drains for field drainage systems and is based on measurements taken from a small number of rural catchments. Runoff is estimated using the following equation.

$$Q = S_T FA \tag{4.2}$$

Where:

Q = one-year return period peak flood flow in l/s assuming grass is the dominant crop type (note this is not the mean annual flood)
S_T = soil type factor (varies from 0.1 for very permeable soil to 1.3 for impermeable soil)
F = factor that is a function of average slope, maximum drainage length and average annual rainfall
A = area of catchment being drained in ha.

Guidance on the choice of factors is given in the report. The method should not be used on sites greater than 30 ha. Flow rates for higher return periods are estimated using appropriate growth curves from the *Flood studies report*.

Advantages

- Quick, simple and easily applied (therefore low-cost)
- Requires few variables, which can be obtained from Ordnance Survey maps
- Accepted by regulatory authorities
- Applicable to a maximum catchment size of 30 ha.

Disadvantages

- Based on relatively few monitored sites.

Flood estimation for small catchments (Institute of Hydrology Report 124)
The method was developed to apply to small catchments of less than 25 km², which is still large in comparison with most development sites. The research was based on 71 small rural catchments. The mean annual flood is determined using the following equation.

$$QBAR_{rural} = 0.00108 AREA^{0.89}\, SAAR^{1.17}\, SOIL^{2.17} \tag{4.3}$$

Where:

$QBAR_{rural}$ = mean annual flood for catchment
AREA = area of catchment in km²
SAAR = standard average annual average rainfall in mm
SOIL = soil index taken from maps in the report.

Floods for higher return periods are estimated using appropriate growth curves from the *Flood studies report*

Advantages

- Based on small rural catchments
- More catchments monitored than ADAS method
- Peak flows for various return periods can be determined using the *Flood studies report* growth curves
- Quick, simple and easily applied (therefore low-cost).

Disadvantages

- Should in theory only be applied to catchments draining to a well-defined watercourse
- Should be applied to catchments larger than 50 ha
- Not suitable for heavily urbanised catchments.

Flood estimation handbook (Institute of Hydrology, 1999)
The general philosophy of the *Flood estimation handbook* (FEH) is that flood frequency is best estimated from gauged data and that estimation from catchment characteristics alone should be used as a last resort. The method uses software packages to determine rainfall and flood flows (WINFAP-FEH, Micro-FSR and FEH CD-ROM). However, the FEH does state that "in sizing minor infrastructure works, such as culverts under forest roads, calculations based on FEH should not necessarily take precedence over those based on simpler formulae".

Advantages

- Uses pooling and transfer of flow data to estimate flows from ungauged catchments
- Characteristics of catchments are calculated from digital terrain model
- Pooling of the flood flow data for defining the growth curve is flexible and tailored to fit the subject site.

Disadvantages

- Cannot be applied to sites less than 0.5 km², which rules out most development sites
- It is complex and requires detailed knowledge of the software and digitally defined catchments
- Requires detailed knowledge of hydrological techniques to apply it and therefore probably not useable by the general civil engineering consultants that undertake development drainage design.

Table 4.2 *Greenfield runoff calculation (National SUDS Working Party, 2003)*

Development size	Method
0–50 ha	Institute of Hydrology Report 124 *Flood estimation for small catchments* (IoH, 1994) is to be used to determine peak greenfield runoff rates. Where developments are smaller than 50 ha the analysis for determining the peak greenfield discharge rate should use 50 ha in the formula and linearly interpolate the flow rate value based on the ratio of the development to 50 ha. FSSR 2 and 14 regional growth curve factors are to be used to calculate the greenfield peak flow rates for 1, 30 and 100-year return periods.
50–200 ha	IoH Report 124 will be used to calculate greenfield peak flow rates. Regional growth factors to be applied.
Above 200 ha	IoH Report 124 can be used for catchments that are much larger than 200 ha. However, for schemes of this size it is recommended that the *Flood estimation handbook* (FEH – IoH, 1999) be applied. Both the statistical approach and the unit hydrograph approach should be used to calculate peak flow rates. The unit hydrograph method will also provide the volume of greenfield runoff. Where, for whatever reason, the FEH is not considered appropriate for the calculation of greenfield runoff for the development site, IoH Report 124 should be used.

4.3.2 Water quality

Impermeable surfaces collect pollutants (see Section 3.1 for the range of pollutants and loadings) and rainfall washes off the accumulated pollution into the drainage system. The level of pollution for any rainfall event depends on such factors as the type of site (industrial areas generally have higher levels of pollution), the length of time since the last rainfall event (antecedent conditions) and the duration and intensity of the rainfall.

Studies have shown that small, frequently occurring storms produce the majority of surface runoff from a site, and consequently generate most of the pollution (Atlanta Regional Commission, 2001; New South Wales EPA, 2001 and Roesner, 1999). For large infrequent events on small catchments it is generally recognised that the initial stormwater runoff from an impervious area is more polluted than that which runs off later, because of the cleaning effect that occurs during the storm (Martin *et al*, 2000a and 2000b). This is the first flush effect (see Section 3.1.4).

To remove the major proportion of pollution it is necessary to capture and treat the runoff from frequent small-scale events and a proportion of the runoff (first flush) from larger and rarer events. Most of the criteria reported in the literature on SUDS are based on capturing a proportion of the average annual runoff (typically 80–90 per cent), even where it is stated as a depth of rainfall. One of the primary objectives of a SUDS design should be to capture the water quality volume and treat it to remove pollution. There are two main criteria that may be used to define water quality volume.

1. As a depth of rainfall falling on the site. Quoted values vary from 10 mm to 32 mm. The depth is usually estimated for a specific area or region to capture between 80 per cent and 90 per cent of the annual average rainfall (Livingstone, 1986).
2. Region-specific equations to capture a proportion of the annual average runoff from a site, typically 80–90 per cent (Maryland Department of the Environment, 2000; Sacramento Stormwater Management Program, 2000; Urbonas, 1997). For designs in the UK, site-specific data should be used to determine the criteria that will capture 90 per cent of the pollutant load.

A balance needs to be achieved between cleaning up polluted runoff and the cost of achieving this. Capture of 80–90 per cent of the runoff will retain the majority of pollution for treatment, but capture of the remaining 10–20 per cent of runoff becomes increasingly ineffective, in terms of both cost and practicality (D'Arcy and Roesner, 1999). This is demonstrated in Figure 4.4.

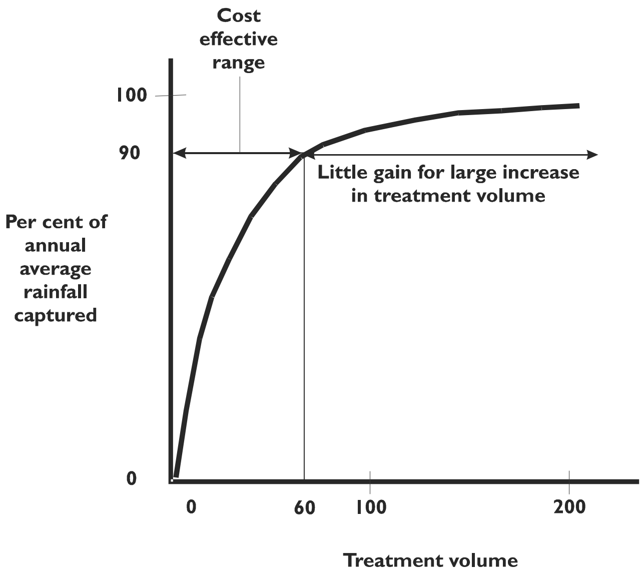


Figure 4.4 *Runoff–capture relationship (D'Arcy and Roesner, 1999)*

The various criteria for determining the water quality volume that are reported in the literature are listed in Box 4.2. For the purposes of determining the water quality volume for SUDS features in the UK, it is reasonable to follow the philosophy adopted in the USA and other countries of capturing 90 per cent of average annual runoff. Although the frequency, duration and intensity of rainfall may vary between geographic locations, the pattern of decreasing returns was observed for all hydrologic regions in the USA (Urbonas, 1997). Scottish experience has also shown this criteria to be applicable in the UK (Martin *et al*, 2000a and 2000b). The depths of rainfall will be country-specific and should be determined using UK rainfall data for the specific site location (Section 4.4). Recommended water quality volume criteria are given in Table 4.3 and are based on the values given in CIRIA publications C521 and C522, since the literature indicates these values are still reasonable for the UK (it is necessary to consider the variability of rainfall with location in this respect).

Table 4.3 *Recommended criteria for determining the water quality volume*

Method	Criteria	Comment
Fixed depth	10–15 mm (depends on the catchment and pollutant characteristics)	CIRIA C521 and C522 (Martin *et al*, 2000a and 2000b) suggest that 11.5 mm will capture 90 per cent of average annual rainfall for a site in Dunfermline
Proportion of average rainfall	90 per cent of average annual rainfall – use equation below: V_t (m^3/total area in ha) = 9.D.[SOIL/2+(1 - SOIL/2).I] Where: SOIL = WRAP soil classification I = Impervious area D = M5 - 60-minute rainfall determined from the Wallingford Procedure (HR Wallingford, 2000)	From CIRIA C521 and C522 (Martin *et al*, 2000a and 2000b) Note: this criterion is based on the use of an extended detention pond with a 24-hour retention period For other techniques use site-specific data obtained from the Met Office to determine the criteria to capture 90 per cent of average annual rainfall

Box 4.2 *Water quality criteria from various sources*

Fixed depth of rainfall

Different sources vary widely in their advice about the depth of rainfall to be treated. Many US stormwater management manuals quote a value of 12.5 mm to be used for design (the half inch rule). In Florida, the first 12.5 mm of runoff from small sites up to 40 ha area have been reported to contain 80–95 per cent of the total annual loading of most pollutants (Livingstone, 1986). For larger sites, the first 25 mm contained the majority of pollution.

Other sources maintain that the use of this value can lead to a significant pollution load being carried into watercourses for sites with a high impermeable area (City of Austin, 1990). The City of Austin report indicates that significant pollutant removal was achieved only by using a value of 32 mm or even 57 mm (depending on site impermeable area). Conversely, in in Edinburgh, Scotland, the capture of 11.5 mm of runoff provided 90 per cent of the average annual runoff for treatment (D'Arcy and Roesner, 1999 and Martin *et al*, 2000b).

Some guidance recommends using different depths for different pollutants on different surfaces, on the basis that pollutants such as oil and grease are harder to wash off (New South Wales Environmental Protection Agency, 2002). They recommend the following values:

- easily mobilised substances such as fine dust or soluble pollutants on an impervious surface – 10 mm
- substances that are less easily mobilised such as oil and grease on an impervious surface – 15 mm
- pollutants on pervious surfaces – 20 mm.

Specific equations to determine 90 per cent capture

Many criteria to achieve the capture of the water quality volume are quoted, particularly in the numerous US design manuals (for example, Maryland Department of the Environment, 2000; Minnesota Metropolitan Council, 2001; New Jersey Department of Environmental Protection, 2000 and Sacramento Stormwater Management Program, 2000).

A review of the criteria for determining treatment volumes (Berry, 2000) indicates that they are based on the principle of providing sufficient retention time in ponds to allow settlement of particles. Most are based on using ponds to provide a 24-hour retention period. They are all based on rainfall patterns specific to the region being considered. They cannot be generally applied unless the assumptions made regarding storage and treatment are applicable to the site and techniques being considered and they are also derived using UK rainfall data.

The criteria for determining the water quality volume that have been derived from UK experience are shown in Table 4.3.

In most cases, the use of a fixed depth of rainfall to define the water quality treatment volume will be acceptable. The time and expense required to determine site-specific values for 90 per cent of the average annual rainfall should be carefully considered against the likely benefits gained from the more rigorous assessment.

4.3.3 River protection

Urban development tends to increase the frequency and duration of bank-full flows in watercourses that receive the runoff (Leopold, 1994). The flow from a storm with an annual probability of occurrence of 50 per cent (1 in 2-year) has been shown to be the major influencing factor on the shape and form of a watercourse channel (Institute of Hydrology, 1999). Excessive flows above this level will cause erosion of the riverbanks, thus increasing sediment load in the watercourse and destroying riverside habitat for wildlife.

The river protection volume should be based on maintaining the post-development runoff to the greenfield rate for a storm with an annual probability of occurrence of 50 per cent or 1 in 2-year return period (Kellagher, 2004). A similar criterion is recommended in US design manuals.

4.3.4 Site level of service

The objective of this criterion is to prevent site flooding from the drainage system, except where it is planned (for example, in specified car park or landscaped areas). Conventional drainage is usually designed so that when the pipes are running full (with no surcharge in manholes) they carry the runoff from a storm event with an annual probability of exceedance greater than 50 per cent (1 in 2-year or less) (BS EN 752-4:1998; WRc, 2001a and WRc, 2001b). Where a building may be at risk of significant flood damage the pipe-full design may be based on a storm with an annual probability of exceedance of 20 per cent (1 in 5-year).

As storage in conventional systems is provided in manholes, a system designed on the preceding pipe-full criterion will often have a no-flooding performance (that is, no water floods from manholes into the site) equivalent to a probability of occurrence of 10–3.3 per cent (1 in 10-year to 1 in 30-year return). BS EN 752-4:1998 provides recommended design flood return periods from conventional drainage systems for various situations (Table 4.4). *Sewers for adoption* requires that site flooding does not occur for a storm event with an annual exceedance probability of 3.3 per cent (1 in 30-year return period).

Table 4.4 *Design flood return periods for site level of service (BS EN 752-4:1998)*

Location	Design flooding exceedance (annual probability, %)	Design flooding frequency (return period) from drainage system into site (years)
Rural areas	10	10
Residential areas	5	20
City centre/industrial/commercial areas with flooding check	3.3	30
City centre/industrial/commercial areas without flooding check	—	—
Underground railways/underpasses	2	50

For SUDS features the pipe-full criterion is not usually appropriate, so the site level of service volume should be the basis for design. The design should be undertaken for a range of rainfall durations to give the worst-case storage volume. This is more onerous than criteria for infiltration systems defined in BRE Digest 365 (BRE, 1991) and CIRIA Report 156 (Bettess, 1996), which require designs to provide storage in the soakaway for runoff from events with an annual probability of exceedance of 10 per cent (1 in 10-year return period). However, for consistency between all drainage techniques, the site level of service criteria should be based on runoff from a storm with a 3.3 per cent annual probability of exceedance regardless of SUDS technique or situation. The exception is where the flooding would affect underground railways, underpasses or similar sensitive infrastructure, in which case the probability from Table 4.4 should be used.

The site level of service criterion should also consider overland flood routeing when the capacity of the system is exceeded (*Sewers for adoption*, 5th edition, WRc, 2001a).

4.3.5 River flood protection

Driving the UK Government's commitment to the use of SUDS in England and Wales is a policy of reducing the impact of development on the frequency of flooding from watercourses (PPG 25, DTLR, 2001). The river flood protection volume will often be the main criterion specified by the regulators for a SUDS scheme in England and Wales (in Scotland the main focus is more on water quality).

The river flood protection volume is site-specific and depends on the characteristics of the particular watercourse catchment. PPG 25 also specifies the requirement to consider the effects of new developments on the flood risk of downstream areas, properties and habitat.

The criteria should be agreed with the Environment Agency, SEPA or Department of the Environment in Northern Ireland at the feasibility stage of design. Typically they require the greenfield runoff rate and volumes (Section 4.3.1) to be maintained after development for a storm event with an annual probability of 1 per cent (a return period of 1 in 100 years). This criterion is also specified by HR Wallingford (Kellagher, 2004) together with a catchment-critical duration (12 hours, in the absence of detailed information). The water does not necessarily need to be stored within the SUDS and can be stored on the surface of the site in locations such as car parks or landscaped areas that can flood occasionally for short periods.

The very low discharge restrictions needed to achieve this effect for small catchments in turn require very small discharge control devices, which are prone to blocking (Chapter 7). To meet this criterion, therefore, it is often necessary either to use source control to limit the overall volume of runoff, or site or regional controls. Geocellular conveyance devices with known flow characteristics may also be used to retard flows.

On some sites, the volume of water stored may need to be retained on site for several days if it is to have any beneficial effect on flooding (HR Wallingford, 2001). This is because, in some cases, runoff from the whole catchment will need to be assessed to avoid simply moving the timing of the peak flow or increasing the peak flow for the whole watercourse rather than reducing flows (Figure 4.5).

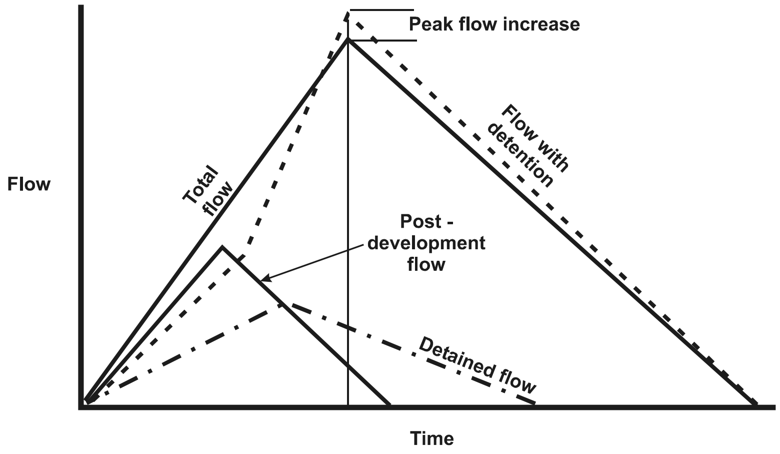


Figure 4.5 *Effects of detention timing (Atlanta Regional Commission, 2001)*

It is also important to consider overall flow volumes from a site, because these can have a significant impact on watercourse flooding. Even if the peak flow rate is attenuated, the longer duration of flow due to the increased volumes may combine with flows from downstream developments and tributaries to increase peak flows at some point further downstream in the receiving watercourse (Figure 4.6). In such cases, infiltration and the use of vegetation to adsorb and evaporate runoff should be maximised to reduce the total runoff volume. For this reason, the Environment Agency, SEPA or the Department for the Environment in Northern Ireland may request that on-site storage of runoff is not used in some locations (usually in the lower reaches of watercourses or areas like the Somerset Levels). It is important, therefore, to reach an early agreement with the regulators about their requirements for attenuation.

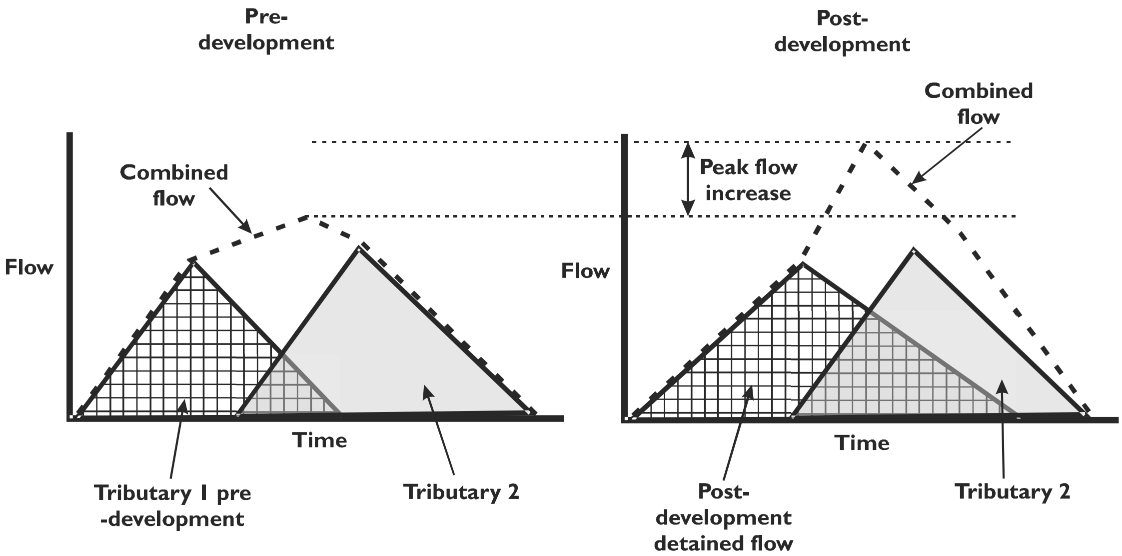


Figure 4.6 *Effects of increased volume and duration of runoff (Atlanta Regional Commission, 2001)*

4.3.6 Building flood protection

The building level of service volume will limit the risk of flooding of buildings within the site to the design criteria. It is important to consider the effects of extreme events and limit the risk of flooding of buildings from the site drainage system. This requires consideration of overland flow routes when the capacity of the on-site SUDS is exceeded. Building floor levels should be set so that flooding does not occur during an extreme event, although controlled flooding of less sensitive areas (car parks, for example) may be acceptable.

The building floor levels and emergency access are maintained above the site flooding level from a storm with a probability of 1 per cent or lower (1 in 100-year return period) (Kellagher, 2004). Icreasingly, insurance companies are specifying an acceptable probability for flooding of buildings of 0.5 per cent (1 in 200-year return period) so that they can provide affordable insurance cover against flooding (Association of British Insurers, 2001).

4.3.7 Recommended methods and criteria

SUDS designs in England and Wales concentrate on controlling the runoff rate to prevent watercourse flooding and, to a lesser extent, on the water quality treatment volume. In Scotland, the main focus is on pollutant removal. The previous sections demonstrate that SUDS designs may require consideration of up to five criteria. The precise considerations will be catchment-specific, and early consultation with the Environment Agency, SEPA or the Department of the Environment in Northern Ireland is required to determine which will be required.

Table 4.5 gives recommended criteria for assessing the storage volumes required for each scenario.

Table 4.5 *Recommended criteria for storage volume design*

Scenario	Criteria
Water quality treatment	Treat 90 per cent of average annual rainfall or the first 10–15 mm of rainfall
River protection	Maintain greenfield runoff rate and volumes for rainfall event with 50 per cent annual probability
Site level of service	Probability of flooding on site maintained at less than 3.3 per cent annual probability
River flood protection	Greenfield runoff rate and volumes maintained for a 1 per cent annual probability event (minimal discharge to receiving watercourses for rainfall depths up to 5 mm). Alternatively, the difference in runoff volume pre- and post-development for the 100-year 6-hour event (the additional runoff generated) should be disposed of by way of infiltration or, where this is not feasible because of the soil type, discharged from the site at flow rates below 2 l/s/ha.
Building flood protection	Floor slabs above 1.0–0.5 per cent annual probability flood level

Adoption of these criteria is likely to lead to the use of more than one technique on large sites to achieve the necessary range of performance. Source control will be particularly effective, but care must be taken to ensure that the storage and treatment volumes are carefully assessed and are provided in the correct location to manage the runoff efficiently. Conversely, for many small sites with a few houses all the criteria may be achieved using one or two techniques (for example, using soakaways with pre-treatment).

An example of a layout for the storage and treatment within a site is shown in Figure 4.7.

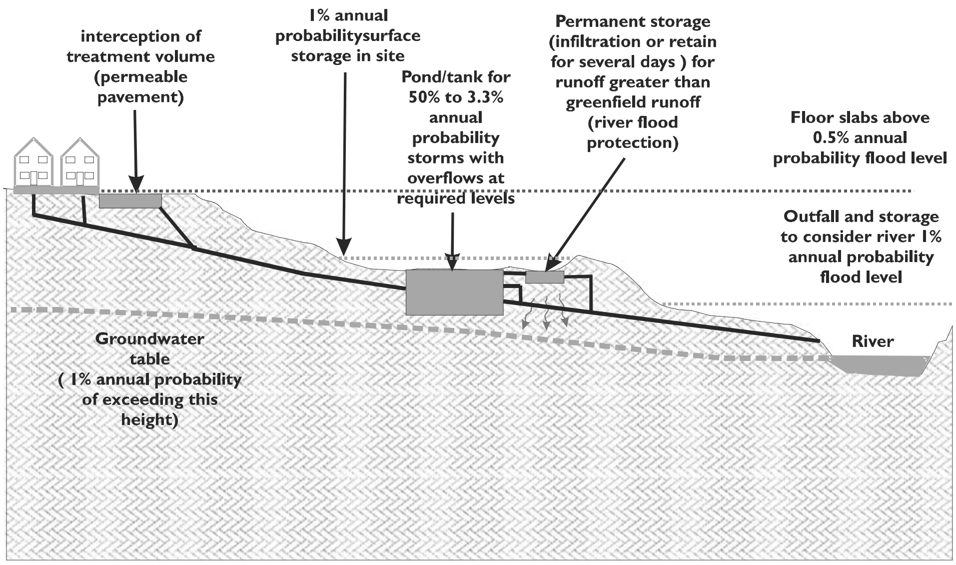


Figure 4.7 *Illustrative schematic of a storage layout (adapted from Kellagher, 2004)*

4.3.8 Groundwater, watercourse levels and time to empty

It is important that SUDS schemes operate effectively throughout their design life, so the design should take careful account of the effects on performance of watercourse flood levels and groundwater levels. For example, a balancing pond located within the watercourse floodplain for a 1 per cent annual probability flood (1 in 100-year return period) will not provide storage for rainfall to protect the watercourse when it is required to do so.

SUDS should be designed to ensure all storage operates when watercourse or groundwater is at a level that has an annual probability of 1 per cent. The outfalls to watercourses should continue to operate, unless there is sufficient storage within the system to allow for reduced operation during periods of flooding in the watercourse.

Ideally, fluctuations in groundwater levels should be determined by monitoring standpipes for at least one year. In the absence of this, a geotechnical specialist (Section 5.1.1) should advise on the likely variations in groundwater levels at a particular site. This should make allowance for the rising groundwater levels that are occurring in many urban areas with the reduction in industrial extraction of groundwater from aquifers (CIRIA SP69, SP92 and R129 – Simpson *et al*, 1989; Knipe *et al*, 1993; CIRIA, 1993, respectively). Advice on fluctuations in groundwater levels in a particular area may also be available from the Environment Agency, SEPA, Department of the Environment in Northern Ireland, local authority building control departments, water companies and land drainage boards.

The time for the storage to empty (drain-down time) so that it can accept further rainfall also needs close attention, especially if flooding affects the outfall. The criteria for each technique are discussed in Chapter 5. Generally, they require features to half-empty the temporary storage within 24–48 hours so that they can receive runoff from following storms. Long-duration events should be assessed to ensure that the storage is not overwhelmed by long periods of low-intensity rainfall.

4.4 MODELLING RAINFALL AND RUNOFF

4.4.1 Behaviour of rainfall

Rainfall patterns vary in several ways and depend on interrelated factors that include the duration, intensity and frequency of events.

The three parameters are linked in an intensity-duration-frequency relationship. The intensity and duration are inversely related to each other (as the duration of rainfall increases the intensity reduces). In addition, the frequency and intensity are also related, so that more frequently occurring events have a lower intensity.

In the UK, the Met Office monitors and collects rainfall data from weather stations around the country. Records of rainfall are available from the Met Office (<www.met-office.gov.uk>) dating back to the 1850s. The data are used to determine the variation in rainfall patterns around the country and can be obtained to aid design. Rainfall data have been published within stormwater design guidance such as the Wallingford Procedure (HR Wallingford, 2000) and included in the software associated with the *Flood estimation handbook* and other drainage design software.

The relationship between depth of rainfall, storm duration and return period has been derived for the UK by analysing rainfall records for different storm durations. From these, the largest depth of rain in that duration has been determined for every year since the records started. Relationships have also been defined to allow the depth of rain to be determined for storms covering a range of durations and return periods. These are discussed in the Wallingford Procedure (HR Wallingford, 2000) and the *Flood estimation handbook* (FEH) and associated software (Institute of Hydrology, 1999), to which further reference should be made. (See Section 4.3.1 for a discussion on the merits of the FEH against currently used methods.)

4.4.2 Rainfall data

British Standard BS EN 752-4:1998 gives three methods of estimating rainfall that may then be used to determine the rate and volume of runoff from a site. The methods can be split into the three groups in order of increasing complexity.

1. Constant rate rainfall.
2. Synthetic rainfall profiles.
3. Rainfall time series.

As the complexity increases there is an associated increase in data requirements and calculation effort. The method used should be appropriate to the site and SUDS features used.

The way in which the rainfall data is to be used also affects the format and type of data required (HR Wallingford, 2000). The data can be used for the following purposes.

1. To design a new drainage system to meet a required performance standard. Typically, constant-rate rainfall is used except for highly complex systems or where the cost of achieving greater accuracy will be outweighed by the benefits (for example, lower construction costs).
2. To predict the performance of a new drainage system under various conditions to compare alternative solutions. Normally, synthetic rainfall events are used to predict the performance of drainage systems under different conditions and assess the risk of flood occurrence. This will be required on larger, complex sites with multiple storage locations to ensure that flooding does not occur.
3. To verify the performance of a system model against observed performance. Real rainfall data is always used for this and is obtained from rainfall gauges within the catchment area being considered. Verification of performance is complex and should be undertaken by experienced drainage engineers; it will not be discussed further here. Additional information is provided in the Wallingford Procedure (HR Wallingford, 2000) and at <www.wapug.org.uk>.

For SUDS on many small sites with a simple treatment train of two or three techniques the simpler analysis using a constant fixed rate may be all that is required. Conversely, for large sites, with a number of subcatchments and a complex management train, modelling may be required to demonstrate that flooding will not occur in excess of the design requirements. In this case, the more complex method using rainfall time series may be appropriate. This is the approach adopted in BS EN 752-4:1998, which provides further information on the choice of analysis and models.

Constant rate rainfall

This is the simplest method of estimating rainfall. The total depth of rainfall falling on a site can easily be determined by multiplying the intensity by the duration.

The depth of constant rate rainfall can be estimated in three ways.

1 Fixed rate (for example, 50 mm/h).

2 Using the Wallingford Procedure.

3 Using the *Flood estimation handbook* and software (FEH CD-ROM).

BS EN 752-4:1998 quotes fixed-rate criteria for the design of paved areas, but for SUDS schemes storage of water is required for a specified limiting outflow. In this case the calculated storage volume will change with duration of storm and a range of durations need to be assessed (see Section 4.5). The use of fixed rates is not appropriate to the design of SUDS techniques except for fixed depths of rainfall for water quality treatment (see Section 4.3.2).

For paved areas up to 200 ha or with a time of concentration of up to 15 minutes BS EN 752-4:1998 recommends that constant-rate rainfall depths can be determined using the maps and methods in the Wallingford Procedure and is applicable for all the volume criteria quoted in Section 4.3. The differences between the rainfall depths derived from the Wallingford Procedure and the FEH are discussed in Section 4.3.1.

Rainfall profiles

More complex analysis is needed to model the performance of systems more accurately or to model flooding. This is carried out using computer simulation software. Normally, synthetic rainfall profiles are used in computer programs, although real data can be used if available. A synthetic rainfall profile is simply an idealised rainfall profile that is designed to reproduce the intensity distribution of a real storm (although it cannot do this perfectly). Rainfall profiles are based on historical rainfall data and are given a statistically based return period. Further information on derivation and use of storm profiles is given in the Wallingford Procedure (HR Wallingford, 2000) and the *Flood estimation handbook* (Institute of Hydrology, 1999).

4.4.3 Runoff

Rain landing on an impermeable surface first wets it, then some is absorbed and after this puddles may form in depressions on the surface. This process continues for a short period, after which time the rain begins to flow over the surface towards drainage inlets. The time taken for rainwater to reach an inlet from all parts of a traditional impermeable surface will vary between two and 15 minutes (HR Wallingford, 2000), dependent upon the intensity of the rainfall and the gradient of the surface. This time is called the time of entry.

The amount of rain required to land on a surface before runoff begins is called the *initial rainfall loss*, or *depression storage*, and typically is under 1 mm for impermeable surfaces.

Runoff from steep-pitched building roofs enters the drainage system very quickly. High rates of flow occur over a short duration, particularly if siphonic roof drainage systems are used.

Most types of impermeable urban surface do not discharge all the rainfall that lands on them after the time of entry has been exceeded, as they have joints and cracks that allow leakage through the surface during runoff. It is generally assumed that this leakage is a constant proportion of the rainfall, once runoff starts, known as the runoff coefficient. The volumetric runoff coefficient can be defined as a measure of the amount of rainfall that is converted to runoff. In natural situations, with no impervious cover, the runoff coefficient is typically in the 0.05–0.10 range. By the time a surface is fully paved with conventional surfacing materials this could have increased to 0.90 (Leggett *et al*, 2001). Note that *Sewers for adoption* and *Sewers for Scotland* specify that 100 per cent runoff should be assumed from impervious areas, which will generally lead to over-design of stormwater drainage systems.

If the amounts of rain and runoff for several storms are plotted on a graph the average values of initial loss and runoff coefficient for a particular surface can be determined (Figure 4.8). The runoff coefficient for the asphalt concrete in this case is 0.984 (98.4 per cent) and the initial rainfall loss is 0.424 mm (Jacobsen and Harremoes, 1981).

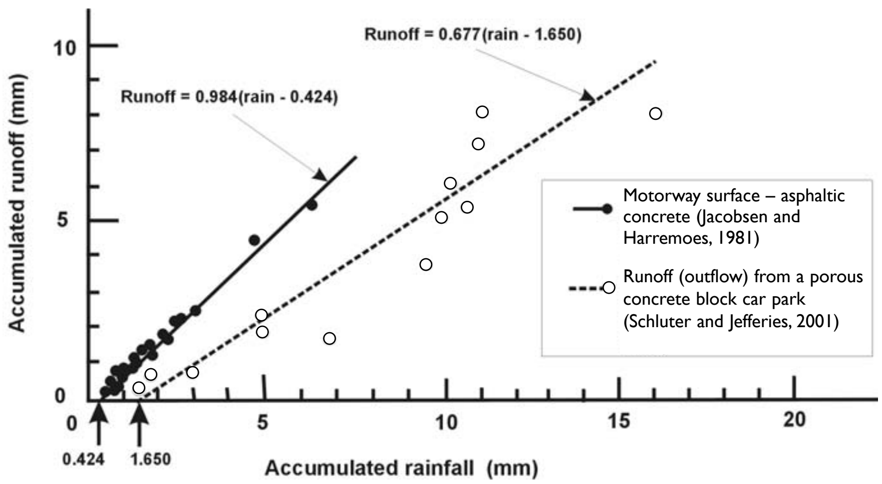


Figure 4.8 *Runoff coefficients*

For any one storm, if the amount of runoff is compared with that of rainfall a measurement known as the percentage runoff may be determined. A wide range of answers for the percentage runoff will probably be obtained if this calculation is undertaken for several storms for the same surface. This is because the response of the surface will vary with factors such as surface dampness from a previous rainfall (antecedent conditions) and duration of the storm event. The initial loss from the rainfall on a surface will similarly vary with these factors, but it is generally assumed that the runoff coefficient remains unchanged for a particular surface.

The efficient removal of runoff from impermeable urban surfaces is assisted by laying surfaces with crossfalls and channels to direct flows to drainage inlets. When a surface is nearly horizontal the correct profiling of the surface becomes important if runoff is to be directed to inlets. The runoff hydrograph into the drainage inlet varies with the nature of the rainfall, but an impermeable surface hydrograph usually shows that:

- runoff begins soon after rainfall starts
- the time taken for the surface to drain after rain stops is short
- the total volume of runoff is often some 80 per cent to 95 per cent of the rainfall volume (Figure 4.9).

In the hydrograph shown in Figure 4.9 runoff starts after 0.5 mm of rainfall and is completed some 10 minutes after the end of rainfall (Pratt *et al*, 1984).

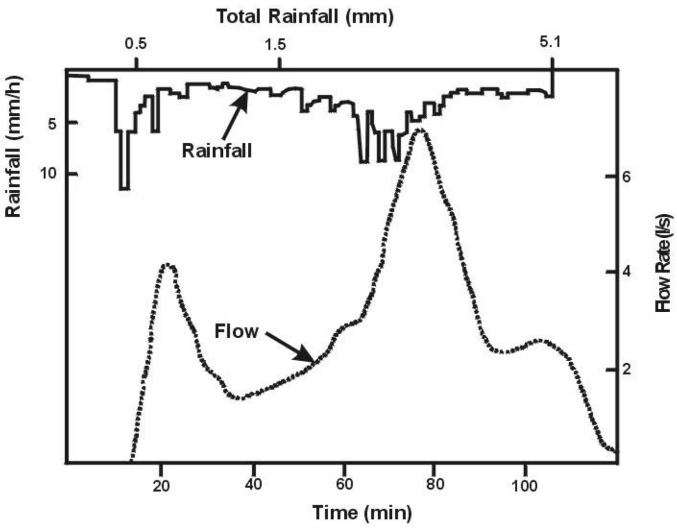


Figure 4.9 *Typical runoff hydrograph for an impermeable surface (Pratt* et al*, 1984)*

Overall, impermeable surfaces respond quickly once rain starts to fall and discharge almost all the rainwater during, or soon after, the period of rainfall. The consequence of this is that impermeable surfaces properly laid and free from puddles shed runoff rapidly into the receiving drainage systems.

Runoff from impermeable urban surfaces also washes off pollution from the surface (which occurs from sources such as atmospheric deposits, oil leaks from cars and tyre wear). The majority is washed off at the beginning of a rainfall event (Section 3.1.4) and is known as the first flush.

4.4.4 Evaporation

Evaporation of water and transpiration by plants can be a significant removal mechanism of water from SUDS techniques. However, it should be relied upon since it is not guaranteed to be effective when required (for example, removal by evaporation would be limited during a long-duration low-intensity rainfall event). In some instances it can be allowed for. One example is in risk assessments of average annual pollutant loading, where an annual average evaporation rate may be estimated with an acceptable degree of confidence.

Further guidance on estimating evaporation rates is provided in Coppin and Richards, 1990 and Novotny and Olem, 1994.

4.4.5 Snowmelt

Snowmelt can cause particular problems for SUDS techniques if not allowed for in design, as large volumes of runoff are released in a short time. The snow also accumulates pollutants, especially from road salting or gritting, and introduces a high load into the SUDS. This is discussed in Section 5.15.

4.5 STORAGE AND FLOW ESTIMATION

Storage volumes for any given design storm are dependent on the rate at which water enters and leaves the storage system. Different storm durations will give different volumes and the critical duration for any part of a system is determined by experiment (Figure 4.10).

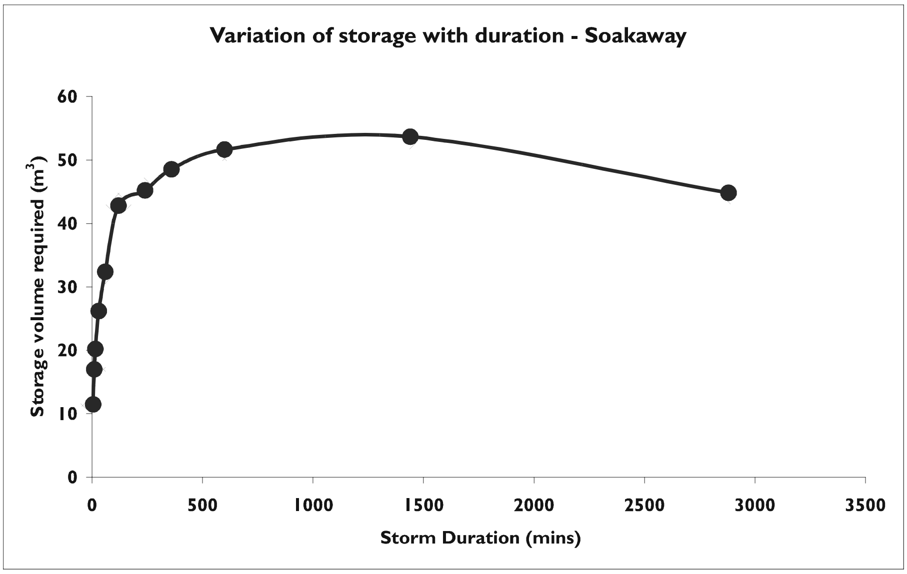


Figure 4.10 *Variation of calculated storage volume with storm duration*

The flow of water within SUDS should be determined using the relevant design method for each particular technique and overall assessment of flows should be undertaken in accordance with the guidance discussed in Section 4.3.

4.6 SENSITIVITY ANALYSIS FOR CLIMATE CHANGE

It is generally accepted that climate change is occurring. The precise effects on the UK cannot be predicted, but some general trends are likely. Studies commissioned by DEFRA (Hulme *et al*, 2002) indicate that:

- winters will be wetter, with an increased frequency of heavy rainfall. There will be a 10–35 per cent increase in winter rainfall volumes, depending on region and the accuracy of assumptions about global emissions of greenhouse gases
- in some areas of the United Kingdom the intensity of winter rainfall will increase by 5–20 per cent
- the intensity of an event with a given probability of occurrence may change. For example, in winter daily rainfall with a 50 per cent annual probability (1 in 2-year return) may increase by up to 20 per cent in some areas of south-east England and sout-east Scotland. Conversely, in summer the intensity for daily rainfall that has a 50 per cent annual probability (1 in 2-year return) may decrease
- summers will be drier, with 35–50 per cent less rainfall across most of the UK, depending on assumptions made about global emissions of greenhouse gases. The intensity of short-duration summer storms may, however, be higher
- the UK will be warmer, with an annual average temperature increase of 2–3.5°C
- there will be significantly less snowfall across the UK.

Other studies have looked specifically at short-duration summer storms and identified that in the UK Midlands one-hour rainfall intensities for return periods of two to five years may increase by 20–40 per cent by 2080 (Firth, 2001). The implication for SUDS is that winter storms may deliver more volume, while summer storms may deliver greater intensities in some areas of the UK. Both can be mitigated by SUDS use.

The effects will occur over the next 70–80 years and the precise extent will depend on whether a reduction in greenhouse gas emissions is achieved across the world. To allow for such effects, a sensitivity analysis should be undertaken for a SUDS design (and for conventional drainage design). Further information on undertaking risk assessments for climate change is provided by UKCIP (Willows and Connell, 2003).

For example, it would not be acceptable to have a system that operates without flooding for storms with an annual probability of 3.3 per cent (30-year return period), but fails and causes severe flooding of the site and buildings with a slight increase in probability (for example, 3.8 per cent). Conversely, the merits of providing an industrial building with a 20-year design life with a drainage system that allows for storage of the full 20 per cent projected increase in rainfall intensity should be carefully considered. Alternatives, such as using the roads for controlled overland flow of extreme events, are likely to be much more cost-effective than increasing storage volumes within a system.

Care needs to be taken when applying the climate change data to a SUDS design. When considered appropriate, factors allowing for climate change should be applied to the design storm intensities. This differs from decreasing the annual probability (increasing the return period) by 20 per cent or adding 20 per cent to the storage volumes calculated for a particular return period. This should not be applied as a blanket requirement across the the UK.

Some of the projected changes will improve the performance of some SUDS; for example, increased temperatures will increase evaporation rates between rainfall events. The *Flood estimation handbook* (Institute of Hydrology, 1999) suggests that the drier summers will lead to greater soil moisture deficits, which will reduce runoff. The time required to replace the moisture during winter could lead to a shorter flooding season and fewer flooding incidents.

It is likely that the Environment Agency will require climate change to be taken into account by increasing the rainfall depth by 10 per cent for computing storage volumes. DEFRA's official advice on river flows is that a 20 per cent increase should be added for climate change. Because the relationship between rainfall and runoff is non-linear, the use of 10 per cent additional rainfall is considered to approximate to a 20 per cent increase in runoff for larger events. No allowance for climate change should be applied to calculated greenfield peak rates of runoff from the site for any hydrological region. It should be recognised that although it is acknowledged that climate change is taking place, certainty regartding the hydrological changes, particularly of extreme short-duration events, is very low.

5 General SUDS design

This chapter discusses general design issues that apply to all SUDS techniques. It begins by identifying the information required to allow a SUDS scheme to be designed and where it may be obtained, together with the design objectives.

It continues with information for clients on the skills needed by design teams, design standards for SUDS and design accreditation.

The chapter includes a discussion on the concept of failure, an explanation of drainage system failure under certain conditions and how the system should be designed to manage this, alongside consideration of design life and risk assessment.

General guidance is provided on specific site constraints that affect the choice of SUDS techniques and consideration of linking SUDS together.

The substantial wildlife and amenity benefits that SUDS can bring to a site are discussed in this chapter and details are provided about planting for sustainable drainage systems.

Information is given on management of silt, which is an important consideration in SUDS schemes.

The chapter also provides guidance on managing the health and safety issues associated with SUDS, along with references to the statutory requirements that must be met.

Geotextiles and geomembranes are often used in SUDS techniques, and advice on the selection and specification of appropriate materials for specific uses is provided.

The issues surrounding the wider concerns of sustainable construction are explored.

The use of SUDS in cold climates requires special consideration and information is provided on how specific problems may be overcome.

5.1 DESIGN INFORMATION

5.1.1 Site investigation

The importance of a well-planned and well-executed site investigation cannot be understated, especially where runoff is to be infiltrated into the ground. A full assessment of ground and groundwater conditions is required to assess the suitability of a site to accept soakaways or other infiltration techniques. The site investigation should be based on the conceptual model of the SUDS so that relevant information is collected from the appropriate areas of the site.

A thorough site investigation should include the following:

- desk study – to identify groundwater protection zones, likely geology and groundwater conditions, and any other constraints that may affect the use of infiltration devices
- full descriptions of the soil types encountered and a conceptual model of the ground and groundwater conditions

- infiltration tests in accordance with BRE Digest 365 (BRE, 1991). Small-scale tests are not suitable as they only test a small volume of soil and do not test the infiltration capacity of a significant ground mass
- tests that are carried out at the depth of the proposed infiltration device with a head similar to that likely to occur within the completed soakaway (Bettess, 1996). For impermeable areas less than 100 m^2 a volume of water of 0.5 m^3 should be used. For greater impermeable areas a volume of at least 1 m^3 should be used.

On their own, infiltration test results are insufficient to allow a soakaway design to be approved. Approval should only be given to infiltration if all the information is provided.

Testing and reporting on the suitability for soakaways should be undertaken by qualified and experienced geotechnical engineers and be approved by a geotechnical specialist, as defined by the Institution of Civil Engineers (Site Investigation Steering Group, 1993).

5.1.2 Services

The location of statutory undertakers' services (including gas, electricity, water and telephone) should be allowed for in the design of SUDS schemes. There should be no conflict between positions of services and the location of SUDS (excavation for repair of services should not affect the performance of the SUDS, for example). The impact on services of water infiltrating the ground needs particular consideration and may preclude the use of infiltration techniques over some buried services.

5.1.3 Information review and checklist

The information review element of the design process should follow the format recommended in Appendix 3, which should minimise the risk of overlooking relevant data. It will also assist in assessing the selection criteria to establish the best options for SUDS techniques for each project. A basic checklist of required information, such as the one in Appendix 3, will be of use in developing a standardised approach in the review process.

When collecting information, designers should consult with the appropriate regulatory authorities to find out if they have any particular concerns or requirements. The local planning authority should also be consulted, as some local authorities in England and Scotland (such as Aberdeen and South Gloucestershire) have particular policies with respect to SUDS.

5.1.4 Design objectives

It is important that the design objectives are clearly defined and agreed at the earliest possible stage and take into account the following criteria:

- site characteristics
- allowable discharge rates and flooding criteria
- groundwater protection
- geological sensitivities
- environmental issues
- type of application
- success/failure criteria
- aesthetic requirements
- maintenance implications.

The decision about whether surface water runoff should be allowed to infiltrate into the ground depends on:

- a risk assessment that shows an acceptable risk to groundwater and infiltration, and that meets regulatory criteria, considering pollution in the runoff or any ground contamination
- the likelihood that infiltrated water will adversely affect building or road foundations (usually less than 5 m away, although this can be reduced on the advice of a geotechnical specialist, see Section 5.1.1)
- the accetability of the depth to the water table and whether it will contribute to localised flooding.

5.2 SUDS DESIGN TEAMS AND STAKEHOLDERS

SUDS are not only about the volumes of water that are dealt with by the drainage system, but also landscaping, pollution removal, the fate and migration of pollutants in the sub-surface, slope stability and infiltration capacity.

A successful SUDS design team therefore incorporates a range of disciplines, of which drainage engineers are just one element. The team has to integrate with other stakeholders involved in the development process, as shown in Figure 5.1. The design team and stakeholders should consider SUDS at the feasibility study stage of development so that the optimum benefit of integrating the SUDS into the development is achieved (Section 2.1).

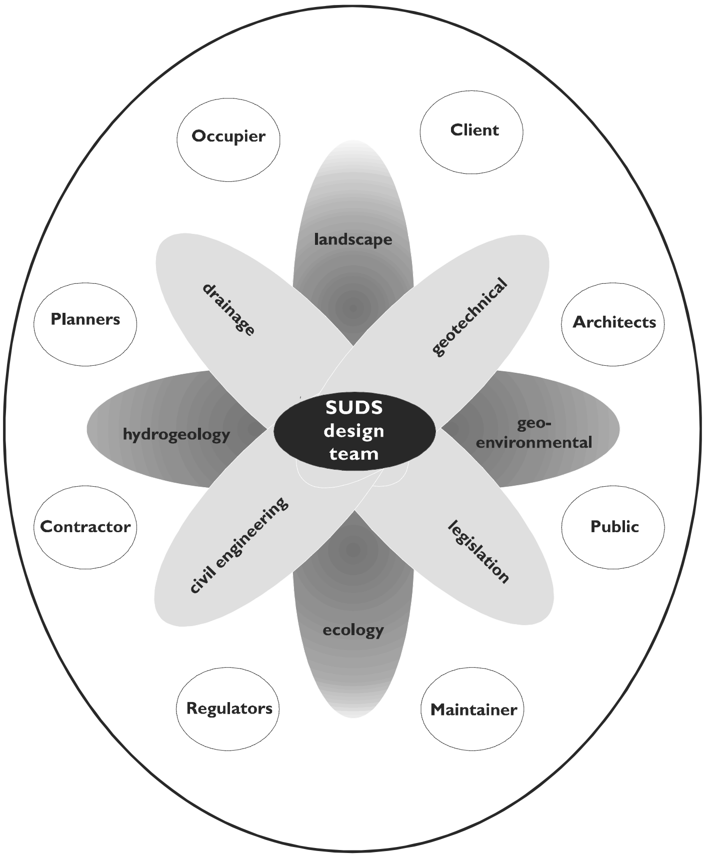


Figure 5.1 *Multidisciplinary SUDS design team and stakeholders*

5.3 DESIGN STANDARDS AND EA ACCREDITATION

SUDS do not provide the answer to all the problems relating to flooding and pollution of surface watercourses. For example, SUDS techniques will not prevent flooding of low-lying sites when the receiving watercourse has high water levels. SUDS will attenuate the rate of surface water runoff from the area served, thereby reducing, to some extent, the risk of flooding to downstream properties. However, if SUDS are poorly designed, constructed or maintained, the risk of flooding or pollution of sites downstream of the development area being served may actually increase. For this reason, it is essential that designs are carried out by teams with all the necessary skills (Section 5.2). The design should be checked against a set of criteria to ensure that the design addresses all the site-specific constraints and other requirements – for example, demonstrating overland flow routes. Appendix 6 illustrates a checklist of this kind that was prepared for the Environment Agency in England and Wales.

A similar requirement is being developed in Scotland, where the Aberdeen drainage impact assessment is used to provide information to the regulatory authorities to demonstrate the application of SUDS in development sites (Aberdeen City Council *et al*, 2002).

The design also needs to be constructed and maintained correctly, so designers should prepare a construction checklist and guidance note for each scheme that summarises key elements of the system and lists mistakes to avoid during construction. This should be written in simple terms without the use of jargon, so that it is easily understood by site personnel. Similarly, a maintenance manual should be provided for every design.

Many of the SUDS techniques discussed in this book rely on natural vegetation, soil/aggregate materials and other features used to attenuate flows and remove pollutants. These are natural systems and will not always conform to theoretical mathematical models. Designers should not totally rely on analysis, therefore, but should also use their judgement based on experience.

SUDS should be designed with easy maintenance in mind, for example by considering access routes to remove silt and clear blockages. Designers also need to consider construction of SUDS schemes and identify how construction runoff will be dealt with.

5.4 FAILURE AND RISK MANAGEMENT CONCEPTS

5.4.1 Design exceedance

A drainage system that never floods would be extremely large and expensive. It is normal practice to achieve a balance between the cost of a drainage system and the risk and consequence of flooding occurring. The balance needs to allow for various factors including:

- the consequences of flooding, and consideration of safety. For example, flooding a landscaped area is more acceptable and less costly than flooding a property
- the cost of repair after flooding has receded.

The practical implications of achieving a balance between cost and benefit are that the capacity of all drainage systems will be exceeded at times and the effects of flooding must be anticipated and managed to minimise the consequences. In particular, public safety should be maintained and the flooding of buildings should be prevented in extreme events. The overland flow paths should be clearly demonstrated (this is a requirement of *Sewers for adoption* and *Sewers for Scotland*; WRc, 2001a and 2001b). It is especially important on steeply sloping sites.

SUDS schemes are designed to remove pollution from runoff and the consequence of failure of the pollutant removal mechanisms needs consideration.

5.4.2 Design life

The design life for a system is the length of time the system is expected to operate without major reconstruction. This does not mean that flooding or failure will not occur, but that risk management can minimise the effects (for example, by the choice of an appropriate annual probability for the design storm). The robustness of the pollutant removal can be increased in the SUDS design to reduce the risk of failure and the consequences if it does occur (see Section 3.4). As SUDS are natural systems the actual performance may vary from that predicted in the design. Monitoring and minor adjustment of systems during and after construction is discussed in Section 6.2.

The design life should consider:

- the length of time the system will continue to remove pollution
- the length of time the system will be required to provide attenuation for runoff flows (this should be related to the design life of a development)
- the acceptable frequency of flooding during the design life
- the consequences and effects of flooding.

These considerations are not unique to SUDS and should be applied to all drainage systems.

5.4.3 Risk assessment and management

Due to the variability of rainfall and the fact that drainage systems are only designed to cope with events of certain probabilities there will be times when extreme events exceed the capacity of the system. SUDS are also natural systems and there will be variations in performance.

Variations and uncertainty should be identified, assessed and managed in the design. From the beginning of any SUDS design, a risk register can be developed that lists all identified risks, together with the likely effects and any mitigation measures that have been adopted. The register should be maintained and updated as design and construction proceeds.

Risk management should not focus entirely on technical issues, as often the perception of the public or other stakeholders needs to be addressed. Such perceptions should not be discounted simply because they are considered unfounded by technically knowledgeable people.

As a minimum, risk management should include consideration of:

- overland flood flow routes during extreme events
- effects of extreme events on the system (erosion, for example)
- effects of reduced pollutant removal in any one technique on the receiving waters
- effects of blockages, for example due to litter, on the system
- effects of failure to maintain the system
- health and safety (see Section 5.10).

Further guidance on risk management is provided in Fleming, 2002.

5.5 GUIDANCE ON SELECTION OF SUDS TECHNIQUES

There are many SUDS techniques that can be used on a site. Selection of the most appropriate set of SUDS techniques for a given situation will be guided by the site's own unique set of factors and constraints. Not all techniques will be suitable on all sites, so it is important to identify the constraints early in the design process.

SUDS is much easier to incorporate if it is considered at feasibility stage and the development layout is designed to accommodate the drainage scheme. Many of the preconceptions about SUDS result from the difficulty in trying to bolt SUDS on to site layouts based on conventional drainage.

The many publications available provide guidance on the factors to consider when choosing appropriate SUDS techniques for a site. Various factors and criteria need to be considered in design. They can be divided into the following nine general categories.

1 Pollution removal provided by the SUDS technique.

2 Hydrological control (volume and flow rate reduction) provided by SUDS technique.

3 Space required for techniques.

4 Land use.

5 Physical site features.

6 Ground and groundwater conditions.

7 Construction and maintenance costs.

8 Community and environmental considerations.

9 Legislation and regulations.

Pollution removal by SUDS technique

Each technique has a different removal efficiency for each pollutant of concern. The techniques that are used on a site must be able to reduce the levels of the pollutants of concern to acceptable levels. Pollutant removal efficiency is discussed in more detail in Section 3.4 and for each individual technique in Chapter 9.

Hydrological control (volume and flow rate reduction) by SUDS technique

SUDS as a concept can be applied to a very wide range of site conditions. However, each technique will be limited to a narrower range of sites. Some techniques provide only limited volume control or flow rate reduction. For example, filter strips will not provide much storage of water to control the rate of flow or volume of water leaving a site.

Space required for techniques

Some SUDS techniques require more land space than others, which is easily recognised in the example of the space required to construct a pond. Although a technique may require a large amount of space, this is not necessarily a barrier to its use, even on high-density urban developments. PPG 3 requires developments to provide sufficient provision for open space and playing fields where such spaces are not already adequately provided within easy access of the new housing. A pond could be included in this area, or the area designed to flood on rare occasions and for a short time during and after extreme storm events. In some instances, ponds have been located outside the development site on other land where the owner has seen the benefit of a pond.

Land use

Certain SUDS techniques, in particular infiltration, may be limited by land use, especially where there is an unacceptably high risk of generating contaminated runoff or where the groundwater is an important resource (groundwater protection zones). In the USA these are known as stormwater hotspots (Maryland Department of the Environment, 2000). In such areas, infiltration should not be used and care should be taken in the choice of SUDS technique. For more details on hotspots and groundwater protection zones, see Section 3.2 and Boxes 3.2 and 3.3.

Physical site features

Physical site features will affect the choice of suitable techniques: catchment area is particularly important since certain techniques are more suited to smaller catchment areas. Swales are usually limited to a maximum catchment area of 5 ha (see Section 9.7). Other techniques (such as wetlands) are most efficient when used to deal with runoff from large catchments (greater than 10 ha).

Ground and groundwater conditions

Ground and groundwater conditions may limit the types of technique that can be used. Infiltration techniques, for example, require at least 1 m of soil between the base of the device and the groundwater table, in addition to soil with a suitable permeability to accept the infiltration. Conversely, where permeable soils are present, ponds require impermeable liners to maintain water levels. It is important to determine where infiltrated water will flow so that there is no danger of SUDS drainage causing flooding at low spots in a site.

Construction and maintenance costs

Construction and maintenance costs vary widely between techniques and on many sites they may be the most important considerations after pollutant removal and hydrological control. Perceived maintenance burdens were identified as a major barrier to the use of SUDS in Scotland (McKissock *et al*, 1999). In practice, these fears are generally unfounded – details on maintenance regimes and costs are provided in Chapter 7.

Community and environmental considerations

Community and environmental issues should be carefully assessed. Ponds are often perceived to be a safety issue, but concerns can usually be overcome if they are addressed at the design stage (see Section 5.10). Some techniques may be more acceptable to the public if they are restricted to, or avoided in, certain locations (avoid the use of swales in gardens, for example). On one development in Scotland, the residents were generally positive about SUDS and they particularly preferred ponds to swales (Apostolaki, 2001).

Often the need to provide something of amenity value influences the number of techniques used within a treatment train. For example, a pond may be sufficient to remove pollution, but to maintain its amenity value another technique may be required before it to prevent gross pollution damaging the pond's aquatic ecosystem. Involving the community in the management of SUDS is discussed in Section 5.7.2.

Aesthetics of SUDS can be important in some locations and the views of the owners and occupiers should be sought at an early stage. They may be willing to pay a premium for enhanced planting to beautify a site.

Legislation and regulations

Legislation and regulations can restrict the use of certain techniques in some locations. In this respect, groundwater protection zones are important, and the risk posed by infiltration techniques to groundwater should be carefully managed (Section 3.3). Details on the environmental legislation relating to SUDS are provided in Section 3.2.

To determine which techniques are suitable for a given site the range of common techniques have to be assessed against the specific site characteristics to screen out those that will not be suitable. The remaining techniques can be chosen on the basis of a cost benefit assessment.

Appendix 1 provides a decision flow chart and a set of matrices that list the most common factors to consider when deciding on the most appropriate techniques for a site. They are based on similar matrices provided in stormwater management manuals from the USA (examples are in Maryland Department of the Environment, 2000; Sacramento Stormwater Management Program, 2000 and New Jersey Department of Environmental Protection, 2000).

Another consideration is the degree of confidence placed in the performance of the chosen techniques, in terms of pollutant removal and control of water quantity. Each technique may be classified in terms of design technology robustness (Urbonas, 1997). Further information is provided in Section 3.

The matrices and decision flow chart may be used as an aid to judgement in the choice of techniques for a site. Sometimes the constraints that apply to an individual technique may be overcome by innovative design. The constraints listed in Appendix 1 should not be used to justify the exclusion of techniques if a designer has adapted them for use on a particular site.

5.6 LINKING SUDS TECHNIQUES TOGETHER

The design of a SUDS scheme normally requires the use of two or more techniques linked together to provide the stormwater management train for a site. Designers should pay particular attention to the hydraulic behaviour of the runoff within the combination of techniques to avoid, for example, providing excessive storage that may render a scheme uneconomic. The flow characteristics of the techniques should also be taken into account, as they may be able to provide sufficient flow control to avoid the need for devices such as vortex flow controllers.

An example would be where the majority of a site is drained by a permeable pavement that flows into a swale conveying runoff to a pond and then an outfall. Some areas may discharge directly into the swale. The storage for most of the site is provided in the permeable pavement, so no additional storage is required and the pond should be sized to deal with the areas that discharge directly into the swale. The attenuation effects of the pervious pavement and the flow along the swale should also be considered, so that the necessary storage is located throughout the system.

The effect of roof drainage discharges into the system also needs to be allowed for. In particular, the use of syphonic roof drainage can cause very high intensity flows in the drainage system. If not controlled, they can lead to erosion within the SUDS.

5.7 WILDLIFE, AMENITY AND COMMUNITY INVOLVEMENT

5.7.1 Wildlife and amenity

Most SUDS techniques can provide some wildlife and ecology benefits and help to achieve the biodiversity action plans prepared by the UK government (Jones and Fermor, 2001). They can also provide aesthetic benefits. Swales and filter strips can be colonised by a variety of wetland plant and animal species, and filter drains and permeable surfaces are likely to be colonised by micro-organisms and pollution-tolerant wetland invertebrates. Well-designed SUDS can provide a valuable wildlife and local amenity. The example shown in Figure 5.2 provides a valuable local wildlife habitat and social resource and it is difficult to tell that its primary function is drainage. It was designed by stream restoration specialists to replicate the local natural environment wherever possible.

Figure 5.2 *SUDS designed to enhance local wildlife and amenity*

The presence of pollutants in water draining into a SUDS means it is likely to support only relatively robust and common pollution-tolerant species, particularly early in the treatment train. The choice of plants should allow for the levels of pollution that are likely to occur (Section 5.8). A study in the UK found that SUDS ponds did not generally have high-quality biotic communities (Powell *et al*, 2001). However, in some ponds BAP species were present and a few of the highest-quality ponds did sustain rich communities. They also identified that careful design and planting could improve the wildlife value of SUDS ponds.

Guidance on designing ponds and wetlands to enhance wildlife and amenity provision is provided in Section 9.11.1 (Design criteria) and in CIRIA Book 14 (Hall *et al*, 1993). It is important to ensure that the water quality in a pond is acceptable for the proposed use so that it does not pose a risk to health (where a pond is to be used for water sports, for example).

The design of a SUDS scheme should ensure that it does not pose a significant risk to wildlife. Inlet and outlet structures should be designed so that amphibians cannot fall into them, or, if they do, that there is an escape route. This generally precludes the use of conventional gullies.

Although SUDS techniques provide wildlife habitat, their prime role is as a drainage system. SUDS sites should not be identified as areas for SSSI status or protected conservation/wildlife zones. Most of the SUDS facilities will require some major maintenance work at some stage to ensure satisfactory operation. Legal protection should not obstruct these operations (although the operations need to be carried out with consideration for the well-being of wildlife – Section 7.6). The possibility of natural colonisation by protected species may need to be considered.

5.7.2 Community involvement

If the local community can be involved in the decision-making on the use of SUDS and their management, it will give them a sense of ownership. This can improve the chances of SUDS continuing to perform in the long term and avoid problems due to lack of education. A committed and educated community is more likely to employ prevention measures. For more than 25 years, many conservation organisations both nationally and locally have enlisted the help of volunteers to develop, manage and sustain natural habitats. These volunteers may start with little or no experience of habitat management, but over time they build up skills and experience, often to the same level as professional ecologists. Organisations such as the wildlife trusts even grant the responsibility of managing nature reserves to management committees composed entirely of experienced volunteers. A similar approach could be adopted on some SUDS schemes.

In Northamptonshire, the county council's "Pocket Parks" initiative, which started in the 1980s, has created a network of green spaces ranging in size from 0.5 ha to many hectares, each green space managed by the neighbouring community. A community trust is set up to own and manage the site, and this trust is run by local people who sit on the board of trustees. The process of creating a trust and charity involves drawing up a constitution governing the operation of the trust. The Charity Commission's procedure for obtaining charitable status demands an exit strategy dictating how the trust's assets will be owned and managed should the trust be wound up.

There are many community environmental charities assisting volunteers to undertake environmental improvement projects (for example, the Stroud Valleys Project, <www.stroudvalleysproject.org>). These train and support volunteers to develop and manage the natural ecology of green spaces, and provide the pivotal link that ensures effective practical site work and continuity of management. In Stroud, many of the sites are much smaller than Northamptonshire's pocket parks, so a sister charity – the Stroud Community Land Trust – acts as the mechanism for owning/leasing and protecting green spaces. Stroud Valleys Project then trains local communities to manage the sites. The same approach could easily incorporate SUDS systems. One such example is at Stroud College, where Stroud Valleys Project's volunteers transplanted excess aquatic vegetation from the local disused canal to the SUDS scheme handling the runoff from the college's new car park complex.

Another site near Stroud includes a pond that is one of the best great-crested newt habitats in Gloucestershire. The planning permission for a new housing development granted by the local council ensured that the pond and surrounding area were protected. Stroud Valleys Project and local volunteers will manage the site in the absence of relevant expertise in the local council. As the site is alongside an estate road, it could easily have used a SUDS system to treat the road runoff, which would have been maintained as just another habitat in the site's management plan. "Rain gardens", which are community-managed detention basins, are another feature that could easily be incorporated in an environmental charity site management plan.

Worcestershire County Council is introducing the "forest school" approach to school campuses to provide opportunities for learning about wetlands, wildlife and natural drainage principles. Young children are encouraged to use hands-on experience of the natural world as "stepping stones" to all six areas of the early learning goals. In particular, the approach develops independence and fosters mathematical, language and listening skills (<www.foresteducation.org.uk>). Education about the environment can take place in a natural setting where health and safety have been considered as part of SUDS design.

The public can also be educated about SUDS through the provision of information boards at SUDS facilities explaining the purpose and function of the systems. The signs should be easily readable and placed in prominent accessible locations.

5.8 PLANTING SUDS

5.8.1 Planting design objectives

The planting of SUDS techniques has to meet the variety of objectives set out below.

Drainage

- Stabilisation of surfaces and erosion control
- interception of silt and prevention of silt re-suspension
- bioremediation substrate for the treatment of pollution.

Health and safety

- Physical barriers to access where necessary
- stabilisation of surfaces where access is acceptable.

Amenity

- Attractive visual character
- all-season interest.

Wildlife

- Create optimum habitat structure
- avoid alien species
- use local provenance species.

Management

- Simple effective maintenance
- easy access
- site management of green waste.

5.8.2 Environment and types of planting

SUDS may incorporate a number of environments, including:

- permanent ponds
- temporary ponds
- wetlands without standing water
- streams or other low-flow channels
- wet grassland
- dry grassland
- natural planting
- ornamental planting.

Permanent ponds contain some water at all times, whereas temporary ponds experience alternating wet and dry periods. Wetlands develop in permanently wet soils with a characteristic vegetation dependent upon water being available at all times. Streams and low-flow channels are linear drainage features that convey water and develop a characteristic vegetation in response to flow. Natural streams are subject to unpredictable flows that can alter the form of the channel by erosion and deposition of silt. Low-flow channels used in SUDS are designed to receive a predictable flow to prevent erosion and create an easily managed conveyance route for runoff. Overflow channels usually develop a wet or dry grassland vegetation depending on the soil's moisture content.

SUDS may include various types of ponds, wetlands and channels with different drainage functions, ecological characteristics and hydrology. Each of these factors has implications for the type of planting suitable for each area. A balance should be struck between planting for design reasons and natural colonisation of habitat types by wild flora.

SUDS features normally require some planting to meet the design objectives, rather than rely completely on natural colonisation. However, it is important to understand the disadvantages and risks of planting ponds and wetlands. There is a perception that pond colonisation takes a long time, so it is necessary to add plants to speed up the process (SEPA, 2000). Studies have shown that colonisation is in fact quite fast, especially if there are other wetland habitats within 1 km.

In some cases, the wildlife benefits of SUDS can be enhanced by relying on natural colonisation of ponds to provide a distinctive environment in their early years when species that require inorganic sediments (such as stoneworts or darter dragonflies) can flourish. As the pond becomes mature these are replaced by more competitive species or those that require organic sediments. Most new ponds or wetlands will colonise naturally and artificial planting can introduce troublesome plants and remove opportunities for native species.

Artificial planting of ponds is not necessarily harmful but some of the valuable early pond stages may be reduced.

5.8.3 Planting-up SUDS ponds, wetlands and streams

The most readily available guidance on planting SUDS techniques is provided by SEPA, 2000.

The main advice is:

- SUDS ponds will normally be planted up with tall emergents, chiefly to aid their functioning and to provide safety screening. In urban areas, planting may be provided to improve aesthetics. Artificial planting is not necessary for nature conservation and should be avoided wherever possible
- new ponds usually show a very rapid rate of natural colonisation with species that are more appropriate to the location than those introduced deliberately. A survey of Scottish SUDS by Pond Action showed that within a year or two of their creation most SUDS ponds supported 15–20 species of native plant which had arrived entirely by natural means.

In urban landscapes, a reasonable level of landscaping around new water bodies may be required. This should:

- be restricted to plants that already grow in the locality (within 10 km of the site)
- include some plant species that are particularly wildlife-friendly, eg grasses such as *Glyceria fluitans* (floating sweet-grass) and *Agrostis stolonifera* (creeping bent), which provide a good habitat for newts and other invertebrate animals
- be appropriate to the physical and chemical conditions (eg do not plant up a pond in an acid water area with species from base-rich soils).

It is usually necessary to specify planting to provide rapid vegetation cover to prevent erosion of the SUDS. There are readily available some very vigorous wetland species that can achieve this requirement. However, it is inadvisable to plant them at the edge of small shallow ponds, unless a marshland pond dominated by tall emergent plants is required, or continuous plant management is to be undertaken. These include:

- great pond-sedge (*Carex riparia*)
- reed canary-grass (*Phalaris arundinacea*)
- reed sweet-grass (*Glyceria maxima*)
- branched bur-reed (*Sparganium erectum*)
- bulrush (*Typha latifolia*).

Once the initial flush of nutrients has occurred in SUDS schemes, largely caused by disturbance, then stormwater runoff will be relatively poor in plant food.

Planting schemes, particularly where a native plant community is desired, should avoid aggressive species and use plants that will allow natural colonisation from local wetland habitat. These may include submerged and floating leaved plants, marginal plants, low-growing herbs and grasses or other aquatic plants (Appendix 5).

5.8.4 Planting for wet benches and margins

Amenity and wildlife benefits are usually enhanced by a habitat mosaic surrounding the SUDS wetland features. The immediate margins to ponds, wetlands and streams should include a “wet bench” safety strip, which provides a level surface as an area of safety for a person who has accidentally entered the water. It also provides a measure of silt control.

It is usually most convenient to turf the level bench, as it is permanently wet and benefits from immediate stabilisation. A standard, locally sourced, managed meadow turf or purpose-grown turf is suitable for the wet bench. Temporary stabilisation is often required to prevent erosion and silt pollution of wetland structures. This can be provided by using either biodegradable coir blankets or jute mesh.

5.8.5 Grass surfaces that are not permanently wet but subject to inundation

Slopes, swales, filter strips and detention basins outside the permanently wet zone of the wetland may experience flowing water across the grass surface. These grass areas will usually require temporary stabilisation to prevent erosion or silt mobilisation and to allow the establishment of a grass sward.

This can be provided by turf if the season and soil condition allows rapid establishment. If this is not possible the following protection can be used:

- a fully biodegradable coir blanket (no plastic reinforcement) – pre-seeded or underseeded for full protection
- a geojute mesh erosion matting that is underseeded for partial protection.

The use of a coir blanket is recommended for structures such as swales and filter strips where regular flows of runoff are expected. Geojute is appropriate for slopes subject to erosion by rainfall.

Although the use of topsoil can contribute to nutrient pollution in wetlands, experience at Oxford Motorway Service Area on the M40 and Hopwood Park MSA on the M42 has demonstrated that bare subsoil can take a long time to develop a full vegetation cover.

Where turfing is to be undertaken it is recommended that 100 mm of medium- to low-nutrient topsoil is used as a rooting medium for the grass and a 50 mm blinding of medium- to low-nutrient topsoil for seeded areas.

Addition of fertilisers to topsoil should be minimised where leaching of nutrients may contribute to the catchment of the SUDS scheme. This practice is also recommended for all ornamental shrub planting or tree planting within the SUDS catchment.

5.8.6 Grassland not subject to inundation

Where low-maintenance or wildflower grass areas are proposed with a low risk of runoff, topsoil can be omitted entirely.

The establishment of low-maintenance and wildflower grassland is covered in English Nature (1999). Amenity grassland requires a minimum of 100 mm topsoil to ensure rapid establishment of turf growth that can resist drought and thereby provide an acceptable visual effect for certain situations in the landscape.

5.8.7 Natural planting

Where natural planting (native tree, shrub and other wild plant species) is proposed within a SUDS catchment it is important that nutrient pollution and silt is prevented from entering the wetland system.

All surfaces should be vegetated as soon as possible – ideally before trees and shrubs are planted. Where topsoil is used in planting pits, additional fertilisers should not be used and surface mulches confined to 1 m diameter round individual items. Weedkillers and herbicides are very damaging to aquatic wildlife and should be avoided as far as possible.

5.8.8 Ornamental planting

Generally, planting to SUDS features should be native and based on habitat management principles. Nevertheless, it is common for ornamental planting to be integrated into SUDS schemes, and increasingly SUDS are being applied to urban situations. By following certain principles, action can be taken to avoid silting of infiltration techniques, nutrient pollution, damage to SUDS features and colonisation by alien plant species.

Protection of SUDS features in urban development should consider the following:

- reduced use of topsoil
  – no topsoil in wetlands
  – 100 mm low-nutrient topsoil for turf areas
  – 50 mm blinding of low-nutrient topsoil for seeded areas
- slopes vegetated above water features as soon as possible
- slopes protected with erosion mats
- silt cut-off trenches near the base of slopes to prevent sediment pollution
- low-maintenance (eg turf or grassland) landscapes next to water features
- landscape planting that does not require soil disturbance, digging, mulching, weeding, fertilisers or pesticides
- direction of runoff from disturbed soils or other silt generators through buffer/filter strips
- plant beds in areas such as car parks should avoid fertilisers with soil profiles 50 mm below edges and include bark/gravel mulches or dense ground cover
- all edges, verges or other areas likely to generate silt should be turfed or fall away from runoff collecting surfaces.

The design of wetland planting in ornamental landscapes should:

- use native species of local provenance wherever possible
- evaluate environmental risk to native habitats where non-native species are used
- include some plant species of wildlife value, eg grasses like *Glyceria fluitans* (floating sweet-grass) and *Agrostis stolonifera* (creeping bent), which provide good habitat for amphibians and invertebrates
- consider native plants with ornamental characteristics as an alternative ornamental (introduced) wetland species.

5.8.9 Alien species

Planting of non-native invasive species can be harmful to the ecology of an area (SEPA, 2000). This occurs through inappropriate specification or contamination of nursery stock. These introductions cause many problems including:

- spreading of non-native species into the countryside, which then out-compete native plants
- diluting the natural genetic difference of native species which are not of local provenance
- threatening colonies of nationally protected species by invasive plants. Where this has occurred the cost of clearing ponds can exceed £50 000.

A survey of SUDS ponds in Scotland in 1999 indicated that planting schemes are spreading alien species either deliberately or by accident. These have included Australian swamp stonecrop (*Crassula helmsii*), which is estimated to be present in 50 per cent Scottish SUDS ponds, parrott's feather (*Myriophyllum aquaticum*), Canadian pondweed (*Elodea nuttallii* and *E canadensis*) and curly water-thyme (*Lagarosiphon major*). Ornamental versions of water lilies, irises, variegated reed sweet-grass and reed canary-grass have also been spread.

To avoid these problems it is important to ensure that plant stock for SUDS is sourced from nurseries that only grow native species of local provenance.

There may be a considerable difference between the specified planting and what is actually delivered to site by nurseries, so the native plant supplier should be selected with care. Consider requiring warranties for correct supply and allow for supervision of planting on site to ensure that the supply of plants meets the specification.

5.8.10 Planting and pollutant levels

Planting schemes should be designed so that they do not increase pollutant levels in SUDS ponds. This can be achieved by:

- ensuring slopes are protected to minimise soil erosion and sediment loads
- creating sediment traps around water features to prevent sediment entering the water body
- avoiding the application of topsoil in areas close to water bodies. Almost all native wetland species will develop well when planted directly into subsoil
- using planting schemes that do not require the application of fertilisers and pesticides that will cause pollution (eg grassland or perennial shrubs)
- avoiding gardened areas that require digging and weeding as this increases soil erosion and sediment loads.

Terrestrial planting beds (ornamental shrubs, for example) should be designed so that nutrient-rich runoff does not enter the SUDS. In particular, the falls for soft landscaping should be away from pervious surfaces.

5.9 SILTING AND ACCESS FOR MAINTENANCE

The design of SUDS schemes to achieve controlled deposition of silt is critical to their long-term effectiveness. Silt should be managed so that it does not block infiltration systems and filters nor accumulate in inappropriate locations such as ponds or wetlands. This normally requires pre-treatment of the runoff to remove silt. This can be achieved using techniques such as filter strips, gravel diaphragms around the edge of impervious surfaces and sediment forebays in ponds and wetlands. The appropriate methods are discussed in the design section for each technique. The silt must also be removed from the pre-treatment devices at the required intervals so that they remain effective.

The design of the SUDS must allow for easy vehicular access to the areas where silt will be deposited. If access for silt removal and maintenance is made easy, it is more likely to be carried out. Access will only be occasional and can be provided using reinforced grass methods to maintain the system's natural appearance.

When removing silt, the requirements for waste management licensing must be considered (Section 7.3). Where necessary (for example, if maintenance cannot be guaranteed and the consequences of flooding are severe), an allowance for loss of storage volume due to silting may be made.

Silt that enters infiltration devices can reduce both the storage volume and the infiltration rate. The effects of this should be carefully considered, as they are likely to be more pronounced in soils with a high initial infiltration rate. In soils with a low initial infiltration rate, the effects of the silt layer that forms in the base will be far less obvious (the permeability of the silt will be closer to that of the surrounding soils).

5.10 HEALTH AND SAFETY

There is a perception that SUDS features, especially ponds and wetlands, are unsafe; specifically, there is a fear of drowning. Other perceived risks include the overturning of vehicles into swales.

With careful thought these risks can be designed out. If ponds are designed with shallow side slopes, shallow shelving edges and strategically placed barrier vegetation, they will be as safe as many watercourses, ponds and lakes that are unfenced in parks, country parks and similar locations throughout the country.

Swales alongside roads that are designed with side slopes of less than 1:3 and are generally shallow will pose much less of a hazard than the ditches that commonly line roads in the UK.

Further information can be obtained from the Royal Society for the Prevention of Accidents (ROSPA) and in CIRIA C521 and C522 (Martin *et al*, 2000a and 2000b).

A further perceived risk is that SUDS features will become breeding grounds for mosquitoes, which can transmit diseases such as west nile virus or malaria. The risk of malaria becoming re-established in Britain is extremely unlikely, even allowing for the effects of climate change (Lindsay and Hutchinson, 2002).

The choice of SUDS technique and design can be optimised to deter breeding of mosquitoes. Most SUDS techniques that have temporary ponding of water will be designed to drain quickly and so should not provide mosquito habitat. For breeding, mosquitoes generally require shallow stagnant water that is in an anaerobic condition (such as stagnant water in buckets). In a well-designed and constructed pond or wetland the water should be moving with a residence time of only a few days, so reducing the risk.

If there is any concern over mosquitoes at a site then the advice of a biologist should be sought so that design features, such as choice of vegetation, can be incorporated to deter mosquito breeding. Emergent vegetation that has minimal submerged growth reduces the locations available for larvae to develop.

The SUDS design must comply with the Construction (Design and Management) Regulations 1994 (see next section). The construction, operation and maintenance of SUDS must comply with health and safety legislation that includes, but is not restricted to:

- Construction (Health, Safety and Welfare) Regulations 1996
- Management of Health and Safety at Work Regulations 1999
- Control of Substances Hazardous to Health Regulations 2002 (COSHH).

More advice may be obtained from the Health and Safety Executive at <www.hse.gov.uk>.

5.10.1 CDM Regulations

The Construction Design and Management (CDM) Regulations 1994, apply throughout the UK. They were enacted to stem the growing number of accidents and fatalities on construction sites, which affect construction workers, the public and maintenance workers. The potential for accidents can be reduced by considering the safety of construction workers at the design stage.

The Regulations place duties on people involved in construction, including clients, designers, specifiers and contractors. The planning supervisor appointed under the Regulations is responsible for overseeing the consideration of health and safety on a project and ensuring that health and safety plans and files are maintained and implemented.

The CDM Regulations apply to most construction work except for very small projects and projects where the householder is the client. Most SUDS schemes will need to comply with their requirements.

Clients must do the following:

- appoint a planning supervisor
- provide information on health and safety to the planning supervisor
- appoint a principal contractor
- ensure that designers and contractors are competent to carry out the work safely and have sufficient resources for the job.

Designers must assess all foreseeable risks during construction and maintenance. The design must minimise risks by (in order of preference):

- avoidance
- reduction
- identification of residual risks that require mitigation.

Designers must make contractors and others aware of risks in the health and safety file. This is a record of the key health and safety risks that will need to be managed during future maintenance work. For example, the file for a SUDS pond should contain information on the collection of hazardous compounds in the sediment so that maintenance contractors are aware of it and can take appropriate precautions.

During construction, the residual risks must be identified and an action plan developed to deal with them safely (the health and safety plan).

In many cases, the use of SUDS has benefits under CDM, because it minimises the need for deep excavations and construction of large engineered structures.

The CDM regulations are specifically aimed at construction and maintenance operations but the principles can easily be extended to cover risks posed to both occupiers and the public by completed SUDS schemes. Further information is provided in CIRIA C604 (Ove Arup & Partners and Gilbertson, 2004).

5.10.2 Safety audit

A safety audit of a SUDS scheme should be undertaken before the design is finalised to ensure that risks to maintenance workers and the public (especially children) have been designed out wherever possible. This may be incorporated into the risk assessments carried out to meet the requirements of the CDM regulations.

An example of a safety audit for a SUDS pond is provided in Table 5.1.

Table 5.1 *Example of a safety audit for a SUDS pond*

Hazard	Who is at risk?	Avoid	Reduce	Mitigate	Residual risk
Sudden inflow of water	Public and maintenance staff	Design to avoid sudden inflows so that warning of flooding is given	Shallow banks so easy to get out	Reed beds or bushes to act as barrier	Very low
Drowning	Public and maintenance staff		Shallow banks so easy to get out, shallow depth to discourage swimming	Reed beds or bushes to act as barrier, warning signs, life jackets for maintenance staff	Very low
Falling from inlet structure	Public	Design inlets so walls not required	Provide barrier	Warning signs	Very low
Entering inlet or outlet pipes	Public	Use small pipes so entry not possible	Provide grills	Warning signs	Very low
Contact with contaminated sediment	Maintenance workers	Design vehicular access to sediment forebays so that excavation is possible by machine	Clean out frequently so that concentrations do not reach hazardous levels	Personal protective equipment for workers during de silting	Very low

5.10.3 Reservoir safety

Any reservoir designed to hold more than 25 000 m^3 of water above any part of the natural ground level around the reservoir will fall under the requirements of the Reservoirs Act 1975. The Act applies in England, Wales and Scotland but does not apply in Northern Ireland, although the Department of the Environment (NI) generally follows its provisions.

SUDS techniques such as ponds, infiltration basins and wetlands could fall into this category if they are formed by constructing embankments to impound water above the natural ground levels.

The Act provides for the appointment of panels of civil engineers that are specialists in dams and reservoirs. The owner of a reservoir that falls under the Act must appoint a "panel engineer" to be responsible for the design and construction of the reservoir. A different panel engineer must then be appointed to inspect the reservoir and dam at least once every 10 years. The engineer who carries out the inspection cannot be an employee of the owner.

The Act is enforced by the local authorities (county councils, unitary authorities, regional authorities) and they must be informed of any intention to construct a reservoir that falls under the Act. Failure to comply with the Act is a criminal offence. If there is any doubt about whether a SUDS structure is likely to fall under the Act, a qualified civil engineer from the appropriate panel should be sought (the names of panel engineers may be obtained from the Institution of Civil Engineers). Further information is provided in CIRIA Book 14 (Hall *et al*, 1993).

5.11 SPECIFICATION

SUDS techniques are generally similar to other areas of construction and maintenance work that require specification, and many of the individual items are the same (for example excavation of a pond, or maintenance of a swale by mowing). There are several specifications that between them cover most of the items required for SUDS and may be adapted for use. These include:

- *Specification for highway works* (Highways Agency *et al*, 1998a)
- *National building specification landscape specification* (<www.thenbs.com>)
- *Sewers for adoption*, 5th edition (WRc, 2001a)
- *Sewers for Scotland*, 1st edition (WRc, 2001b)
- *Civil engineering specification for the water industry*, 5th edition (WRc, 1998)
- *National SUDS Working Group – framework document* (NSWG, 2003).

5.12 GEOTEXTILES AND GEOMEMBRANES

5.12.1 Geotextiles

Geotextile layers are an important element in some SUDS schemes either as a filtration layer or as a separation layer at the interface between filter layers and the surrounding soils. Designers need to take careful consideration of geotextile properties with respect to the selection and specification of geotextiles. Many designers refer to layers within the construction that require specific properties merely as "geotextiles", yet those that are commercially available span an enormous performance range. They can vary in thickness from a few microns to tens of millimetres, can be manufactured from a diverse range of raw material (polyethylene, polypropylene, polyesters, for example) and be any blend of the foregoing with various mixtures of virgin or recycled material. Geotextiles can be woven, non-woven, needle-punched or thermally bonded, all with different pore sizes and permeability.

As well as this wide range of physical properties and performance, geotextiles vary in their UV resistance, durability and robustness during installation. All too often designers specify a geotextile based on a popular brand name alone without giving sufficient consideration to its material properties.

Important aspects to consider for geotextiles are:

- pore size, which should be designed and specified to assist in filtration and prevent migration of fine soil particles. This can be achieved using equations in Box 5.1
- permeability and breakthrough head. The geotextile should not limit flow of water in the system, so it should have a permeability similar to or greater than the surrounding materials. With certain thermally bonded geotextiles an initial head of water is required before the geotextile will allow fluids to pass through. This is known as the "breakthrough head". What this means in practice is that if a designer specified a "geotextile layer" requiring filtration capabilities, at a distance of typically 130 mm beneath the surface layer of a pervious block paved surface, the contractor could quite easily install a thermally bonded geotextile. If the breakthrough head for the geotextile selected was 200 mm, flooding would occur to a depth of 70 mm before infiltration through the geotextile occurred
- puncture resistance. The geotextile must be able to resist the punching stresses caused by loading on sharp points of contact
- tensile strength. The geotextile must have sufficient strength to resist the imposed forces during its design life.

Box 5.1 *Recommended geotextile filter criteria*

Many different criteria have been defined for geotextile filter design. Most of are quite similar and use the upstream soil particle size characteristic and compare it to the O_{95} of the geotextile. In the case of SUDS, the upstream particle size is most likely to be the sediment grain size of the solids carried in the flow. The following simple criterion is defined by the American Association of State Highway and Transportation Officials (AASHTO, 1990).

O_{95} is the geotextile pore size opening for which 95 per cent of the holes are smaller.

AOS is the largest soil particle that would effectively pass through the geotextile.

For soils < 50 per cent passing 75 micron sieve

O_{95} < 0.59 mm (ie, apparent opening size $(AOS)_{fabric}$ > 600 micron) (5.1)

For soils > 50 per cent passing 75 micron sieve

O_{95} < 0.3 mm (ie, apparent opening size $(AOS)_{fabric}$ > 300 micron) (5.2)

An alternative method is to compare geotextile opening sizes direct to a soil particle size (Carroll, 1983):

$$O_{95} < (2 \text{ or } 3)\ D_{85} \quad (5.3)$$

D_{85} is the soil particle size in millimetres for which 85 per cent of the soil is finer.

There are many others proposed depending on the geotextile type, soil type, flow regime etc.

The US Federal Highway Administration (FHWA) gives the following requirements (Holtz *et al*, 1995):

For fine-grained soils > 50 per cent passing 75 micron sieve

Woven geotextiles – apparent opening size $(AOS)_{fabric} < D_{85}$

Non woven geotextiles – apparent opening size $(AOS)_{fabric}$ < 0.3 mm or > 300 micron
Apparent opening size $(AOS)_{fabric} < 1.8D_{85\ soil}$

For granular soils < 50 per cent passing 75 micron sieve

All geotextiles – apparent opening size $(AOS)_{fabric} < B \times D_{85\ soil}$ (5.4)

Where

$B = 1$ for $2 > C_u > 8$
$B = 0.5$ for $2 < C_u < 4$
$B = 8/C_u$ for $4 < C_u < 8$
and $C_u = D_{60}/D_{10}$ (ie uniformity coefficient).

5.12.2 Impermeable geomembranes

Care should be taken in the choice of selection criteria and specification of impermeable geomembranes to the base and sides of SUDS techniques where infiltration is unacceptable. These criteria are critical if the impermeable geomembrane is protecting sensitive aquifers beneath. With impermeable geomembranes, it is crucial that the material specified is able to withstand the rigours of installation and that they possess the required physical characteristics to resist:

- puncture
- multi-axial elongation stress and strains associated with settlement
- environmental stress cracking, so that they remain intact for the design life.

It is also critical that the joints between adjacent sheets of impermeable geomembranes are sealed correctly. Geomembranes designed to be impermeable should be seamed using proprietary welding techniques. It is worth noting that the integrity of joints is equally as critical as the selection of the geomembrane. For example, a correctly specified geomembrane would not be fit for purpose if jointed with tape, as the integrity of the system relies on the mechanical properties of the tape. It is also important to be able to demonstrate the integrity of joints by non-destructive testing. Advice on seam testing is given in CIRIA Special Publication 124 (Privett *et al*, 1996). It is recommended that heavy-duty geotextiles are placed both above and below the geomembrane to provide further assurance of the installed system's integrity.

During the construction phase of the works a comprehensive CQA protocol should be in place for installation of the geomembranes and geotextiles. This should include, as a minimum, material delivery inventories, documented storage conditions, non-destructive seam testing results and visual inspection reports for each element of the system during the installation of the components.

5.13 GEOTECHNICAL CONSIDERATIONS

A number of geotechnical considerations may affect the choice of location of SUDS techniques. The main concerns are the introduction of water into the soil and the effects this can have on the engineering properties. In particular, specialist advice from a geotechnical engineer should be sought where:

- infiltration of water will occur close to buildings
- infiltration will occur in areas where it can cause settlement of the ground surface or foundations by washing out fines, causing consolidation of loose soils or causing solution features
- SUDS techniques are located close to the top of toe of slopes where the presence of water could cause instability to occur
- techniques are located close to structures in soils that suffer large changes in volume due to variations in moisture content.

5.14 SUSTAINABLE CONSTRUCTION

SUDS systems should be considered within a holistic science-based framework of sustainability (Everard and Street, 2002). This means that all environmental costs, together with economic and social factors, should be assessed in the decision-making process, especially when comparing SUDS to conventional drainage.

A detailed sustainability analysis based on the preceding framework is provided in *Sustainable drainage systems: an evaluation using the natural step framework* (Everard and Street, 2001). This identifies factors that need to be considered such as the energy required to construct trenches for conventional drainage, loss of habitat through development and impacts of flooding on property values. Other system factors to consider include the energy used and other environmental costs in the extraction and processing of plastics compared to the use of quarried aggregate. In this respect, recycled plastics or aggregate may be more acceptable than virgin materials.

A SUDS scheme should aim to protect the environment whilst minimising the use of finite natural resources and energy and also provide reasonable value to those involved in the design, construction and operation. Further information on undertaking sustainability analyses that can be applied to the design and construction of SUDS schemes is provided in CIRIA C563 (WS Atkins Consultants, 2001).

A key factor is the potential for minimising or reusing materials in SUDS. Examples of opportunities for this include:

- reuse and recycling of on-site earthworks and demolition materials
- reduction of waste by monitoring the volume of materials ordered and used
- use of aggregates or plastics produced from recycled or waste materials
- on-site treatment and composting of silt and other waste from SUDS to reduce the volumes of material removed from site.

The impact of aggregate and landfill taxes and transport costs may mean that opting for these more sustainable options also produces cost savings.

5.15 COLD CLIMATES

Winter conditions with snowfall, sub-zero temperatures and snowmelt pose particular design considerations for SUDS techniques, although in Britain these probably are relevant only in Scotland. SUDS techniques are used successfully in locations where winter conditions can be far more severe than in the UK.

The major factors that affect the performance of SUDS in cold climates are:

- freezing of pipes and the permanent pool of water in ponds and wetlands, which reduces the available storage volume. When water enters a pond with a frozen surface it either flows above or below the ice layer. If it flows below it can cause scouring and resuspension of sediment from the base. If it flows over the surface the water receives little treatment and if sediment is deposited on the ice it is easily resuspended
- reduced oxygen levels and biological activity in frozen ponds
- shorter growing season
- reduced infiltration into basins and pervious surfaces due to frozen ground
- reduced settling, because the viscosity of water increases as it becomes cooler
- high runoff volumes and pollutant loads during snow melt.

The reduced effectiveness of SUDS in cold climates should be allowed for in design where necessary. The size of ponds or other storage techniques can be increased to allow for the reduction in treatment volume and other removal mechanisms that occurs when frozen and to deal with snowmelt conditions. The pool depth at inlets and outlets can be increased to create a greater volume and reduce the effects of ice formation.

Where biological mechanisms are an important removal mechanism it may be necessary to provide other techniques in the management train to maintain the effectiveness of the system during cold periods.

The correct management of winter maintenance is also required (Section 9.3.3). Stockpiled snow should be placed to release water slowly into the SUDS system and the use of de-icing should be minimised.

The frequency of inspections of SUDS in cold climates should be increased during cold weather when freezing may reduce their effectiveness. Where ice is causing blockages or reducing the effectiveness of the system it should be removed or broken up if possible.

6 Construction of SUDS

This chapter includes information on:

- the education of site staff to ensure that they understand the implications of their actions and how it can affect the performance of SUDS
- the changes to construction practice that may be required so that the SUDS are not damaged before the site is completed, by either erosion or silting
- the required standard of construction and the need for CQA systems and independent inspections to ensure that the SUDS are constructed in accordance with the design requirements.

6.1 EDUCATION OF SITE STAFF

Correct construction of SUDS is as important as design if they are to be successfully implemented, and the key to this will be education of site staff. They should be made aware of how the SUDS scheme operates, its design requirements, and how their actions on site can affect the scheme's final performance (Box 6.1). It is important to talk to people on site, especially operatives, and to ensure that all sub-contractors and their staff are also involved in this process.

Box 6.1 *Example information checklist for site staff*

Sustainable drainage scheme on this site

Site name ....

A new type of drainage known as a sustainable drainage system (SUDS) is being used on this site. This uses environmental techniques such as grass channels (called swales), ponds and pervious surfaces (car park surfaces that allow water to soak through).

The system relies on soakage of water into the ground and into the hard surfaces and can easily become clogged by muddy construction water.

A simple list of do's and don'ts will help to ensure that the SUDS does not become damaged.

Do's

- Do make sure that your supervisor has explained fully the construction sequence for the SUDS
- Do make sure that you know the location of all SUDS features on the site
- Do make sure that only clean rainwater enters the drainage system. Muddy and pumped water should be discharged to a settling tank or lagoon to remove mud
- Do make yourself aware of spill procedures on the site.

Don'ts

- Do not let muddy water flow into the SUDS system unless this has been approved by the designer
- Do not run plant over SUDS areas, as it compacts the soil and stops water soaking into the ground
- Do not stockpile materials in SUDS areas, as soil particles and mud can cause clogging
- Do not run plant over pervious car park surfaces
- Do not hose down concrete trucks or other equipment into the SUDS.

Staff should also be taught how to install critical items if necessary, for example where geotextiles and geomembranes are placed in the construction (in one case an impermeable geomembrane was placed in a pervious surface in place of the geotextile).

6.2 CHANGES TO CONSTRUCTION PRACTICE

The construction requirements specific to each technique are discussed in detail in Chapter 9. There are some overriding considerations that apply to most SUDS techniques and require changes to be made to conventional construction practice.

1. Normally, drainage is one of the first items to be constructed. For SUDS, although the form of the drainage will be constructed during earthworks, the final construction should not take place until the end of development, unless adequate provision is made to remove any silt that clogs the system during construction operations.
2. Traditional car parking and other paved areas are constructed early (or partially constructed) and then are used as access roads and storage areas. If pervious surfaces are used, the pavement construction should be undertaken at the end of the development programme (or protected from clogging once it has been constructed).
3. Construction runoff must not be allowed to enter SUDS drainage systems unless it has been allowed for in the design and specification (see Section 6.4). Construction runoff is heavily laden with silt, which can clog infiltration systems, build up in storage systems and pollute the receiving waters.
4. Before runoff is allowed to flow through SUDS techniques such as swales, they must be fully stabilised by planting or temporary erosion protection. This will prevent erosion of the sides and base and clogging of other parts of the system by the silt that is generated.
5. Provision should be made in the contract to review the performance of the SUDS when it is completed and to allow minor adjustments and refinements of the system to be carried out, based on the observed performance.

6.3 EROSION

Erosion of SUDS techniques will reduce their effectiveness and add to the silt load that any other downstream techniques have to deal with. Design requirements to help prevent erosion are discussed in Chapter 9 for each technique (for example, maintaining water velocities in swales below erosive levels).

Other methods may be used, such as reinforcing grass with geogrids, or the utilisation of cellular confinement or concrete systems. Further guidance is provided in CIRIA Report 116 (Hewlett *et al*, 1996) and CIRIA Book 10 (Coppin and Richards, 1990).

6.4 PREVENTION OF DAMAGE AND POLLUTION DURING CONSTRUCTION

The guidance provided in Sections 6.1 and 6.2 should help prevent damage to SUDS techniques during the construction of developments. Guidance on pollution prevention during construction is provided in CIRIA C532 (Masters-Williams *et al*, 2001) and in the Pollution Prevention Guidelines produced by the Environment Agency and SEPA.

The main requirements are to control surface water runoff and pumped water from sites to avoid pollution of controlled waters (see Section 3.2 for definition), for example by the use of settling tanks. The safe storage of materials and fuels is also necessary so that if spills occur they are contained (by the use of berms, check ditches or other techniques) and do not cause a pollution incident.

Figure 6.1 *Geotextile silt fence to remove silt in runoff*

Surface water runoff over bare soils picks up large sediment loads. A simple and effective way of controlling this is to use straw bales or geotextile fences (Figure 6.1) to direct the flow and filter out sediment.

6.5 CONSTRUCTION STANDARDS AND TOLERANCES

The implementation of a comprehensive CQA regime is fundamental to the achievement of a minimum standard of workmanship. It is generally accepted that a high proportion of the perceived failures of SUDS techniques are a direct result of either poor-quality workmanship at the installation stage or damage during construction.

Guidance on construction standards for each individual technique is provided in Chapter 9.

6.6 INSPECTIONS

Inspection of the construction of a SUDS scheme by the design consultant is vital to ensure that the system is being constructed correctly and that design assumptions and criteria are not invalidated, for example, by construction methods, or changes made on site or by variations in ground conditions.

Inspections should be undertaken as necessary but as a minimum would generally be expected to include the following.

1. Pre-excavation inspection to ensure that construction runoff is being adequately dealt with on site and will not cause clogging of the SUDS scheme.
2. Inspections of excavations for ponds, infiltration devices, swales etc.
3. Inspections during laying of any pipework.
4. Inspections and testing during the placing of earthworks materials or filter materials.
5. Inspection of prepared SUDS technique before planting begins.
6. Inspection of completed planting.
7. Final inspection before handover to client.

A checklist of inspection items is provided in Appendix 7. The contractor that is installing the SUDS scheme must be made fully aware of the requirement for inspections so that they can call the consultant to site when necessary and avoid work being undertaken that cannot be validated.

On completion of construction the consultant should provide a validation report that discusses the inspections, the reasons for any variations made to the design, any non-compliances identified and how they were rectified.

During the first year of operation the system should be observed to identify any modifications that may be required to optimise performance. The scope of monitoring will be site-specific and dependent on the sensitivity of the design and the consequences if the SUDS does not perform as designed.

7 Management

This chapter provides information on the management requirements for owners, operators and adopters of SUDS schemes.

It includes information on inspection regimes, the difference between routine maintenance and major overhauls and on the need to safely dispose of silt and other waste caused by the maintenance of SUDS schemes.

It also describes how maintenance should be carried out in such a way that adverse impacts on wildlife are minimised.

7.1 INSPECTION

Inspections during construction are discussed in Section 6.6. As part of the ongoing maintenance requirement of most SUDS techniques there is a need for regular inspections to ensure that blockages, silt and excess litter are not adversely affecting the system. It is important that this is carried out and time is allowed for corrective action to be taken. Where the SUDS techniques depend on landscape maintenance, the inspection requirement can be included within the landscape maintenance contract. Alternatively, it can be carried out by the site owner or operator.

7.1.1 Pre-handover inspection

The pre-handover inspection is discussed in Section 6.6. Its objective is to provide the client with a durable SUDS scheme that is unlikely to suffer premature failure due to construction defects or clogging caused by heavy silt loads in construction runoff.

7.1.2 Routine inspection

Routine inspections should be carried out once a month for most techniques, although some, such as infiltration devices, require less frequent visits. Site managers and/or landscape contractors should be used to inspect the SUDS. The advantage being that they have intimate knowledge of the development and visit the site on a frequent basis. This recurring attendance ensures monitoring of the drainage system, a rapid response to problems and "ownership" of the SUDS features. The inspections should be recorded on the maintenance record, which should include the following:

- date and time of inspection
- list of features to be inspected
- brief description of general condition of SUDS
- details of any problems with the system and action taken.

7.2 OPERATION AND MAINTENANCE

7.2.1 Owner's manual

As SUDS differ from conventional drainage systems and require different maintenance regimes, the owners of developments that incorporate them should be provided with an owner's manual.

This should include the following:

- location of all SUDS techniques in a site
- brief summary of how the techniques work, their purpose and how they can be damaged
- maintenance requirements (a maintenance plan) and a maintenance record
- explanation of the consequences of not carrying out the maintenance that is specified
- identification of areas where certain activities are prohibited (for example, stockpiling materials on pervious surfaces)
- an action plan for dealing with accidental spillages
- advice on what to do if alterations are to be made to a development, if service companies undertake excavations or other similar works are carried out that could affect the SUDS.

The owner's manual should also include brief details of the design concepts for the SUDS scheme and how the owner or operator should ensure that any works undertaken on a development do not compromise this. For example, householders should be made aware that surface water drainage is connected to soakaways and that any alterations or extensions should not damage the system. The difference between the surface water and foul sewer should be highlighted, as should the premise that foul sewage systems should not be connected to the surface water system.

7.2.2 Routine maintenance

The design of all SUDS should allow for easy access by people and vehicles to undertake maintenance.

Most of the features used in sustainable drainage are usually visible and understandable by people charged with maintenance of the systems. When problems occur they are generally obvious and for most techniques can be remedied using standard landscape methods. The maintenance of surface SUDS techniques can be undertaken as part of normal site care by site staff or landscape contractors, although more engineered techniques may require a conventional drainage maintenance approach. Landscape maintenance specifications, such as those included the National Building Specification (NBS), can be adapted to suit surface SUDS schemes. Engineering specifications are more suited to techniques such as filters.

Landscape maintenance contract periods usually last for one or three years. The three-year period is increasingly common, as it ensures continuity and commitment to long-term landscape care and is ideal for the maintenance of any SUDS. The frequency of routine landscape maintenance tasks in a contract period can range from daily to once in the contract period. In practice, most site tasks are based on monthly or fortnightly site visits except where grass or weed growth requires more work. Certain SUDS maintenance tasks fall outside this monthly cycle and need to be accommodated into the contract period.

The two most obvious are:

- wetland vegetation maintenance
- silt management.

The effect of silt or erosion on SUDS techniques also means that one-off remedial works may be required and the provision for this should be made in any maintenance contract.

The routine maintenance requirements for each technique are provided in the relevant parts of Chapter 9. A record of all inspections and maintenance should be kept for each SUDS scheme.

7.2.3 Major overhauls

There will come a time with most SUDS techniques when a major overhaul of the system is required to remove clogged filters, geotextiles and the like. This will typically be 10–25 years, depending on the technique and factors such as the type of catchment and sediment load.

The SUDS design should allow for vehicle access during this work and should ensure that overhaul can take place without causing major disruption. For example, by using geotextiles close to the surface in pervious surfaces most sediment is trapped where it is easily accessible. Reconstruction of the surface and bedding layer is all that is required, rather than reconstruction of the whole pavement depth.

Major overhaul is most likely to be required on techniques that rely on filtration through soils or aggregates, such as sand filters and infiltration devices. Other SUDS techniques are unlikely to need major overhaul if routine maintenance is undertaken as required (ponds and wetlands, for example). The requirements should be identified in the owner's manual.

Where major overhauls are likely to be required they are identified for each technique in the relevant part of Chapter 9.

7.2.4 Extreme pollution events

The maintenance regime of a site also needs to allow for response to extreme pollution events. A response action plan should be developed and communicated to all those involved in the site operation, so that if a spillage occurs it can be prevented from causing pollution to receiving waters.

7.3 WASTE MANAGEMENT

As discussed in Section 7.6, organic waste should be used around the SUDS to form wildlife piles. If this is not practical it should be composted or, as a last resort, removed to a licensed landfill site.

Inorganic silt (from closed silt traps, basins, ponds and wetlands) is the material likely to be most polluted. This should ideally be stacked on site, dewatered and then spread on banks and berms to design levels or removed from site (see below for waste management requirements).

Sediment waste arisings from SUDS maintenance for removal from the site must be treated as controlled waste and are therefore subject to control under the Waste

Management Licensing Regime. The Special Waste Regulations 1996, may also be relevant. All maintenance of SUDS and disposals must be undertaken within the relevant statutory frameworks (particularly the Waste Management Regime) and advice can be sought from the Environment Agency (Box 7.1).

Box 7.1 *Waste disposal of sediments*

Under the Controlled Waste Regulations 1992, the sediments removed from a SUDS for disposal will be regarded as industrial, and therefore controlled, waste (as is the case with liquid or sediment removed from conventional gullies). This places duties on the owner of the SUDS to dispose of the material in accordance with the relevant legislation.

Legislation to note is listed below.

Environmental Protection Act 1990 – introduced the statutory duty of care in relation to waste and provides a definition of waste.

Environmental Protection (Duty of Care) Regulations 1991 – place a statutory duty of care upon any one who produces or disposes of controlled waste or, as a broker, has control of such waste. The practical implications are that waste sediment must be removed by a registered haulier to a registered waste disposal site, that is licensed to accept such materials. The waste must be accompanied by a consignment note that accurately describes the waste and the volumes being removed.

Waste Management Licensing Regulations 1994 – provides definition of waste.

Special Waste Regulations, 1996 as amended – these define special waste on a hazard basis. The practical implications are that only a certain limited number of landfill or treatment sites are licensed to accept special waste and the Environment Agency must be notified in advance of any material being removed to the disposal site. Consignment notes are used to track special waste from source to disposal.

Special Waste Regulations (NI) 1998 – these apply to the disposal of special waste on Northern Ireland.

Waste sediment will also be subject to landfill tax, under the *Landfill Tax Regulations 1996*, at the prevailing rate if it is removed to landfill.

The frequency of sediment removal should be considered on a case-by-case basis by conducting intermittent inspections as part of the maintenance to monitor the build-up of sediment in SUDS schemes. It should be noted that most sediment accumulates during construction. The frequency should also take account of wildlife (Section 7.6).

Sediment should be removed when it is assessed to be adversely impairing the performance of the SUDS, for example by clogging the system, reducing storage volumes or increasing pollution risk due to resuspension. The frequency of removal will be lower for systems dealing with runoff with low sediment loads (Table 7.1).

Table 7.1 *Sediment removal frequency (National SUDS Working Group, 2003)*

Likely sediment removal	SUDS type
Low frequency	Clean roof water discharging to a detention basin in which pollutants are degraded, which has an overflow discharge to a watercourse
High frequency	Car/lorry parks or road drainage discharging to a retention pond, with less degradation of pollutants, which has an overflow discharge to a watercourse (high sediment load with hydrocarbon pollutants etc)

Other aspects of the SUDS also need to be assessed when considering sediment removal, such as the impact on wildlife (more frequent removal of limited areas is better – see Section 7.6) or the generation of odours from anaerobic decay.

The Environment Agency may grant an exemption from the requirements of waste management licensing for SUDS techniques (National SUDS Working Group, 2003). In such cases, sediment from SUDS can be placed at an area within the site near its point of removal. This should be no more than 10 m from the edge of the SUDS structure. For SUDS that are authorised, the Environment Agency will place conditions on the authorisation to control the deposit of sediment removed as part of maintenance. Depending on the scale of operations and the amount and form of deposited material, it is possible that planning permission may be required. This should be checked with the local planning authority.

Vegetation containing seeds and root-stocks of troublesome aliens such as Japanese knotweed or giant hogweed should be removed to approved tips for safe disposal.

7.4 RELIABILITY

The reliability of SUDS is critically dependent on the quality of the design and construction, in particular the management of silt. If the guidance provided by CIRIA and other organisations is followed, there is no reason why SUDS cannot provide a durable and reliable drainage solution.

SUDS have a design envelope within which they are intended to operate, in terms of water quality, flow rates and volumes. Events that exceed the design criteria may cause flooding or increased levels of pollution in the outflow and the consequences of this must be carefully assessed. If necessary, the design envelope should be enlarged so that the risks associated with a SUDS scheme are acceptable (this is no different to a conventional scheme).

In many respects the reliability of SUDS schemes is likely to be less problematic than with some conventional techniques, since if failure does occur the results are likely to be above ground and visible.

7.5 SILTING

Silting or sedimentation is one of the primary pollutant removal mechanisms in most SUDS schemes and it must be managed. Failure to manage silt effectively is one of the main causes of early failure of SUDS.

The design must identify where silt is to be collected in the system and how it can be easily removed. Most systems will require pre-treatment devices, such as filter strips or sediment forebays, to catch sediment, and these require the sediment to be removed to maintain their effectiveness.

Designers should provide the client, owner or operator with a management schedule that identifies all areas from which sediment is to be removed, together with the likely frequency. The consequences of failing to comply with these requirements should be made clear. It is important to make clear the sediment removal requirements when SUDS are proposed for a site, so that they do not come as a surprise later in the project.

Silt removal operations should comply with waste management licensing requirements and take due consideration of wildlife (Sections 7.3 and 7.6).

7.6 WILDLIFE

Wildlife conservation will be affected by the management of SUDS features so it is important to consider the manner, timing and frequency of maintenance operations.

Maintenance of SUDS features should generally follow the guidelines set out in *Flood defence conservation requirements for watercourse maintenance work*s (Environment Agency, 1998a). Further guidance is also provided by SEPA, 2000.

Wherever possible, only part of the banks (25 per cent maximum) to wetlands should be cut in any one year and some vegetation should be retained around each wetland feature at any one maintenance visit. Areas identified as supporting particularly rich plant communities will require special treatment at specific times of year.

Specific wildlife considerations that need to be addressed are:

- all wetland edges should have an uncut fringe at the margin of the lower bank and the water during normal maintenance
- care must be taken to avoid damage to nesting birds during the breeding season (mid-March to mid-July). Where work within the breeding season is unavoidable it must be undertaken with hand-held tools to minimise disturbance and prevent accidental damage
- work should not be undertaken without first checking for nests, which, if found to be occupied, should not be disturbed. The client should then be informed
- water voles are legally protected and it is an offence to damage, destroy or obstruct access to their shelter or to disturb them while they are using a particular area. Further details are provided by the Wildlife Conservation Research Unit, 1998
- maintenance work should be carried out at least 1 mile from wetland edges to protect banks and between September and November to avoid sensitive breeding times for the animal
- great crested newts are legally protected under the Wildlife and Countryside Act 1981 (as amended). Newts visit ponds to breed in early spring and may remain through to July, although the young can be in the ponds until September. Work to ponds should not be undertaken between February and August inclusive. The work required to keep SUDS ponds in optimum condition (that is, occasional removal of limited quantities of silt and aquatic vegetation with only moderate shading) is completely compatible with great crested newt conservation. Further guidance is provided by Froglife, 2001.

Maintenance of SUDS features should use appropriate methods at the least damaging time of the year. Generally it will be practical to undertake maintenance work between September and November for both protected species and as good practice for conservation purposes.

Bank clearance waste and aquatic vegetation can damage ground flora, affect water quality and also amenity if left in place It can also provide an opportunity to enhance wildlife habitat if managed in an appropriate manner. The best way to deal with this type of organic waste (such as grass cuttings, prunings, aquatic plant dredgings and organic silt) to benefit wildlife habitat is (in order of preference):

- construct wildlife piles on site
- compost the material on site
- remove material from site.

Wildlife piles are heaps of dry vegetation that provide refuges, hibernation shelter, food and egg-laying sites for a large number of animals, including hedgehogs, voles, snakes and bumble bees. They also avoid the need to remove green waste from site. After three to five years they provide compost, which can be used as a surface dressing to ornamental planting. Further information is provided in Box 7.2.

Box 7.2 *Wildlife piles*

The key design and construction considerations for wildlife piles are to:

- locate them in sunny or semi-shaded areas away from direct access by people
- locate them above normal flood level of watercourses or protect them with hedges or similar features
- construct the base using substantial prunings or other branch material laid in a criss-cross pattern
- add seasonal shrub and other woody prunings through winter
- add non-woody and grass cuttings through summer
- create tidy piles up to 1.2 m high and with ground area to suit
- construct new wildlife piles each year and use old wildlife pile as compost to plant beds if required after three to five years.

7.7 ADOPTION

Adoption of SUDS in England and Wales is currently the focus of several studies, one of which is being completed by CIRIA. Further information on the issues surrounding the adoption of SUDS schemes may be found in CIRIA C625 and C626 (Shaffer *et al*, 2004a and 2004b) and the National SUDS Working Group framework document (NSWG, 2003), which will be developed into an interim code of practice for SUDS.

In Scotland, the Water Environment and Water Services (Scotland) Act 2003 puts a legislative framework in place to allow Scottish Water to adopt SUDS and to obtain appropriate funding to maintain them. It places SUDS on an equal footing with conventional drainage in this respect.

8 Economics of SUDS

This chapter provides an overview of the economics of using SUDS techniques. It discusses the construction costs, maintenance costs and whole-life costings.

8.1 CONSTRUCTION COSTS

It is difficult to provide unit cost data for SUDS techniques because of the wide range of site-specific variation in size and details. Site-specific constraints can also affect the cost of a particular technique. This chapter provides general guidance on the factors that may be considered when estimating the cost of providing a SUDS scheme.

Individual rates for constructing SUDS techniques can be readily obtained from civil engineering, building or landscaping cost databases such as *Spon's landscape and external works price book* (Davis Langdon and Everest, 2003) or *Civil Engineering Standard Method of Measurement (CESMM3) price database* (Harris, 1999). Typical items will include excavation, trimming of excavations, disposal of excavated material, importing, placing and compacting earthworks materials, importing aggregates, and provision and planting of the landscaping. An example bill of quantities for a SUDS scheme is provided in Box 8.1.

Comparing the cost of a SUDS scheme with those for a conventional system is not always straightforward because of the hidden savings often associated with SUDS. These elements are not usually included in the cost comparison because they are not drainage items. An example is the reduced cost of excavation and disposal of soil that may be possible by reducing the need for deep drainage trenches if pervious surfaces are used.

Design costs for both SUDS schemes and conventional drainage should be considered together with the cost of any monitoring or testing that may be required.

It is important that the cost of all items affected by the choice of scheme is considered in cost comparisons. This should include the cost of discharge consents, enabling works that increase the capacity of downstream sewers, costs of kerbs and gullies that the SUDS scheme may not require, and the reduced volume of excavation and disposal that may be necessary. Conversely, for SUDS, the cost of any extra land take that may be required should be considered (if the SUDS cannot be incorporated into existing landscape provision).

The cost of upgrading or connecting to existing surface water sewers can be a significant element that may be removed or reduced by using SUDS. At a site in Derby the local statutory water undertaker would only allow discharge of stormwater from a development site into a surface water culvert at around 30 m depth. The cost of constructing a shaft to this would have been around £250 000–400 000. A review of the site drainage allowed a combination of pervious surfaces and attenuation tanks to be used so that the existing discharge limit into a shallow foul sewer was not exceeded. The cost of the revised system was around £100 000.

Box 8.1 *Example bill of quantities for a SUDS scheme*

		Quantity	Unit	Unit rate	Total
1.1	**Initial works**				
	Strip all existing vegetation in SUDS working areas as described below and stack in an agreed position to form compost/wildlife heap as directed on site	3148	m^2		
	Strip topsoil (approx 150 mm deep) from all SUDS working areas and stack in convenient piles no higher than 1 m for reuse	3148	m^2		
	Erect temporary fence to indicate area of work protecting existing vegetation and proposed playing field	250	m		
	Allow to lightly rip all subsoil with 150–300 mm-deep tines as soiling proceeds to reduce surface compaction and smearing	3148	m^2		
1.2	**Storage basins**				
	Excavate storage basin as drawing 390/03 and following agreed setting out	975	m^2		
	Stack or spread excavated subsoil as instructed on site		m^3		
	Spread reserved topsoil 100 mm deep to all excavated 1 m level margins, slopes to wet benches and wet benches excluding permanent pools	973	m^2		
	Cultivate all topsoil to 50 mm as necessary to obtain level surface removing all debris and lumps in excess of 50 mm diameter	973	m^2		
	Supply and lay turf as spec to level margin, slopes to wet benches and wet benches excluding permanent pools. All slopes pegged at 600 mm centres with 300 x 25 x 25 wooden pegs as instructed	973	m^2		
	Cultivate all other bare soil areas as specification including existing soil surfaces breaking up ground to form even running surfaces with blinding of topsoil at edges and junctions as required		m^2		
	Supply and sow grass seed at 35 gm/m^2		m^2		
	Supply and plant the base of the basin along the line of the edge of the turf at 5 plants per m	200	Nr		
	25 Butomus umbellatus 1L				
	25 Cyperus longus 1L				
	25 Filipendula ulmaria 1L				
	50 Iris pseudacorus 1L				
	25 Lythrum salicaria 1L				
	25 Mentha aquatica 1L				
	25 Veronica beccabunga 1L				

8.2 MAINTENANCE COSTS

8.2.1 Routine maintenance

Many SUDS techniques are easily maintained as part of the landscape maintenance for a site. The costs for such maintenance are usually comparable to or lower than those for a conventional drainage system. A comparison of maintenance costs for SUDS schemes at motorway service areas on the M40 and M42 are shown in Table 8.1. These schemes used predominantly "green" techniques such as filter strips, swales and wetlands. The M40 site also included pervious surfaces.

Table 8.1 *Maintenance costs for SUDS schemes*

Item	Cost (£, 2003 prices)	
	M40 Oxford MSA	**M42 Hopwood MSA**
Total annual landscape maintenance cost	27 650	9650
Cost of maintenance attributed specifically to the SUDS	8269	2280

These costs should be compared to the maintenance costs associated with conventional systems such as frequent emptying of gully pots and oil interceptors.

8.2.2 Remedial maintenance

Remedial maintenance will be required when a system nears the end of its design life. This can include taking up pervious surfaces or sand filters to replace clogged geotextiles and filter materials. The cost of remedial maintenance can be estimated from civil engineering, building or landscaping cost databases since the works are basically partial reconstruction of the systems.

An estimate of the remedial maintenance costs for a permeable paving system and filter drain are provided in Table 8.2 and illustrates the wide variation in costs for differing sizes of system.

Table 8.2 *Estimated remedial maintenance costs (at 2003 prices)*

Item	100 m	1000 m
Filter drain (0.5 m wide) Remove and wash 20–40 mm aggregate to 150 mm depth, Remove and replace geotextile and dispose of geotextile and washings	£1995	£9910
Permeable block paving		
Remove paviours and jet wash, remove and wash 5 mm aggregate, remove and replace geotextile, replace blocks and aggregate, dispose of waste	£3600	£23 330

8.3 WHOLE-LIFE COST COMPARISONS

Whole-life costs look at both the construction and the maintenance costs to give the overall cost of a system throughout its design life. The significance of whole-life costing is that systems with high construction costs may have much lower operation and maintenance costs than systems that are cheaper to construct (for example, ongoing connection charges for sewers). An example of the way in which SUDS can reduce the operation and maintenance costs is given in Case Study No 3 (Appendix 4).

The importance of each element depends on the perspective from which the assessment is made. If a SUDS scheme is to be adopted, the developer may seek lower construction costs and will not be concerned with maintenance costs. On the other hand, the adopter will not be concerned about construction costs but will want low maintenance costs if these are not going to be covered by the developer (for example, by the use of commuted sums).

Further information is provided in CIRIA Report 156 (Bettess, 1996) and in Woods Ballard and Malcolm (2003).

Part 2
Information for individual techniques

What does this part include?

Detailed information on the pollutant removal performance of each technique.

Detailed information on the hydraulic performance of each technique.

Discussion of design criteria and methods of analysis where applicable.

Design details.

Information on the maintenance requirements for specific techniques.

9 Design issues

9.1 PREVENTATIVE MEASURES

Prevention or good site practice is the most effective way to deal with stormwater problems (Section 2.1). The following common preventative measures may be considered during the design of a SUDS scheme.

1. Design the site to minimise impermeable areas and so reduce runoff.
2. Sweep impervious surfaces frequently to reduce pollutant build-up.
3. Minimise the application of de-icing products. Instead, use alternative techniques, such as wet gritting to reduce total chloride load, or alternative products, such as CMA, that have been shown to decrease sodium levels in runoff (Minnesota Metropolitan Council, 2001).
4. Choose carefully, and minimise the application of, herbicides and fungicides on landscaped areas.
5. Manage construction sites to limit soil erosion and the volume of sediment in runoff (see CIRIA C532 – Masters-Williams *et al*, 2001).
6. Ensure that adequate procedures and equipment are in place to deal with spillage of materials quickly using dry rather than wet techniques.
7. Limit the potential for runoff to come into contact with pollutants (for example, by bunding and separation).
8. Educate the public to reduce fertiliser application to gardens and minimise runoff from activities such as washing cars or bins and to discourage the disposal of liquid waste to surface water drains.

9.1.1 Minimise impermeable areas

Impermeable areas can be minimised by employing constructed pervious surfaces for car parks and by connecting roof drainage to infiltration devices so that the runoff does not affect watercourses. Careful design of the street layout and the form of turning heads in cul-de-sacs can also reduce the amount of impervious area. A T-shaped turning head is likely to reduce the impermeable area by a significant amount compared with a circular one.

For large sites comprising varying geology, new impermeable areas such as vehicle parks may be constructed over clayey soils in preference to more permeable soils.

9.1.2 Sweeping

Frequent sweeping of car parks and roads can help to reduce the pollutant loads entering the SUDS scheme. It is most effective in removing coarse sediment, leaves and litter. As a minimum, a pavement should be swept twice a year, in spring and in autumn to remove leaf fall. The sweeping pattern should avoid pushing material towards the inlets to the SUDS and should be undertaken by an experienced operator.

9.1.3 De-icing

Winter de-icing of pavement surfaces using road salt can be a significant source of pollutant loading. In addition, the chlorides and other contaminants are unlikely to be substantially reduced by SUDS techniques, so prevention is the main way to reduce their impact on receiving waters. Salt should be applied only when absolutely necessary (based on meteorological forecasting) and the rate of application should be kept to the minimum required for safety. Alternative de-icing agents and methods, such as CMA or wet gritting, may be used, but they are generally more expensive.

De-icing grit should be stored so that the runoff is collected and safely disposed of and does not enter any SUDS.

9.1.4 Landscape management

Landscape management in developments can add to the pollutant load of runoff in a variety of ways, all of which can be reduced with careful thought.

1 *Sediment load* – design landscaping areas to fall away from impermeable areas so that sediment is not washed off (or provide a sediment trap at the edge of the landscaping).

2 *Over-application and misapplication of fertilisers* – increases nitrogen and phosphorous in runoff. Do not apply immediately before rainfall. Apply compost or mulch where possible to replace slow-release fertilisers.

3 *Leaves, grass cuttings and other debris* – increases level of nutrients in runoff when they decompose. Leave grass cuttings on lawns to provide nutrients. Compost leaves and other plant debris.

4 *Over-application and misapplication of pesticides* – increases level of pesticides in runoff. Many of these chemical compounds are difficult to remove using SUDS techniques. Do not apply before rainfall. Hand-pull weeds or spot-treat. Apply mulch to reduce weeds and introduce an overall pest-management system based on balancing natural mechanisms.

Landscaping areas should be designed using native species that require low levels of maintenance and reduce the need for fertilising. It can be helpful to educate the public to reduce fertiliser application in private gardens.

Providing bins in open spaces for the dumping of dog faeces, together with signs to educate the public, is also useful.

9.1.5 Construction runoff

Construction runoff is a major cause of significant pollution incidents to watercourses. Guidance on preventing pollution from construction sites is provided in CIRIA C532 (Masters-Williams *et al*, 2001). It provides a series of checklists to help ensure that construction site runoff does not adversely affect watercourses. Avoidance methods include the use of silt traps, sediment ponds and other techniques. Careful storage of materials and fuels on site is also required. The Environment Agency and SEPA also provide guidance in their Pollution Prevention Guidelines, which can be obtained from their websites. More details are provided in Chapter 6.

9.1.6 Chemical storage and spillages

The Environment Agency and SEPA Pollution Prevention Guidelines, and CIRIA C598 *Chemical storage tank systems – good practice* (Cassie and Seale, 2003), provide more advice on the storage of chemicals and other materials to reduce the risk of causing pollution. Potentially polluting materials or chemicals should be stored in contained areas such as bunds, and a system should be in place to deal rapidly with any spillages that do occur.

On a more general scale, cleaning of vehicles and windows can introduce detergents and other pollutants to runoff. Education is required to persuade people to contain dirty water in buckets and dispose of it to the foul sewer or on to gardens.

9.2 PERVIOUS PAVEMENTS

This section of the book summarises the design information provided in CIRIA C582 (Pratt *et al*, 2002).

Box 9.2.1 *Key considerations for pervious pavement design*

Description

Pavement constructions that allow rainwater to infiltrate through the surface into an underlying storage layer.

Design criteria

- Structural design methods same as conventional pavement but allowing for different properties of materials and presence of water in construction.
- Hydraulic design to provide storage based on relationship between rainfall and outflow during storm.

Pollutant removal

Good.

Applications

Most sites, especially useful on urban sites where use of some other techniques may be limited owing to space constraints.

Limiting factors

- Land use (eg industrial areas are often not suitable)
- Site slope
- May need membrane to protect weak subgrades or prevent infiltration.

Maintenance

- Monthly inspections for clogging and water ponding
- Sweeping twice a year.

9.2.1 Description

Pervious surfaces are pavement constructions that allow rainwater to infiltrate through the surface and into the underlying construction layers, where water is stored prior to infiltration to the ground, reuse or being released to a surface watercourse or other drainage system.

Pervious surfaces can be either porous or permeable. The important distinction between the two is:

- *porous* surfacing infiltrates water across the entire surface of the material forming the surface, for example grass and gravel surfaces, porous concrete and porous asphalt
- *permeable* surfacing consists of material that is itself impervious to water but, by virtue of voids through the surface, allows infiltration through the pattern of voids, for example concrete block paving.

Many variations of each type are commercially available, including reinforced grass or gravel, porous asphalt and permeable concrete blocks. If storage is required or infiltration to the ground is to be prevented, the base and sides of the pavement will be provided with an impermeable membrane.

Figure 9.2.1 *Pervious pavement*

Pervious areas are often required only to handle rainfall landing directly upon their surfaces, but their capacity is such that they may also be used to provide a drainage path for water discharged from adjacent areas, such as roofs or impermeable areas of car park. It is advisable to release any additional waters either on to the surface of the pervious construction or via a debris trap, in order to prevent clogging of the sub-surface layers. Care must be taken to ensure that runoff does not collect excessive sediment that will clog the pervious surface.

Pervious surfaces for source control do not include conventional porous asphalt surfacing, which has been used in trials on some motorways and trunk roads to reduce spray and noise. This comprises a thin layer of porous asphalt over conventional impermeable materials.

9.2.2 Suitable applications

The concept can be used on a wide variety of sites for both infiltration and attenuation of surface water collected from paved (hard and soft landscaping) areas and roof catchments. They can temporarily store runoff from events with an annual probability of less than 1 per cent (greater than 1 in 100-year return period). They are also suitable for incorporation into rainwater utilisation projects. There are some limitations to the use of pervious surfaces (Box 9.2.2).

Box 9.2.2 *Locations for use of constructed pervious surfaces*

The use of constructed pervious surfaces as a source control technique is currently limited to highways with low traffic volumes, axle loads and speeds (less than 30 mph limit), car parking areas and other lightly trafficked or non-trafficked surfaces. Many developments have a substantial area for car parking that can be constructed with a pervious surface to attenuate runoff into the local sewers or watercourses.

Outside the UK pervious surfaces have been used in some locations with heavy axle loads and this is starting to occur in Britain too. The issues discussed in this book will still be relevant, but at present such pavements should be designed on an individual basis in conjunction with experienced geotechnical and pavement engineers.

The Highways Agency will not use pervious pavement systems for roads under its control. The potential failure of pervious pavements on high-speed roads, the safety implications of ponding, and disruption arising from reconstruction are areas of particular concern.

Infiltration techniques cannot be used below pervious surfaces in stormwater hotspots (Section 3.2).

PPG 3 (DETR, 2000), requires housing developments to have a high density of dwellings. In addition, industrial developments usually require a high percentage of hard cover and these issues are often perceived as a barrier to using SUDS techniques in urban situations. The use of pervious surfaces for car parks and other hard areas is a valuable technique that should widen the use of SUDS in urban situations, allowing the requirements of both PPG 3 and PPG 25 (DTLR, 2001) to be achieved.

Pervious surfaces may also appear as "soft" landscaping, as it is possible to "green" a surface using grass protection type systems.

An oil interceptor device can also be incorporated into pervious pavements to improve the pollutant retention and removal performance when catastrophic spillages occur (Wilson *et al*, 2003).

9.2.3 Advantages and disadvantages

The advantages and disadvantages of constructed pervious surfaces are summarised in Table 9.2.1.

Table 9.2.1 *Advantages and disadvantages of pervious surfaces (Pratt* et al*, 2002)*

Advantages	Disadvantages
Reduces the volume and rate of runoff	Frequent sweeping is required to maintain the infiltration rate
Reduce the effects of pollution in runoff on the environment	Poorly designed and maintained landscaped areas can cause blockages
They can be used in confined urban situations with a range of surface finishes	Unsuitable for industrial areas where a large sediment load in the runoff can cause early blockage of the pavement (for example, wood yards)
There is a reduced need for deep excavations for drainage	Needs change in construction practice so that pervious surfaces are constructed at the end of the programme to avoid clogging by sediment
It is a flexible solution that can be tailored so that construction costs suit the proposed usage and design life	Can be damaged by inappropriate excavations and reinstatements by utility companies (although this can be designed out by providing service corridors)
Costs are comparable to or lower than conventional surfacing and drainage solutions	
Ponding does not generally occur	

9.2.4 Performance

Pollutant removal

Pervious surfaces limit the concentration of pollutants in surface water runoff by immediate, localised interception. As water does not flow across the surface, pollutants either remain there or are taken below the surface by the local percolating water.

There is no documented case where the use of pervious surfaces has been found to cause a deterioration in the quality of receiving waters. All the evidence to date has demonstrated an improvement in water quality. Pervious surfaces can be designed to provide several interception mechanisms that mitigate against the risks posed to controlled waters.

Available methods include:

- filtration
- biodegradation of organic pollutants, such as petrol and diesel
- adsorption of pollutants (pollutants attach or bind to surfaces within the construction), which depends on factors such as texture, aggregate structure, moisture content
- settlement and retention of solids
- use of sealed bases to prevent infiltration to groundwater
- use of enhanced soils to improve treatment within the pervious pavement system. This can be achieved using either proprietary systems or by adding small amounts of substrate or materials with a high adsorption capacity to conventional aggregates (sawdust, peat, clay soils, granular activated carbon can all increase adsorption). The additional materials should not reduce the structural or hydraulic performance of the aggregates. The required microbes are usually present in the ground and additional applications of microbes are not required.

The use of pervious surfaces should also benefit water quality as a result of attenuation, which enhances the settlement and biodegradation of pollutants. Where the outflow is released to surface waters the reduced peak flow causes less of a short-term shock pollutant load to the receiving waters and allows increased dilution.

Three mechanisms reduce the concentrations of pollutants discharged (Day *et al*, 1981; Pratt *et al*, 1995 and Pratt, 1999).

1 Pollutants are retained within the pervious construction, physically trapped or adsorbed on materials.

2 The volume of water discharged is reduced hence the mass of pollutant being conveyed is itself reduced at any given concentration.

3 Hydrocarbons and other organic materials trapped in the upper layers of the construction are degraded by micro-organisms.

Removal

Significant removal of pollutants from runoff from pervious surfaces has been reported by several studies (Day *et al*, 1981 in the UK; Australian Water Technologies, 1999 in Australia; Macdonald and Jefferies, 2001 and Schluter and Jefferies, 2001 in Scotland).

The study by Day *et al* compared the pollutant concentrations in runoff from various permeable surfaces with that from a concrete slab. There was generally a reduction in pollutants from the permeable surfaces, and the load being discharged in the surface waters was much less for the pervious surfaces because of the significant reduction in runoff volumes.

Pratt, 1995, found that the concentration of suspended solids in runoff from a pervious surface varied from near zero to 50 mg/l. This is considerably less than is typical for discharges from impermeable surfaces (typically 30–300 mg/l but up to 1000 mg/l). Hydrocarbons were never detected in the runoff, suggesting that significant biodegradation was occurring.

One study in Scotland was on a porous car park without a sealed base and the adjacent impervious car park was also monitored (Macdonald and Jefferies, 2001). The other study monitored a porous car park with a sealed base (Schluter and Jefferies, 2001).

The results of the studies in Scotland on lined pavements indicate differing improvements to water quality. The first study did report increased TON in runoff from pervious surfaces, which was attributed to possible decay of organic matter from plant debris. The results for the heavy metals and general quality parameters for the second study were below the levels required for drinking water (Water Supply (Water Quality) Regulations 2000) where standards are provided. A summary is provided in Tables 9.2.2, 9.2.3, 9.2.4 and 9.2.7.

Table 9.2.2 *Water quality result for general quality parameters (Schluter and Jefferies, 2001)*

Event date		06/06/00 to 07/06/00			09/07/00 to 09/07/00			09/08/00 to 10/08/00			Spot sampling		
		min	max	mean	min	max	mean	min	max	mean	min	max	mean
pH	[-]	7.8	8.2	8.0	8.1	8.2	8.1	7.9	8.6	8.1	7.4	8.2	8.0
Conductivity	[uS/cm]	281	615	447	550	581	553	365	929	541	358	730	544
TSS	[mg/l]	6.6	39.9	23.2	3.7	8.2	6.0	0.0	68.0	11.6	1.0	16.1	8.2
BOD	[mg/l]	1.6	3.0	1.96	3	10	4.38	2	2	2	0.7	3	2
NH_4-N	[mg/l]	0.03	0.57	0.11	0.04	0.06	0.05	0.02	0.20	0.10	<0.02	0.04	0.03
Oxidised-nitrogen	[mg/l]	1.05	2.04	1.58	2.75	3.02	2.92	1.23	1.23	1.48	1.15	2.15	1.53
Ortho-phosphate	[mg/l]	0.05	0.23	0.14	0.04	0.11	0.07	0.02	0.24	0.06	0.01	0.04	0.03
Chloride	[mg/l]	13.5	32.7	23.8	20.2	24.3	21.8	6.4	42.6	20.0	8.5	34.9	24.8
No of samples	[-]		22			5			42			9	

Table 9.2.3 *Water quality results for hydrocarbons (Schluter and Jefferies, 2001)*

Start and end time of sampling		31/07/00 to 01/08/00			09/08/00 to 10/08/00			Spot sampling		
		min	max	mean	min	max	mean	min	max	mean
Hydrocarbons	[mg/l]	0.375	3.35	1.97	0.1*	0.1*	0.1*	0.1*	0.27	0.1
Number of samples taken	[mg/l]		12			12			6	

* values below detection limit

Table 9.2.4 *Results from heavy metals analysis (Schluter and Jefferies, 2001)*

Pollutant	Cadmium µg/l	Lead µg/l	Chromium µg/l	Copper µg/l	Nickel µg/l	Zinc µg/l
Minimum	<0.066	0.9	<1.7	1.7	0.81	9.0
Maximum	<0.066	2.6	4.5	9.5	4.0	32.0
Mean	<0.068	1.8	2.2	5.2	1.7	22.2
Number of samples			9			

Location of pollutants

The pollutants are trapped within the construction at various locations according to the type of pervious construction. In cases where a geotextile is installed much of the pollution is retained on it, regardless of whether it isin the upper layers or at the base. It has been found that the geotextile retains 60–90 per cent of the oil entering the construction, with some 99 per cent from the runoff being trapped in the construction as a whole over a four-year period (Pratt, 1999). In another test, most of the mass of total sediment, organic material and lead was retained in the 50 mm gravel layer and on the geotextile (Schofield, 1994).

The long-term capacity of the structure to retain oils has been investigated (Pratt, 1999). These tests showed that some 9.5 kg of oil could be retained per square metre surface area with the percentage retained in each layer shown in Table 9.2.5.

Table 9.2.5 *Retention of pollutant within pavement structure (Pratt, 1999)*

Pavement layer	Oil retention capacity of material (g oil/kg material)	Percentage retention within as-built structure (per cent)
Concrete blocks	17	12
Gravel bedding layer	36	29
Geotextile	3190	5
Granite sub-base	7	54

A similar laboratory study was carried out to assess pollutant transport and retention within porous asphalt (Hogland *et al*, 1990). The pollutant retention of the pavement in service was monitored for simulated periods up to 30 years. The concentrations of pollutants retained varied with depth, with the highest occurring on the geotextile on the construction's base. The exception was chloride and nitrite/nitrate, which was highest in the porous asphalt.

Organic sediment, accumulated on top of the geotextile, adsorbs heavy metals and accounts for their elevated levels at that depth in the pavement. Nitrite/nitrate and ammonia concentrations were also higher at the geotextile than within the sub-base generally. Pollutants were also trapped in the soil below the geotextile. Analysis of drain effluent showed that concentrations of suspended solids, total solids, chromium and aluminium were markedly lower than typical discharges from impermeable surfaces and that concentrations of copper, zinc and lead were reduced, but less so. An increase in concentration was found for nitrite/nitrate, ammonia and chlorides, though in part this was due to the use of de-icing agents.

Investigations of the pollutants retained below soakaways (Mikkelsen *et al*, 1997; Pratt, 1996 and Legret *et al*, 1999) have shown that much is retained within 500–700 mm of the base of the soakaway. Dissolved pollutants will pass directly through infiltration devices, with the possible threat of groundwater contamination. If the risks to groundwater are considered unacceptable, or the pervious constructions are located in a stormwater hotspot (Section 3.2), infiltration should not be allowed and outflow should be by a pipe conveyed to an outfall.

Biodegradation

Besides trapping some pollutants it has been found that oils held in some types of pervious construction may be degraded by micro-organisms (Pratt, 1999). The degradation of the stored oil was monitored in a laboratory experiment over two years. It was estimated that it would take more than 100 years to saturate this type of pervious construction with oil, even at an inflow concentration of 1800 mg/l and at the observed rate of degradation. The effluent oil concentration was in the range 3.8–39.5 mg/l.

The fact that degradation was occurring was established by measuring elevated levels of carbon dioxide within the pavement and by the use of a second model, which allowed a mass balance for oil to be constructed. The measured oil degradation rate using granular nutrients was equivalent to 356 g/m^2/year and it was estimated that the mean residence time of the oil in the structure was some seven months.

Hence oil saturation of the pavement is unlikely where supply is evenly spread over time. A major oil spill could overwhelm the system, but this can be overcome by using an oil interceptor incorporated into the pavement (Section 9.15).

Studies of the microbial communities that became established in model permeable pavements of the Nottingham type, have shown that it is unnecessary to inoculate the surface to establish microbial populations. It has been observed that indigenous communities exist on construction materials, when delivered, and that wind-blown deposits provide another effective inoculation route. The nutrient concentrations in the flow from the laboratory model pavement were of acceptable levels, as shown in Table 9.2.6.

Table 9.2.6 *Nutrient concentrations in flow from laboratory pavement (Bond* et al, *1999)*

Nutrient	Concentration in flow (mg/l)
Total nitrogen	2.33
Nitrite/nitrate nitrogen	1.16
Phosphate phosphorus	1.10
Potassium	3.13

It is thought likely that nutrients occurring in the environment near pervious surfaces, such as in grass cuttings, leaves and animal droppings, may well provide the required stimulus for indigenous microbial community development.

Effect of construction and materials on pollutant retention

The type of construction can also affect pollutant removal. For example, one study found that four different sub-base aggregates produced different pollutant removal performances (Pratt, 1995). The pH and alkalinity of the effluent were lower for the blast furnace slag sub-base discharges compared with those from the limestone aggregate sub-base. Similarly, hardness and lead were lower in discharges from the limestone aggregate sub-base.

The available information on the water quality performance of pervious surfaces and structures demonstrates that they are capable of retaining pollutants that are sediment-associated and capable of being filtered or deposited, or those that are adsorbed on to the construction materials. Where such structures are open-textured and internally well-aerated, bio-degradation processes also reduce the levels of organic materials in the runoff. The removal efficiencies are provided in Table 9.2.7.

Hydraulic performance

Pervious pavements have been shown to reduce both the rate of runoff from hard surfaces and the overall volume. Monitoring at two sites in Scotland demonstrated the effectiveness of pervious pavements in reducing the peak outflow rate and total volume of runoff (Schluter and Jefferies, 2001 and Macdonald and Jefferies, 2001). An example hydrograph from one of the sites is provided in Figure 9.2.2.

A comparison of rainfall with outflow is provided in Figure 9.2.3.

Table 9.2.7 *Various quoted pollutant removal efficiencies for constructed pervious surfaces*

	Removal efficiency (per cent)							
Reference	Day *et al*, 1981	Australian Water Technologies, 1999	Macdonald and Jefferies, 2001	Napier and Jefferies, 2003	Atlanta Regional Commission, 2001	New Jersey Dept of Environmental Protection, 2000	Winer, 2000	Design values from Section 3.4.2 of this book [1]
Method of estimation	Mass loading and EMC	EMC	EMC	EMC	Unknown	Unknown	Various	
Total suspended solids	—	82.8	32	—	—	60	95	60–95
Nitrate/ nitrogen	70–80 (organic N)	25.9 (organic N)	-165 (organic N)	—	65–80	—	83	65–80
Total phosphorous	> 75 (increased retention with depth and the presence of clay-sized particles)	78.6	-157 (ortho-phosphate	—	50–80	50	65	50–80
Hydrocarbons	—	83.8 (PAH)	69	—	—	—	—	70–90
Cadmium	—	—	3	92–99	60–90	60	—	60–95
Copper	—	93.6	-580	80–99			—	
Lead	94–98	99.4	66	51–100			—	
Zinc	90–97	97.9	42	0–95			99	

Notes

1 Use lower values for sites where maintenance may not occur or to give increased confidence that design parameters will be met.

2 Negative values indicate an increase in pollutants in the outflow.

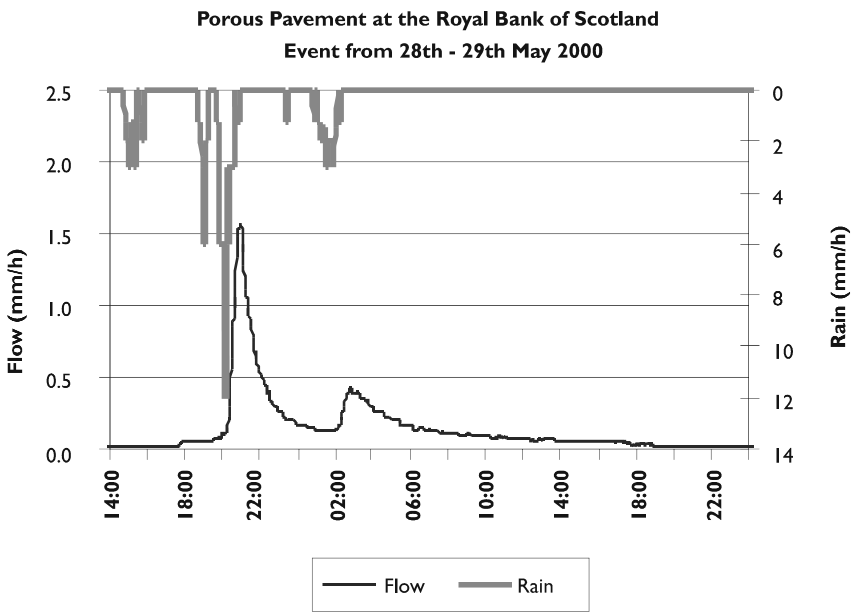


Figure 9.2.2 *Example hydrograph from pervious surface (Schluter and Jefferies, 2001)*

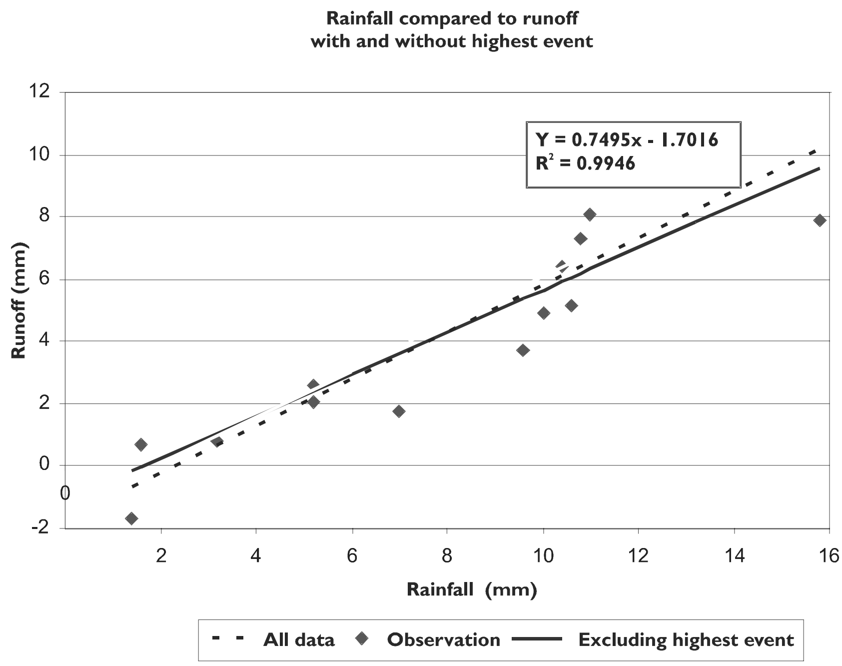


Figure 9.2.3 *Comparison of rainfall with outflow (Schluter and Jefferies, 2001)*

The lag time between the centre of gravity of the rainfall to the peak outflow varied from 29 minutes to 600 minutes for the Macdonald and Jefferies study. This was much greater than an adjacent impervious surface, which had values of -158 minutes to 123 minutes, with an average of 9.3 minutes (negative values mean that the peak flow was before the centroid of total rainfall). The lag time for the pervious surface in the Schluter and Jefferies study was between 43 minutes and 143 minutes and the study found that the shorter times related to medium rainfall events.

The overall variation in percentage outflow from both studies was between 2.5 per cent and 79.5 per cent. The precise percentage was observed to depend on the duration of the rainfall event, total rainfall and antecedent precipitation in the Schluter and Jefferies study but only a relationship with total rainfall was observed in the Macdonald and Jefferies study. This compares to values of 21.4–72.8 per cent for an adjacent impermeable area in the Macdonald and Jefferies study. The difference was attributed to evaporation or retention within the pervious pavement construction.

The reduction in peak flows from the pervious area compared to the impermeable area in the Macdonald and Jefferies study varied from 23.7 per cent to 98.4 per cent, with a mean of 76.8 per cent. For the pervious surface, an average of 7.4 mm of rainfall was required before runoff began (range 3.6–18.6 mm) and for the conventional surface it was only 0.76 mm (range 0–2.6 mm). Initial losses were also estimated for both surfaces and gave the following average values for initial runoff loss:

- pervious surface IRL = 5.6 mm
- impermeable surface IRL = 0.8 mm.

Monitoring of a pervious pavement below a car park at the Oxford services of the M40 was undertaken after construction (Abbott *et al*, 2000). Monitoring was undertaken at a chamber 150 m downstream from the car park between December 1998 and January 2000. An example hydrograph is shown in Figure 9.2.4.

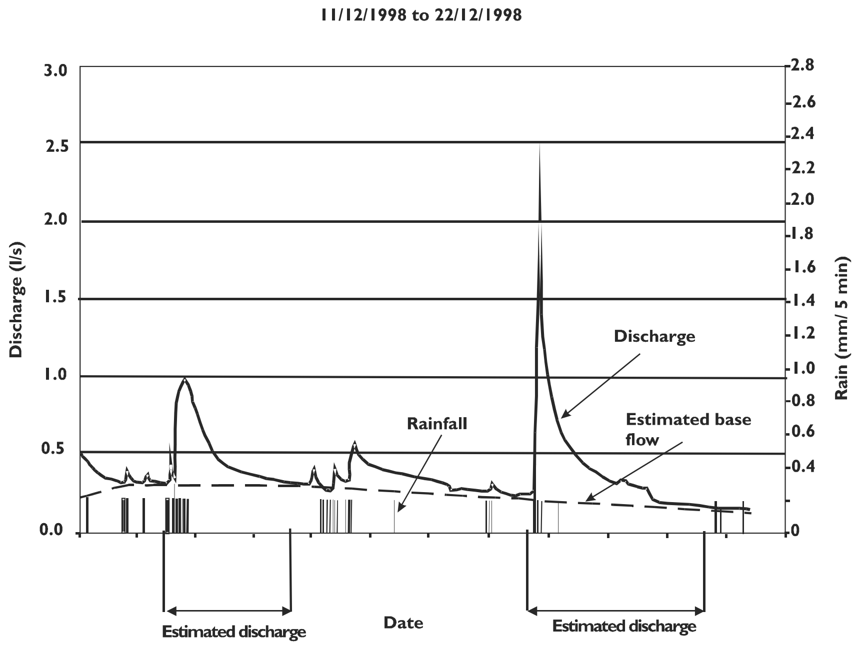


Figure 9.2.4 *Example hydrograph from outfall of pervious pavement at Wheatley MSA*

The peak discharge rates varied from 0.9 l/s to 13.5 l/s and the peak outflow corresponding to a rainfall intensity of 12 mm/h was only 0.37 mm/h, demonstrating the effective attenuation of the stormwater. The average peak discharge compared to peak rainfall varied from 1 per cent to 33 per cent. The time delay (similar to lag time) between rain falling on the surface and a rise in flow in the outlet varied from five minutes up to more than two hours. The delay between the storm peak and the peak discharge varied between five minutes and over nine hours. On average, the discharge lasted 14 times longer than the rainfall, again demonstrating effective attenuation.

The observations suggest that an average of 67 per cent of rainfall actually percolated through the system. The remaining volume is removed by mechanisms such as evaporation, loss through defects in the geomembrane and lateral overflow from the system.

Laboratory results of the runoff and retention were reported in 1981 by Day *et al* for various permeable surfaces. The mean percentage runoffs for the surfaces are given in Table 9.2.8.

Table 9.2.8 *Mean percentage runoff from pavement surface (Day* et al*, 1981)*

Type of surface	Percentage runoff
Large elemental, permeable block	0
Continuous-laid permeable	0.5
Concrete paved	78

The infiltration rates of rainfall through pervious surfaces have been investigated in several studies, which are summarised in Table 9.2.9.

Table 9.2.9 *Surface infiltration rates (Pratt* et al*, 2002)*

Reference	Location	Infiltration rate
Pratt, 1995	Nottingham (Gill Street)	Permeable concrete blocks 1000 mm/h when new 100 mm/h after six years – no maintenance
Pratt, 1995	Nottingham (Clifton)	Porous asphalt – 10 mm gap graded aggregate. 39 000 mm/h mean value after 4.5 years – no maintenance
Pratt, 1995	Reading, Shire Hall	1700 mm/h to 3600 mm/h (mean of five tests, 2600 mm/h). – no maintenance over 5 years
Abbott *et al*, 2000	Wheatley (M40) motorway service station	Porous blocks – mean infiltration rate of 1080 mm/h reducing to zero over 10 months. Gaps between the blocks – mean rate of 51 000 mm/h, after 10 months mean rate of 130 000 mm/h
Abbott *et al*, 2000	Bognor Regis Sports Centre	Porous blocks – mean infiltration rate of 550 mm/h Gaps between the blocks – mean rate of 27 000 mm/h
Bond *et al*, 1999	Laboratory tests	Permeable block surface – 4500 mm/h
Martin *et al*, 2000b	n/a	Quoted figures as general design values Permeable concrete blocks – 4500 mm/h Porous macadam – 10 000 mm/h Concrete grass paviours – >50 mm/h Gravel – > 5000 mm/h
Smith, 2001	Various locations	New permeable block surface – 229 mm/h Two-year-old car park permeable block – 152 mm/h Four-year-old car park permeable block – 75 mm/h Five-year-old car park permeable block – 127 mm/h

The infiltration rate of pervious surfaces may be very high when first installed (table 9.2.9). Much of the evidence indicates that a significant factor in whether a pavement clogs is the presence of adjacent landscaping. American, Japanese, French and German experience with permeable concrete block surfacing suggests that the design infiltration rate should be 10 per cent of the initial rate to allow for clogging over a 20-year life (Smith, 2001 and Abbott *et al*, 2000).

The presence of a geotextile that is subject to clogging may reduce the surface infiltration rate further (Pratt, 1999). A laboratory study (Schofield, 1994) showed that some 600 g/m^2 of silts derived from gully pot liquors would reduce the flow rate through a geotextile (130 g/m^2 non-woven heat-bonded continuous filament) to 2 mm/h. This significant flow reduction does not necessarily lead to problems at the pervious surface since there is some storage capacity in the bedding layer. The exact infiltration rate of a clogged geotextile will depend on the specification.

If blockage does occur in some areas then a degree of short-term standing water on some localised areas of pervious surfacing is not typically a problem. Often the entire surface will have a far higher average infiltration capacity than required; therefore standing waters in some blocked areas will simply flow into adjacent parts of the construction.

9.2.5 Design criteria

Soil and groundwater requirements

Pervious pavements can be constructed in all soil types. If infiltration is required then the infiltration rate should be greater than 10^{-6} m/s based on information provided in CIRIA Project Report 21 (Watkins, 1995) and Report 156 (Bettess, 1996). This means that clayey soils are not generally suitable for infiltration. Infiltration tests will be required in accordance with BRE Digest 365 (BRE, 1991); see Section 9.8.

If infiltration is required, groundwater must be at least 1 m below the base of the construction (and possibly greater) and the design must comply with Environment Agency policy on infiltration (Section 3.2). If infiltration is not required, the highest groundwater level should be below the base of the pavement structure.

Unlined pavements should not be used in locations where infiltrating water may cause slope stability or foundation problems (eg in areas of landslides, at the top of cutting or embankment slopes, close to building foundations), unless a full assessment of the risks has been carried out by a chartered geotechnical engineer or engineering geologist.

The effects of water storage on the structural capacity of the underlying soils must be carefully assessed. Unlined pavements should not be used on contaminated sites unless it has been clearly demonstrated that the risk posed by leaching of contaminants is acceptable (see Section 2.7).

Hydraulic design

There are three aspects to the hydraulic design of pervious pavements.

1 Infiltration of rainwater through the surface.

2 Storage of the relevant volumes.

3 Flow of water out of the pavement structure.

The design surface infiltration rate (see Table 9.2.9) should be greater than the design rainfall intensity (including allowance for runoff from adjacent impermeable areas). The infiltration rates of most pervious surfaces are so much greater than rainfall intensity that even when left unmaintained the infiltration rate of pervious surfacing may still be sufficient to allow infiltration of the design rainfall events. A reduction in the design infiltration rates of 90 per cent should be allowed for in design to allow for clogging.

Storage volume may be calculated based on the volume and porosity of the underlying storage layer (either aggregate or geocellular plastic systems) as described in CIRIA C582 (Pratt *et al*, 2002). The storage volume should take between 24 hours and 48 hours to empty.

Outflow via infiltration should be assessed using the methods described in CIRIA Report 156 (Bettess, 1996) as described in Section 9.8. For outflow via piped systems the storage below the pavement should be designed as a tank system with a limiting discharge rate.

Where the surface slopes, the water storage will be in a wedge at the lowest point and storage will be reduced. This needs to be allowed for to prevent water ponding at the surface. Intermediate dams within the pavement construction can be provided.

The geotextile is an important part of the pollutant removal of the system and should be designed in accordance with the criteria specified in CIRIA C582.

Pollutant removal

The contribution of constructed pervious surfaces to the pollutant removal of the management train may be estimated using the design values in Table 9.2.7.

Erosion

Erosion of pervious surfaces is not usually a problem (although the underlying materials must be specified so it does not occur). Erosion of soil or mulch from adjacent landscaping areas can be a problem and must be avoided (see section on design details).

Extreme events

The storage capacity of pervious pavements is often quite large because the pavement thickness is based on structural requirements rather than drainage needs. The surface storage and overland flow routes required to cope with rainfall events that exceed the design events should be carefully assessed.

Structural design

The design of each layer of the pavement is determined by the likely traffic loadings and its required operational life. There is no current structural design method in the UK specifically for pervious pavements. They have, however, been in service in car parks in the USA for more than 20 years and are used widely in Germany for applications such as bus and lorry parks, where heavy axleloads occur. Adverse structural effects have not been reported.

Conventional pavement design methods can be used for the design of pervious pavements. The key to successful structural design and performance is to recognise the difference between pervious and conventional pavements and make due allowance for the following factors in the design and specification of materials. The main considerations are set out below.

1. Pervious pavements use materials with high permeability and void space. All the current structural pavement design methods commonly used in the UK are based on the use of conventional materials (which are dense and relatively impermeable). The stiffness of the materials to be used must, therefore, be assessed. This can be based on equivalence factors.
2. Water is present within the construction and can soften and weaken materials. This must be allowed for.
3. The design methods assume full friction between layers. Geotextiles or geomembranes must be carefully specified to minimise loss of friction between layers.
4. Porous asphalt loses adhesion (binder stripping) and becomes brittle as air passes through the voids. Its durability is therefore lower than conventional materials.
5. The single-size grading of the materials used demands that care be taken to prevent loss of finer particles between unbound layers.

Pervious pavements can be as structurally competent as conventional pavements, provided certain aspects are given careful consideration at the design stage. The single-size nature of the aggregate materials used to create high voids ratios and permeability means that they can be less stiff than continuously graded materials. Porous asphalt is also less stiff than dense bituminous materials (Potter and Halliday, 1981) and ages faster as air comes into contact with the binder and causes embrittlement. Conversely, concrete block paving has a stiffness comparable to or greater than dense bituminous materials. The pavement designers should satisfy themselves that the materials to be used do not invalidate the assumptions made in the structural design methods.

The other major difference between conventional and pervious pavement systems relates to the presence of water. In conventional systems the design attempts to minimise water infiltration through the pavement, whereas water infiltration is the main reason for using pervious pavements.

The effect of water on the structural performance of the system and particularly the strength of the pavement sub-base layers and foundation subgrade need careful consideration. If this is done they will be less affected than conventional impermeable sub-bases, which can trap water within them.

The CBR value used in the design of pervious pavement systems should be measured or estimated for the saturated foundation soils, unless an impermeable geomembrane is provided to prevent water infiltration. If it is to be measured directly, CBR samples should be taken and soaked in water in accordance with BS 1377:Part 4:1990. This should give a good estimation of the performance of the foundation soils under a pervious pavement.

The use of equivalence factors is a method that allows experience gained from previous full-scale trials on proven materials to be applied to paving materials of which there is little or no previous experience. The thickness of any layer in the pavement is converted to an equivalent thickness of one that would limit vertical strain to the same amount. Equivalence factors for a range of materials are provided in Table 9.2.10 for guidance on replacing DBM with porous asphalt and sub-base in designs.

Table 9.2.10 *Material conversion factors from BS 7533-1:2001 and Knapton, 1989*

Category of material	Suggested material conversion factor (mcf)
Dense bitumen macadam 100 pen	1.0
Hot rolled asphalt	1.0
80 mm blocks on 30 mm laying course	1.0
Open textured macadam	0.7
Type 1 sub-base over material with CBR> 5%	0.3
Type 1 sub-base over material with CBR< 5%	0.2
CBM 1	0.4
CBM 2	0.5
CBM 3 or 4	0.7
Subgrade improvement material (capping layer)	0.1

The reliability of the equivalence factors depends on the accuracy of laboratory testing to determine equivalence and may overlook the long-term benefit or disbenefit, durability and fatigue resistance of a material. Care is also required when the two materials being compared differ greatly in their engineering properties.

Design details

Encouraging laboratory research data and field monitoring of long-term performance have predicted lifespans of at least 20 trouble-free years. Where clogging has occurred it has often been due to runoff carrying soil from adjacent landscaping areas. It is recommended that where pervious pavements are used the landscaping areas should not slope towards the pavement and that they should be constructed at least 50 mm below the pavement edge level or the top of the kerb (whichever is applicable), as shown in Figure 9.2.5.

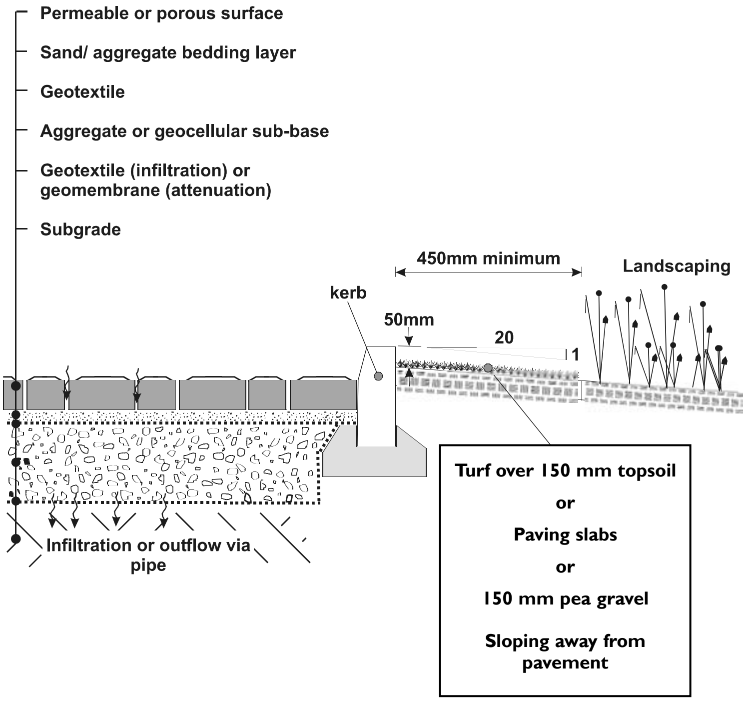


Figure 9.2.5 *Pervious pavement details*

To prevent ice causing damage to the pavement construction if water freezes, a permanent air space must be provided in the storage area (allow a 30 per cent increase in volume) to allow the ice to expand. This will also provide an insulating layer to minimise the risk of freezing.

Recommended gradings for aggregates used in pervious pavements are provided in Table 9.2.11.

Table 9.2.11 *Recommended grading requirements from BS 882:1992*

	Percentage passing		
Sieve size mm (nearest UK equivalent)	**Coarse aggregate 40 mm to 5 mm**	**Coarse aggregate 20 mm to 5 mm**	**Single-size aggregate 5 mm**
50	100	—	—
37.5	90–100	100	—
20	35–70	90–100	—
14	25–55	40–80	—
10	10–40	30–60	100
5	0–5	0–10	45–100
2.36	—		0–30

Note Based on BS 882:1992 *Specification for aggregates from natural sources for concrete.*

As the sub-base and capping are also going to be in contact with water for a large part of the time, the strength and durability of the aggregate particles when saturated and subjected to wetting and drying should be assessed. The materials should also not crush or degrade either during construction or in service. The specification of Los Angeles Abrasion test values, 10 per cent fines tests and flakiness tests will address these issues (Box 9.2.3).

Box 9.2.3 *Recommended specification of aggregate for strength and durability*

The requirement for low fines content means the load in the sub-base will be carried essentially by point-to-point contact between aggregate particles. To maximise the friction between particles, and thus increase strength, the soil particles should be rough and angular to give good interlock between particles. Crushed rock (granite, basalt, gabbro) or concrete with greater than 90 per cent fracture faces or blast furnace slag is required to achieve this, and sand and gravel with rounded particles should not be used in pervious pavement sub-base construction.

Blast furnace slag should comply with British Standard BS 1047:1983. The presence of contaminants within the slag leaching out into the percolating rainwater should be considered and leaching tests should be undertaken to confirm that this will not occur at significant rates. Leaching tests should be carried out in accordance with either the former National Rivers Authority method (Lewin *et al*, 1994) or the Toxicity Characteristic Leaching Procedure (Federal Register, 1986).

Aggregate for use in the sub-base and/or capping layers below pervious surfaces should also comply with the following requirements.

Los Angeles abrasion test – The test determines the resistance of rocks to abrasion and drying/wetting. Aggregates for use in pervious pavements should have values of percentage of wear < 25 per cent.

10 per cent fines test – this gives an indication of an aggregate's resistance to crushing. For pervious pavements, the test should be carried out on saturated samples. To provide sufficient strength and durability to resist crushing under compaction and traffic loads granular materials in pervious pavements should have a 10 per cent fines value of greater than 100 kN when tested in accordance with BS 812: Part 111:1990, *Testing aggregates. Methods for determination of 10% fines value*.

Flakiness index – this gives a measure of the flatness of the aggregate particles. A lower value represents more cuboid particles. A maximum value of 25 per cent should ensure acceptable performance in granular materials below pervious pavements, when tested in accordance with BS 812:Section 105.1:1989 *Flakiness index*.

Plate bearing tests on placed material

Plate bearing tests can be used on coarse aggregates that have been placed to determine the CBR value, in accordance with BS 1377: Part 9:1990. The use of a 300 mm-diameter plate ensures that the presence of larger particles does not adversely affect the test results. The minimum CBR of open-graded aggregates should be 30 per cent.

Horizontal forces (for example from braking or turning of heavy vehicles) need to be considered as they may cause granular layers to move over any impermeable geomembranes used to prevent infiltration. Again, the use of geogrids, geocellular confinement or roughened geomembranes should be considered in areas subject to a high level of braking or turning.

The strength of granular layers can be improved by incorporating a geogrid or geocellular confinement system into the unbound layers. These give the material increased tensile resistance and stiffness to improve performance over weak subgrades and increase the design life of open-graded materials – see CIRIA Special Publication 123 (Jewell, 1996).

9.2.6 Construction

Failure of pervious pavements is usually due to clogging that occurred during construction. It is important that site staff are informed of the purpose of the pervious pavement and that it is kept clean once installed.

Once installed the pervious surface should not be allowed to collect runoff from elsewhere in the site. It should be fenced off so that site traffic cannot pass over it and to prevent stockpiling of materials on to it.

This concept is unlike traditional construction practice where pavements are installed as soon as possible so that they can be used as site roads. Therefore the use of pervious pavements needs to be addressed as soon as construction programming begins. As they need to be constructed last, or protected from site use when completed early, pervious areas may have to be limited to selected areas of the site and impermeable areas used where site traffic will need access.

9.2.7 Operation and maintenance

The useful life of a pervious pavement is directly related to the frequency of maintenance and effective operation is dependent on maintenance. If correctly designed and maintained, pervious pavements can provide a design life of at least 20 years.

The recommended maintenance schedule for pervious pavements is provided in Table 9.2.12.

Table 9.2.12 *Maintenance requirements for pervious pavements*

Operation	Frequency
Inspection for clogging, litter, weeds and water ponding	Immediately before handover to client then monthly (48 hours after heavy rainfall to identify areas of ponding)
Vacuum sweeping litter and weed removal	Pervious surfaces should be vacuum-cleaned twice a year using commercially available sweeping machines Site owners should be given a clear checklist of the monitoring and maintenance requirements (Cahill, 2000). Experience to date in the UK is limited, but advice issued with permeable precast concrete paving in public locations has been for a minimum of three surface sweepings per year as follows: ● end of winter (April) ● mid-summer (July/August) to collect flower and grass-type deposits ● after autumn leaf fall (November). Use a brush and suction cleaner (lorry-mounted or a smaller precinct sweeper).
Reconstruction	As required. Likely to be every 15–25 years (or greater) depending on use and maintenance. Lift surface layer and bedding layer. Remove geotextile filter layer and relay geotextile, new or refurbished bedding layer and geotextile. Lower aggregate layer should still be serviceable.

Inadequate maintenance will almost certainly become evident through standing water on the pervious surface for unacceptably long periods. If cleaning does not restore infiltration rates then reconstruction of part or the whole of a pervious surface may be required. This process should be considered during design and specification of the pavement. The time before this becomes necessary can be roughly estimated by considering the factor of safety applied to the surface infiltration rate and the estimated time for the underlying layers to reach their maximum adsorption capacity for contaminants. Hydraulic failure will require that the affected surface area is lifted for inspection of the internal materials to identify the location and extent of the blockage. Inspection wells should also be installed into the sub-base layers to monitor performance and give advance warnings of any potential problems (Smith, 2001).

9.3 GREEN ROOFS

Box 9.3.1 *Key considerations for green roof design*

Description

A multi-layered system that covers the roof of a building with vegetation over a drainage layer. This reduces the volume of runoff and attenuates peak flows from roofs.

Design criteria

- The hydraulic design of green-roof drainage should follow the advice in BS EN 12056-3:2000
- impact of green roofs on below-ground drainage can be allowed for in sizing SUDS. Generally can attenuate storms up to 50 per cent annual probability (1 in 2-year return period).

Pollutant removal

Good.

Applications

Ideal for use on flat or gently sloping roofs to commercial buildings, sports centres, schools and similar buildings. Also suited to urban city centre settings where there is limited space for other techniques.

Limiting factors

- Perception that it is a new technique in UK
- cost (although this is mitigated by increased life of roof waterproof membrane).

Maintenance

- Irrigation during establishment of vegetation to provide sufficient moisture as required in first two years
- six-monthly inspections and replacement of bare patches and removal of litter.

9.3.1 Description

Roofs are one of the most significant contributors to rainfall runoff in drainage systems. Green roofs can be used to reduce the volume and rate of runoff (Tarr, 2002) so that other SUDS techniques in the scheme can be significantly reduced in size.

A green roof is a multi-layered system that covers the top of a building with vegetation. Below the surface, green roofs can include various soil or substrate, drainage, protection, waterproofing and insulation layers. There are two main types of green roof (British Council for Offices, 2003).

1. **Extensive**. The extensive roof covers the entire roof area with low-growing, low-maintenance plants. They are accessible only for maintenance. Extensive green roofs typically comprise a 25–125 mm-thick soil layer in which a variety of hardy, drought-tolerant, low plants are grown
2. **Intensive**. These are landscaped environments for recreation that include planters or trees and are usually publicly accessible. They may also include water features and storage of rainwater for irrigation. Intensive roofs generally impose far greater loads on the roof structure and require significant ongoing maintenance. They may be used over the podium decks to underground car parks (Figure 9.3.2).

Some combinations of green roof combine both types in a single roof system.

Extensive green roofs are most appropriate for use in SUDS, as they are simpler, lightweight, cost-effective and can be used in a wide variety of locations with minimal maintenance (Figure 9.3.1).

Green roofs can be used to help achieve the targets set in biodiversity action plans, and some have been used with success in parts of London (<www.blackredstarts.org.uk>). The layout, design and planting of the roof must be targeted towards achieving the desired habitat for the species concerned.

Figure 9.3.1 *Extensive green roof*

Figure 9.3.2 *Intensive green roof (Atlantis Water Management Ltd)*

Extensive green roofs are also known as sedum roofs, ecoroofs or vegetated roof covers.

The successful design of a green roof will require collaboration between structural engineers, landscape architects, ecologists, horticulturalists and drainage engineers. It also requires consideration of the maintenance that will be required and access to undertake the maintenance easily and safely.

9.3.2 Suitable applications

Green roofs can be used on a variety of sites. They can be used on most roofs but are ideal for use on flat or gently sloping roofs to commercial buildings, sports centres, schools and similar buildings.

They are also suited to urban city centre settings where there is limited space for other techniques, especially if multistorey buildings are proposed. They are feasible on most roofs because of the development of geosynthetics to provide lightweight drainage layers.

Green roofs can be easily retrofitted providing there is sufficient capacity in the roof to support them. With careful choice of materials lightweight systems can be designed for most situations.

9.3.3 Advantages and disadvantages

The advantages and disadvantages of green roofs are summarised in Table 9.3.1.

Table 9.3.1 *Advantages and disadvantages of green roofs*

Advantages	Disadvantages
Can be used in high-density urban areas where space may limit the use of other techniques	Damage to water proofing membrane can be more critical since water is encouraged to remain on roof
Reduce both volume and rate of runoff, so they mimic pre-development state	Maintenance is higher than a conventional roof. The levels of maintenance are dictated by the type of system installed
Provide valuable wildlife habitat in urban areas	
Provide attractive views from other buildings	
Peripheral benefits include extended roof service life, increased energy efficiency, aesthetic benefits and improved sound absorption	

9.3.4 Performance

Pollutant removal

Pollutant-removal mechanisms in green roofs include filtering and adsorption by the substrate and drainage layers and retention by plants. The removal efficiency depends on a number of factors, including:

- plant layer
- season
- nature of pollutants
- temperature
- light levels.

Green roofs remove leaves and roof litter from runoff and also reduce pollutant load from roofs. They also filter out any heavy metals present on the roof from atmospheric fallout. Pollutant-removal efficiencies for green roofs are not quoted in the literature. It is anticipated that they will behave at least as well as pervious pavements to remove heavy metals (60–90 per cent) and suspended solids (60 per cent) from the runoff.

Hydraulic performance

When rain hits a green roof it will first pass into the substrate and possibly pass through until the adsorbancy of the soil is activated (although through flow will generally be low). It is then absorbed by the substrate (and possibly the drainage layer) and taken up by plants in the same manner as a greenfield site. For most small storms the rainfall is removed by evapotranspiration (Section 4.4.4). Only when the soil is fully saturated will water percolate through to the underlying drainage layer in significant volumes.

The green roof influences the runoff hydrograph in two ways, therefore.

1 Interception and retention of rainfall from the early part of a storm.

2 Limiting the maximum release rate of runoff.

The processes involved in the operation of a green roof are (Tarr, 2002):

- retention of rainwater in substrate and drainage layers
- uptake of water and release by plants as vapour (transpiration)
- uptake of water and biochemical incorporation by plants (photosynthesis)
- evaporation from substrate due to wind and sun.

The influence of a green roof on the runoff hydrograph is shown in Figure 9.3.3. Once the field capacity of the soil layer is reached, the water drains through to the drainage layer below at a rate that is roughly equal to the saturated hydraulic conductivity of soil or growth medium. The hydrologic performance is specific to the growth medium and plants used (as these soak up most of rainfall and then release it). The relationship between plant and soil system and rainfall retention is complex and interrelated (Tarr, 2002). Temperature, wind speed, substrate depth and growing season are three factors that will affect water removal from system and the total volume of runoff released to drainage system.

The composition of the substrate is a major factor in the performance of green roofs. The mineral components commonly used have a water retention capacity of 18–50 per cent. Aggregate drainage layers can also retain water.

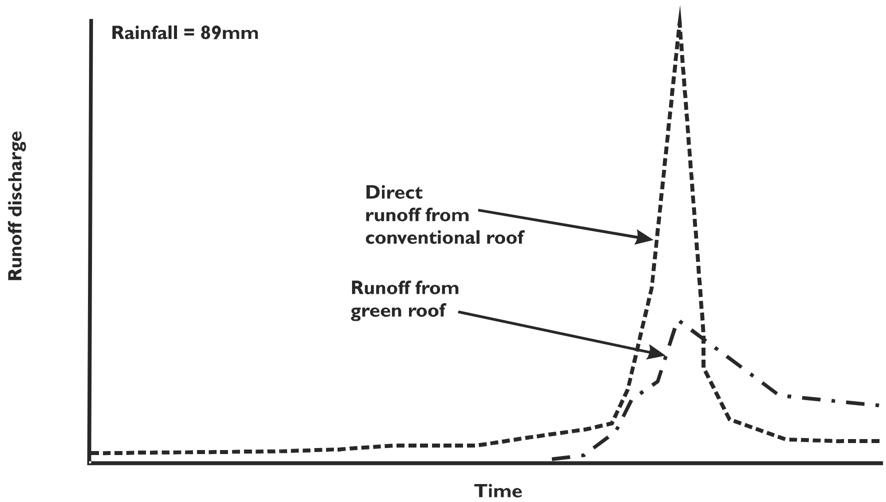


Figure 9.3.3 *Runoff hydrograph from a green roof (New Jersey Department of Environmental Protection, 2000)*

Studies of the performance of green roofs in Germany indicate that green roofs can generally retain 40–100 per cent of rainfall depending on the season (Tarr, 2002).

A demonstration project reported by the United States Environmental Protection Agency in Philadelphia (USEPA, 2000) was designed to detain a 24-hour duration rainfall event with an annual probability of 50 per cent (1 in 2 years). The extensive roof cover had an overall thickness of 70 mm and used a growth medium with a saturated moisture content of 45 per cent. The saturated infiltration capacity was 89 mm/h. Monitoring of a trial section found that negligible runoff occurred from rainfall events of less than 15 mm depth. The most intense storm occurred after the roof was already saturated from a previous extended period of rainfall, yet attenuation was still significant (Figure 9.3.4). This suggests that even when retention has stopped, the effects of vegetation on the surface and the infiltration capacity of the substrate continues to slow down the rate of runoff from the roof.

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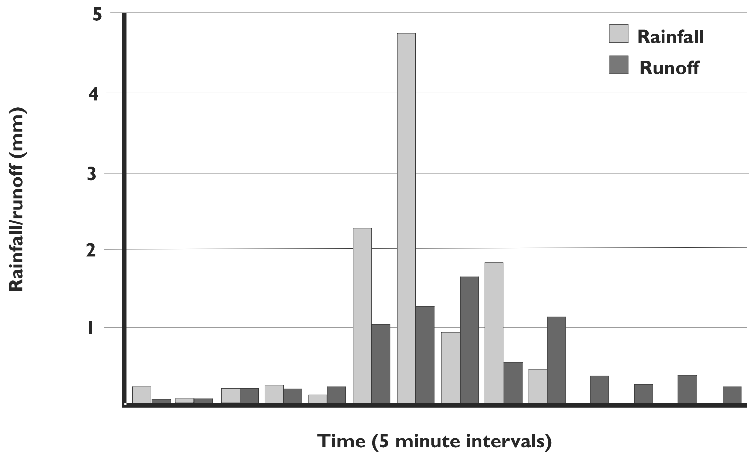

Figure 9.3.4 *Runoff attenuation for trial roof in Philadelphia (USEPA, 2000)*

9.3.5 Design criteria

Hydraulic design

Hydraulic design of green roof drainage should follow the advice in BS EN 12056-3:2000 (though the Standard relates to the design of normal roof drainage). BS 6229:1982, *Code of practice for flat roofs with continuously supported coverings* provides useful information too.

Guidance from the USA suggests that green roofs are designed to attenuate storms with up to a 50 per cent annual probability of exceedance (a 1 in 2-year return period) (New Jersey Department of Environmental Protection, 2000). They do contribute to attenuation of flows from larger storms and this should be taken into account when sizing other SUDS devices on a site. For larger storms, direct runoff is allowed to occur after the field capacity of the system has been reached, but a significant proportion will still infiltrate slowly through the substrate and vegetation will retard surface flow. Green roofs could be allowed for in SUDS design by assuming a runoff coefficient that recognises the beneficial effects (for example, 30–50 per cent would be similar to values applied to small gardens or permeable surfaces – National SUDS Working Group, 2003).

A well-designed and properly installed drainage layer is extremely important to prevent water ponding on the roof surface or within the green roof construction on top of the waterproofing layer. The soils need a sufficient infiltration rate for the design storm and a field capacity to absorb water to reduce runoff volumes. The drainage layer should be designed to carry the necessary volume of water from the roof, based on the transmissivity of the layer, without ponding on top of the waterproofing. The New Jersey Department of Environmental Protection, 2000, recommends a minimum transmissivity of at least 186 litres per minute per metre, but the value for any site depends on the site-specific parameters. Good drainage is vital to the long-term performance of a flat roof. To ensure the minimum finished fall of 1:80 recommended in BS 6229, falls should be designed to 1:40. Falls should be consistent, without deflections or depressions in which large quantities of water may pond.

The plants in a green roof system remove a significant proportion of rainfall by transpiration and evaporation so that green roofs significantly reduce the overall volume of runoff. A cautious approach should be taken to quantifying this element of the green roof system and the worst-case values for winter should be allowed for in design.

Multiple outlets should be provided to green roofs to minimise the risk of a blockage with serious consequences. They should also be easily accessible.

Pollutant removal

Poorly-designed systems that do not fully consider all the factors that affect performance may not give good pollution removal efficiencies. The contribution of green roofs to the pollutant removal within the management train for a site may be estimated using the values of removal efficiency quoted in Table 3.6.

Erosion

Protection from erosion is needed until the green roof vegetation becomes established. Erosion is caused by the following three mechanisms.

1. Wind blow.
2. Wind suction.
3. Rainfall.

It can be minimised by:

- specifying the correct substrate formulation (mass and grading)
- using rapidly stabilising plant cover
- ballasting vulnerable areas.

The soil layer can also be protected from wind erosion using mulch or erosion control mats (Minnesota Metropolitan Council, 2001), although the main aim should be to establish vegetation as quickly as possible.

Extreme events

The green roof should be designed in accordance with BS EN 12056-3:2000 to deal with short-duration extreme events so that the runoff does not compromise the performance of the structure.

Structural design

The design of a structure to carry the loads imposed by a green roof should only be undertaken by a chartered structural or civil engineer.

Typically, a green roof applies a load of between 0.7 kN/m^2 and 2.4 kN/m^2 depending on factors such as soil thickness and water-retention capacity. The design load should assume a saturated soil. Live loading on the roof should consider the presence of people on the roof undertaking maintenance.

The green roof system must be designed to resist wind uplift forces. Since uplift pressures are greater at the corners of a roof, pavers can be placed there instead of vegetation. The waterproofing membrane may need to be anchored to the roof to resist wind uplift forces.

Green roofs are composed of a multilayered construction, which is described below. The precise details depend on the design criteria for each roof.

Design details

Example design details for green roofs are provided in Figure 9.3.5.

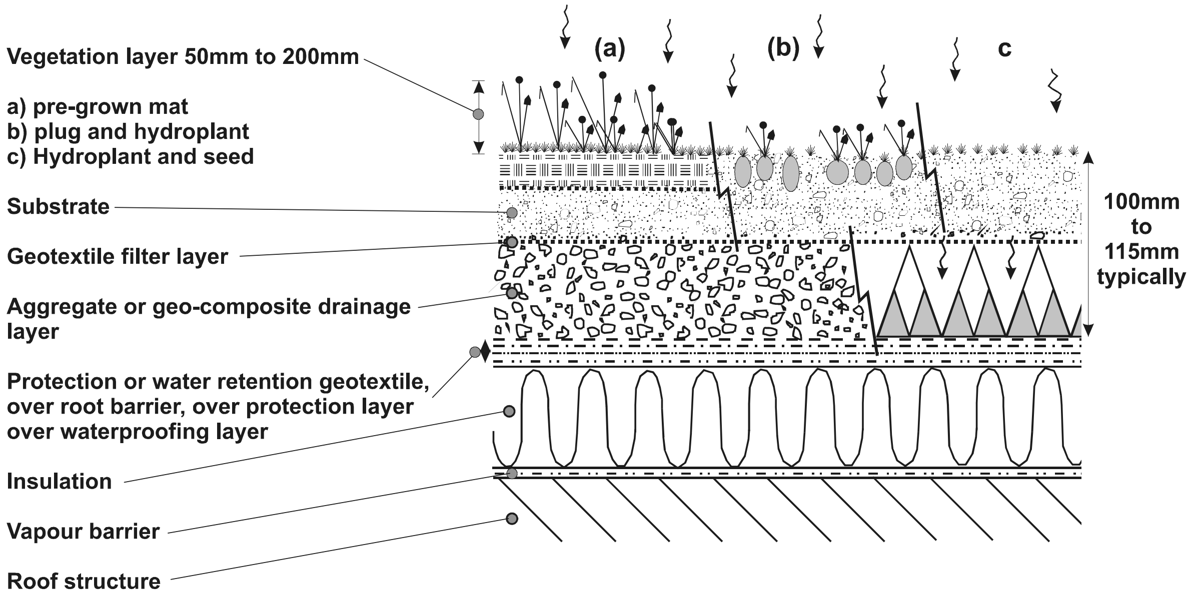

Figure 9.3.5 *Example details of a green roof (Tarr, 2002)*

Waterproofing layer. A high-quality robust waterproofing layer is required and is a vital component of the system. Two common types of membrane may be used.

1 Rubberised asphalt applied directly to the roof as a hot liquid.

2 Single-ply thermoplastic sheet membranes that are typically installed over a vapour barrier and insulating layer.

The drainage layer. Located over the waterproofing layer, this underlies the entire green roof and is connected to gutters and downpipes. It keeps the growing medium aerated, holds some water for times of drought and drains excess water. Typically geocomposite drainage systems are used, as they are lightweight and provide efficient drainage. The layer must have sufficient capacity and be laid to the required gradient to prevent ponding of water over the membrane.

Geotextile separation layer/root barrier. This prevents clogging of the drainage layer, and prevents roots penetration of both the drainage layer and the underlying waterproofing layer. The robustness of the root barrier depends on the type of waterproofing system used.

Lightweight soil/growth medium. This is kept as thin as the planting will allow – typically, 75–100 mm thickness is acceptable. Low-density soils with good water retention are required and include mixtures of organic and mineral material (for example, crushed pumice and expanded clay). They are required to retain between 40–60 per cent water by weight and have a bulk density of between 560–800 kg/m^3. A retention of 40 per cent would allow a 100 mm-thick layer to retain the first 40 mm of rainfall. Normal topsoil is too heavy for use on green roof systems. The soil must be carefully formulated to provide the oxygen, nutrient and moisture needs of plants.

The key attributes of the soil are:

- grain size distribution (clay content must be low)
- porosity
- moisture content at maximum water capacity
- moisture content at field capacity (ie measure of water retention in dry periods)
- moisture content at wilting point (wilting point nominally 0.33 bar)

- saturated hydraulic conductivity
- void ratio
- organic content (less than 33 per cent for fire protection)
- maximum salinity
- total nitrogen.

Detailed guidelines for the specification of soils for green roofs have been developed in Germany by FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V, 1995) and the specification for soil for use on extensive roofs is provided in Table 9.3.2.

Table 9.3.2 *Specification of soil cover for extensive roof (FLL, 1995)*

Physical property	Single-layer system	Multi-layered system
Water retention	Min 25 per cent	Min 35 per cent
Water permeability	Min 60 mm/min	Min 0.6 mm/min
Air content (fully saturated)	Min 25 per cent	Min 25 per cent
Density (fully saturated)	0.8–1.4 g/cm³	1.0–2.2 g/cm³
Chemical property		
pH	6.5–9.5	6.5–8.0
Salt content of water extract	Max 1 g/l	
Initial organic matter content	3–8 per cent	
Nitrogen (N) slightly soluble	Max 60 mg/l	
Phosphorous (P_2O_5)	Max 15 mg/l	
Potassium (K_2O	Max 150 mg/l	
Magnesium (Mg)	Max 120 mg/l	

Vegetation. A robust vegetation layer is required (see section on planting below).

For roof slopes with a gradient greater than 1.5 per cent, cross-battens may be required to hold the drainage layers in place and soil erosion control will need to be considered (Minnesota Metropolitan Council, 2001).

It is also important to consider the fire resistance of green roofs. All openings should be surrounded by non-vegetative materials such as pavers. Green roofs must have adequate resistance to the external spread of fire as required by Building Regulation B4 (Regulation 19 in Scotland), for which a risk assessment should be undertaken. It should consider factors such as the substrate's organic content, the type of vegetation and the effects they will have on the spread of fire.

If geosynthetic drainage layers are used the risk of fire creep within the geosynthetic layer must be considered. The weight of the soil above may cause collapse of the synthetic when it is subject to heat from a fire, thus preventing the fire spreading. If not, then fire breaks may be required.

Outlets

Guidance on the capacity and location of rainwater gutters and outlets is given in BS 12056-3:2000. Rainwater outlets should accept runoff from both the drainage layer and the system surface.

An example detail of an outlet to downpipes is given in Figure 9.3.6.

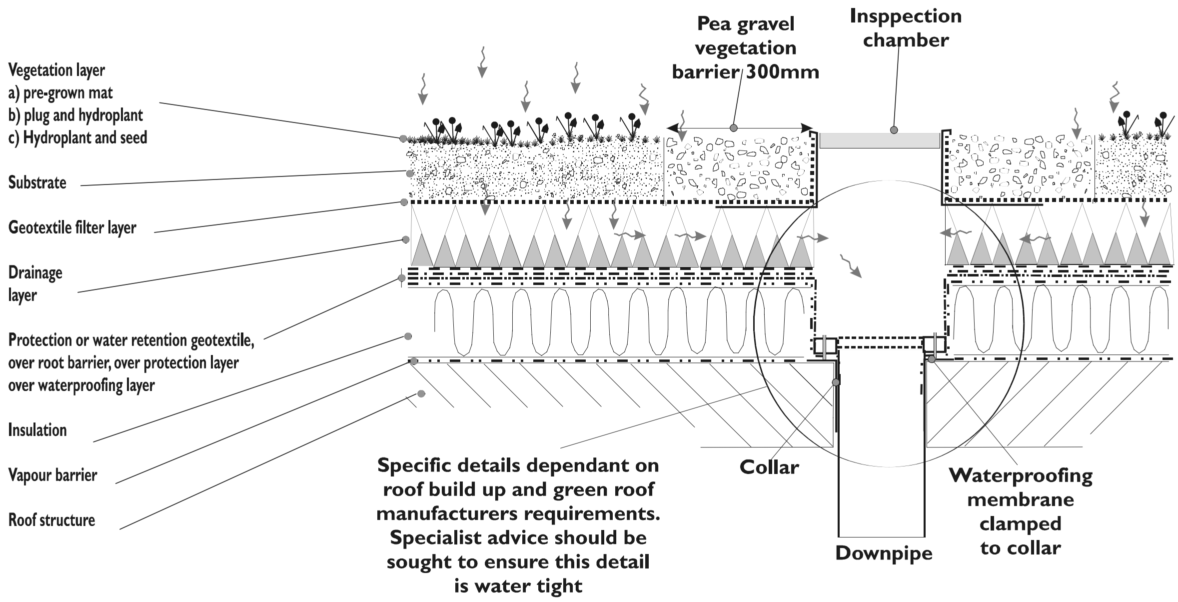

Figure 9.3.6 *Example detail of outlet from green roof*

9.3.6 Construction

The correct application of the water proofing system is essential to the performance of a green roof. This should be undertaken in accordance with the relevant standards for normal roofs. CQA of the installation helps to reduce the risk of leakage, as does testing for water-tightness using 24-hour water tests on completion of installation.

Temporary ballasting of individual components may be required during construction to prevent uplift due to wind.

Plants may require irrigation until they are established if natural rainfall is insufficient.

Erosion protection will be required until vegetation is established if the roof is planted with plugs or seeds. This can be achieved using a protective mulch or blanket.

Safe access is required for construction of the green roof. To reduce the risk of damage, the roof ideally should be installed when no follow-on trades need to use the roof after installation.

9.3.7 Planting

The roof-top microclimate is a difficult environment for plants to survive in, and the advice of a landscape architect or similar professional with experience of green roofs is essential. The vegetation has to cope with periodic rainfall interspersed with hot and dry drought periods. Plants also have to contend with high winds and low winter temperatures (due to a lack of ambient heat stored in the ground).

To be able to survive plants must:

- tolerate poor soil
- tolerate mildly acidic conditions
- prefer well-drained conditions
- be able to colonise quickly.

The choice of plants also depends on the other layers in the roof design (and vice versa) and on sun and shade conditions. The plants chosen should be appropriate for the substrate used, its thickness and the environmental conditions.

To meet these requirements alpine or sub-alpine species are best suited to green roofs. Some sedum (*Sedum*) species are well adapted as are sedge (*Carex*), fescue (*Festuca*) and feather grass (*Stipa*). It is also best to choose plants that will not require irrigation and are low maintenance with no need for mowing or fertilisers (City of Portland Environmental Services, 2002).

Many variations in planting are possible and the advice of a specialist should be sought. There may be very good reasons to widen the range of plants, such as to improve water storage, enhance the aesthetics of the roof or encourage biodiversity Dunnett (2003). The use of a wider range plants is dependent on other layers in the system and the accessibility or visibility of the roof (Table 9.3.3).

Table 9.3.3 *Planting for green roofs (Dunnett, 2003)*

		Accessibility and visibility of roof			
		Inaccessible/ not overlooked	**Inaccessible/visible from a distance**	**Inaccessible/visible from a close distance**	**Accessible**
Depth	0–50 mm	Simple sedum/moss communities	Simple sedum/moss communities	Simple sedum/moss communities	Simple sedum/moss communities
	50–100 mm		Dry meadow communities/ low-growing drought tolerant perennials, grasses and alpines, small bulbs	Dry meadow communities/ low-growing drought-tolerant perennials, grasses and alpines, small bulbs	Dry meadow communities/ low-growing drought-tolerant perennials, grasses and alpines, small bulbs
	100–200 mm			Semi-extensive mixtures of low medium-dry habitat perennials, grasses and annuals, small shrubs, and lawn/turf grass	Semi-extensive mixtures of low medium-dry habitat perennials, grasses and annuals, hardy subshrubs
	200–500 mm				Medium shrubs, edible plants, generalist perennials and grasses
	Greater than 500 mm				Small deciduous trees and conifers

Plants can be installed as pre-grown mats that are simply rolled out over the roof area, by direct on-site planting of sedum plugs/potted plants or by seeding. In Europe, hydro-seeding is used for roofs that are difficult to reach. Mats give instant coverage and erosion control and do not require mulching. They also minimise weed intrusion and need little maintenance in the establishment period.

Planting of plugs and seeds takes longer to achieve full coverage and may need erosion control. They require mulching and more maintenance during the establishment period.

It is best to install green roofs in spring or autumn (<www.greenroof.com>).

9.3.8 Operation and maintenance

Green roofs have relatively low maintenance requirements once they are established. If correctly designed and maintained they will prolong the life of the roof waterproofing system. The recommended maintenance schedule for green roofs is provided in Table 9.3.4.

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Table 9.3.4 *Maintenance requirements for green roofs*

Operation	Frequency
Irrigation during establishment of vegetation to provide sufficient moisture	As necessary during first two years
Inspection for bare patches and replacement of plants	Six-monthly
Removal of litter and other debris	Six-monthly

Extensive green roofs do not normally need irrigation or mowing. Safe access for construction and maintenance is required and should be included in the design of the green roof (harness anchor points, for example).

9.4 BIORETENTION

Box 9.4.1 *Key considerations for bioretention design*

Description

Shallow depressed landscaped areas that are underdrained and rely on enhanced vegetation and filtration to remove pollution and reduce runoff volumes.

Design criteria

- Provide sufficient area to store the water quality volume as a thin layer on the surface (maximum 150 mm deep)
- calculate infiltration time through filter based on permeability of filter and head of water. Time of infiltration to be greater than 40 hours.

Pollutant removal

Very good.

Applications

Ideally suited to car parks and roads where the entire system can be located within the landscaping with no extra land take.

Limiting factors

- Catchment area limited to between 1000 m^2 and 8000 m^2 to avoid clogging of the bioretention area
- cannot be used where heavily contaminated runoff is likely (industrial areas) unless base is sealed.

Maintenance

- Monthly inspections
- monthly litter removal
- annual weeding
- annual replacement of top mulch layer
- annually replace damaged vegetation
- pruning every two years
- spiking or scarifying every three years.

9.4.1 Description

Bioretention areas are similar to dry swales (Section 9.7) but rely on enhanced vegetation and filtration to remove pollution and reduce runoff volumes. Originally, they were designed to behave like forested ecosystems, but the latest design guidance in the USA (Winogradoff, 2002) has expanded the concept to include ornamental gardens, meadows, hedgerows and wildlife habitats. Pollution is removed from the runoff by a combination of sedimentation, filtration, adsorption, phytoremediation and biological action. The bioretention area is only used for treating the water quality volume and is normally placed off-line. The water quality volume of runoff is diverted into the bioretention area and allowed to pond. Storm runoff in excess of the water quality volume is typically directed to another drainage system (for example, a piped system with some form of attenuation or infiltration).

The bioretention area can be easily incorporated into landscaping areas as a series of shallow depressions (Figure 9.4.1).

Figure 9.4.1 *Bioretention area*

It comprises a grass filter layer over a sand filter and/or organic filter, which is underdrained. Runoff enters the bioretention system and filters through to the underdrain and is then returned to the drainage system or it can be infiltrated to the ground. An overflow is also provided to increase the capacity of the system (usually a gravel or sand trench so that some filtration will occur).

The planting in the bioretention area will remove a percentage of the runoff by evapotranspiration and should also remove nutrients from the runoff.

Although bioretention is presented as a separate SUDS technique, the concept can also be included in swales (Section 9.7) and infiltration basins (Section 9.9) to improve pollutant removal and enhance amenity value.

Trees are important in the bioretention concept as they intercept precipitation and provide the following two stormwater management functions.

1. **Flow control**. Trees hold water on their leaves and branches from where it evaporates. This detains the flow and dissipates the energy of runoff. The most efficient types are large trees with small leaves. Trees also facilitate stormwater infiltration and groundwater recharge.
2. **Pollution reduction/stormwater cooling**. Trees provide shade over large areas of impervious surfaces. The hard surface is protected from direct solar exposure, which reduces heat gain in the pavement, which in turn reduces the heat that is absorbed by stormwater as it flows over the surface.

9.4.2 Suitable applications

Bioretention is ideally suited to car parks and roads where the entire system can be located within the landscaping areas. It can be used in most sites, but the base will require lining where infiltration to the ground is not appropriate (in industrial sites, for example). Generally, the technique is applied to small catchments (larger sites can be subdivided into smaller sub-catchments). US design manuals recommend a maximum catchment area of 1000–8000 m^2 to avoid clogging of the bioretention area (Minnesota Metropolitan Council, 2001; Claytor and Schueler, 1996 and Bitter and Bowers, 2000).

Bioretention is also suitable for dense urban sites where, with imaginative site design, it can be incorporated into the landscaping (and the landscaping and site layout designed to allow this). Early consideration of bioretention during the feasibility stage of a project allows the facilities to be incorporated throughout a site. Because of this, it is known in the USA as an integrated management practice (IMP).

The runoff can eventually be either infiltrated to the ground or removed to an outflow, so the technique can be used in any ground conditions. Where contamination is present in the ground it may require lining with a membrane to prevent leaching of contaminants into the groundwater (Section 2.7).

Bioretention areas typically require 5–10 per cent of the overall site area (Claytor and Schueler, 1996 and Minnesota Metropolitan Council, 2001), although they can be incorporated into landscaping so as to minimise the overall extra land take.

9.4.3 Advantages and disadvantages

The advantages and disadvantages of bioretention areas are summarised in Table 9.4.1.

Table 9.4.1 *Advantages and disadvantages of bioretention areas*

Advantages	Disadvantages
Improved aesthetics over other systems	Cannot treat large drainage areas (but this can be overcome by splitting into sub-catchments)
Reduces volume and rate of runoff	Susceptible to clogging (this can be prevented by pre-treatment)
Very effective pollutant removal	Can take up space
Flexible layout to fit into landscape	Construction cost higher than other basic techniques
Suited to highly impervious areas such as car parks	

9.4.4 Performance

Pollutant removal

Pollutant removal in bioretention systems is a complex process involving several mechanisms. The critical processes for pollutant removal are (Winogradoff, 2002):

- *sedimentation* – as runoff slows down within the bioretention area, particles and suspended solids fall out of the water and are retained in the surface of the area
- *evaporation* – the very shallow ponding area promotes evaporation and reduces the volume of runoff
- *filtration* – particles are filtered as the runoff passes through the mulch and soil to the underdrain. The geotextiles incorporated at various levels are particularly effective at filtering
- *assimilation* – nutrients and metals are taken up by plants and used for growth and other biological processes
- *adsorption* – the mulch and soils in the filter system adsorb pollutants and retain them with the bioretention area
- *nitrification* – natural bacteria within the system can oxidise ammonia and ammonium to form nitrate that is readily used by plants
- *denitrification* – nitrates can be oxidised to nitrous oxide and nitrogen, which are returned to the atmosphere
- *biodegradation* – natural bacteria in the soil degrade hydrocarbons and other organic material in the runoff to carbon dioxide and water.

Because several processes are occurring, the bioretention area can have a significant amount of redundancy in pollutant removal. This improves reliability.

Based on the number and redundancy of pollutant removal mechanisms, it is assumed that the pollutant-removal efficiency is similar to that of a dry swale (high), although there is limited monitoring data to support this. Results of tests that examined the pollutant removal of bioretention areas with varying thicknesses of soil filter are shown in Table 9.4.2 and suggest that a soil filter 1 m thick gives the maximum efficiency.

Table 9.4.2 *Variation in pollutant removal with depth for bioretention areas (Winogradoff, 2002)*

	Cumulative percentage removal				
Depth of soil filter (m)	**Copper**	**Lead**	**Zinc**	**Phosphorous**	**Total nitrogen**
0.30	90	93	87	0	-29
0.61	93	99	98	73	0
0.91	93	99	99	81	43

A study of a bioretention area serving a car park of some 3160 m^2 was undertaken in the USA (Shaw *et al*, 2001). At the time of the study the vegetation had not matured, so the results probably underestimate performance for a bioretention area. The area was constructed off-line to treat the first flush and was monitored between September and November 1999. The results reported were conservative, because removal efficiency was calculated on the basis of the mean inflow and outflow concentrations rather than mass loadings. The removal efficiencies are provided in Table 9.4.3, together with the results from several other studies in the USA that have monitored the performance of bioretention areas.

Table 9.4.3 *Pollutant removal efficiencies for bioretention areas*

<table>
<tr><th>Pollutant</th><th colspan="8">Removal efficiency (per cent)</th></tr>
<tr><th>Reference</th><th>Claytor and Schueler, 1996</th><th>Winogradoff, 2002 (for 1 m thick soil filter)</th><th>New Jersey Department of Environmental Protection, 2000</th><th>USEPA, 2002</th><th>USEPA, 1999a</th><th>Shaw et al, 2001</th><th>Winer, 2000</th><th>Design values from Section 3.4.2 of this book [1]</th></tr>
<tr><td>Method of estimation</td><td>Predominately mass loading</td><td>Unknown</td><td>Unknown</td><td>Unknown</td><td>Unknown</td><td>EMC</td><td>Various</td><td></td></tr>
<tr><td>Total suspended solids</td><td>90</td><td>—</td><td>80</td><td>—</td><td>90</td><td>53</td><td>—</td><td>50–80</td></tr>
<tr><td>Nitrate/nitrogen</td><td>50</td><td>43</td><td>50</td><td>49</td><td>68–80 (TKN)</td><td>—</td><td>49</td><td>40–50</td></tr>
<tr><td>Total phosphorous</td><td>65</td><td>81</td><td>60</td><td>65–87</td><td>70–83</td><td>13</td><td>65</td><td>50–60</td></tr>
<tr><td>Hydrocarbons</td><td>—</td><td>—</td><td>—</td><td>—</td><td>90</td><td>66</td><td>—</td><td>50–80</td></tr>
<tr><td>Cadmium</td><td rowspan="4">80–90</td><td>—</td><td rowspan="4">80</td><td>—</td><td></td><td rowspan="4">—</td><td>—</td><td rowspan="4">50–90</td></tr>
<tr><td>Copper</td><td>93</td><td>43–97</td><td rowspan="3">93–98</td><td>97</td></tr>
<tr><td>Lead</td><td>99</td><td>70–95</td><td>—</td></tr>
<tr><td>Zinc</td><td>99</td><td>64–95</td><td>95</td></tr>
</table>

Notes

1 Use lower values for sites where maintenance may not occur or to give increased confidence that design parameters will be met.

Hydraulic performance

There is no published data on the hydraulic performance of bioretention areas. Their performance is expected to be similar to that of swales in that they will slow down and attenuate flows and reduce the volume of runoff from a site, although this is difficult to quantify at present.

9.4.5 Design criteria

Soil and groundwater requirements

Bioretention areas can be constructed in any soil types. If infiltration is required, then the infiltration rate should be greater than 10^{-6} m/s based on information provided in CIRIA Project Report 21 (Watkins, 1995) and Report 156 (Bettess, 1996). This means that clay soils will not generally be suitable for infiltration. Infiltration tests will be required in accordance with BRE Digest 365 (BRE, 1991); see Section 5.1. Care should also be taken not to compact soils below bioretention areas during construction as this will reduce the infiltration capacity.

If infiltration is required, groundwater must be greater than 1 m below the base of the bioretention area and the design must comply with Environment Agency policy on soakaways (Section 3.2). If infiltration is not required, the highest groundwater level should be below the base of the underdrain.

Unlined bioretention areas should not be used in locations where infiltrating water may cause slope stability or foundation problems (for example, where there are landslides, at the top of cutting or embankment slopes, or close to building foundations), unless a full assessment of the risks has been carried out by a chartered geotechnical engineer or engineering geologist.

Unlined bioretention areas should not be used on brownfield sites unless it has been clearly demonstrated that the risk posed by leaching of contaminants is acceptable (see Section 2.7).

Hydraulic design

Bioretention areas are normally designed as off-line water quality treatment areas because runoff from less frequent storm events can cause erosion. The main areas requiring hydraulic design are therefore the inlet and outlet structures.

The diversion inlet should be designed to pass the water quality volume into the bioretention area and pass larger volumes of runoff to the overflow system using conventional hydraulic design criteria for flow over paved surfaces. The underdrain should be sized using conventional hydraulic design methods to carry away the infiltrating water and to ensure that the overlying soils do not become saturated.

The bioretention area itself should be designed to provide sufficient area to store the water quality volume as a thin layer on the surface (maximum 150 mm deep) to enhance removal by evaporation and minimise the amount of time that the water is standing.

Pollutant removal

Water that percolates through the sand filter should be retained within it for at least 40 hours to maximise filtration and adsorption (Claytor and Schueler, 1996). A similar requirement is proposed in other US design guidance (Winogradoff, 2002) that recommends a bioretention system should dewater within 48 hours of a design storm occurring. This gives sufficient contact time to remove pollutants but allows the storage on the surface to half-empty in around 24 hours, ready to receive any following storms.

The surface area needed to achieve this can be found using the following equation:

$$A_f = Q_{wq} \times d_f/[(k \times (h + d_f)(t_f)] \quad (9.4.1)$$

Where:

A_f = surface area of bioretention planting bed (m^2)

Q_{wq} = water quality treatment volume (m^3)

d_f = planting soil bed depth (m)

k = coefficient of permeability of water (m/s)

h = average height of water above bioretention bed (half maximum height) (m)

t_f = time required for water quality treatment volume to percolate through treatment bed (s)

Erosion

To prevent erosion during extreme rainfall events, bioretention areas are normally designed to operate as off-line systems. If they are designed as on-line systems then the same requirements to prevent erosion of swales should be applied (Section 9.7).

Extreme events

Bioretention areas are designed to treat the water quality volume and the inlet to the system should be designed so that runoff from extreme rainfall events is bypassed to either another drainage system or follows a suitable overland flow route.

Design details

There are six key elements to a bioretention area that need to be correctly designed to ensure that the system provides effective and durable pollutant removal (Claytor and Schueler, 1996; Bitter and Bowers, 2000; Winogradoff, 2002).

1 **Pre-treatment**. This is required to reduce inflow velocities and remove silts and sediment that could cause clogging of the bioretention area. The use of pre-treatment extends the design life of the system and should not be omitted. Pre-treatment can be provided using grass filter strips (Maryland Department of the Environment 2000) or, where space is limited, a gravel diaphragm along one edge (Figure 9.4.2).

2 **Ponding area**. Ponding of the water on the surface of the bioretention area allows settling of sediment and encourages evaporation of water from the system. Ideally, the ponding depth should be 75–100 mm to allow quicker dissipation of pooled water; normally a maximum depth of 150 mm is adopted. This is based on ponding only occurring for three to four hours so as not to limit the choice of plant species.

3 **Surface mulch layer**. This provides a suitable environment for plant growth by maintaining moisture within the soil. It also filters and traps fine particles from the runoff and provides a substrate for bacteria that break down hydrocarbons. It helps to avoid surface sealing of the bioretention area, which reduces soil permeability. The mulch layer should comprise standard landscape mulch (chipped or shredded hardwood that has been aged for at least 12 months), which should be laid to a maximum depth of 75 mm. Grass cuttings should not be used as the surface mulch, as they will increase the level of nutrients in the outflow waters. Alternatively, a pea gravel layer may be provided.

4 **Soil bed**. This holds water and nutrients for the plants and adsorbs pollution. It must be sufficiently permeable to allow water to pass through it to prevent the surface of the retention area becoming waterlogged. The soil layer also promotes microbial activity to remove pollutants. Design guidance from the USA suggests that the soil layer should be a sandy loam or a loamy sand mixture with the proportions provided in Table 9.4.4.

Table 9.4.4 *Soil specification for bioretention areas (Claytor and Schueler, 1996 and Winogradoff, 2002)*

Component	Proportion in soil mixture, % (Claytor and Schueler, 1996)	Proportion in soil mixture, % (Winogradoff, 2002)
Sand	35–60	50–60
Silt	30–55	—
Clay	10–25	Less than 5
Organic matter	1.5–4	20–30 (leaf compost)
Topsoil	—	20–30

Further guidance on the definition of sandy loam and loamy sand is given in British Standard BS 3882:1994, *Specification for topsoil*.

The permeability of the soil should be at least 3.5×10^{-6} m/s and it should not be compacted during construction. The pH value of the soil should be in the range 5.2–7.

It should be uniform and free from stones, stumps, roots or any other coarse objects that are greater than 50 mm diameter. It should also be free of all noxious weeds such as Japanese knotweed and hogweed.

A minimum soil depth of 1 m (1.2–1.5 m if trees are planted) should be provided. This can be reduced to 0.45 m if shallow rooted plants are used, although this may reduce the pollutant-removal efficiency (see Table 9.4.2). Other guidance suggests a minimum depth of 1.2 m.

5 **Sand filter**. This is provided at the base of the soil layer over the top of the underdrain. This should be a minimum of 300 mm thick of 0.5–1.0 mm sand.

6 **Underdrain and overflow**. These remove treated water and prevent the soil becoming saturated. The underdrain can be constructed using slotted pipes or geocellular units. It should be wrapped in a geotextile to minimise the risk of fine soil particles and sediment being carried into it. The underdrains must connect to positive outflow. The gravel around the underdrain should comprise a 12.5–25 mm sized aggregate (In the UK the closest standard specification is a 20 mm to 5 mm aggregate in accordance with British Standard BS 882:1992). Geotextiles should be correctly designed to suit the required permeability and filtration requirements (Section 5.12). The underdrains (especially the side slots) must have a greater hydraulic capacity than the surrounding soils. An observation cleanout pipe should be provided to the underdrain that is securely capped to prevent vandalism.

An example detail for a bioretention area is shown in Figure 9.4.2.

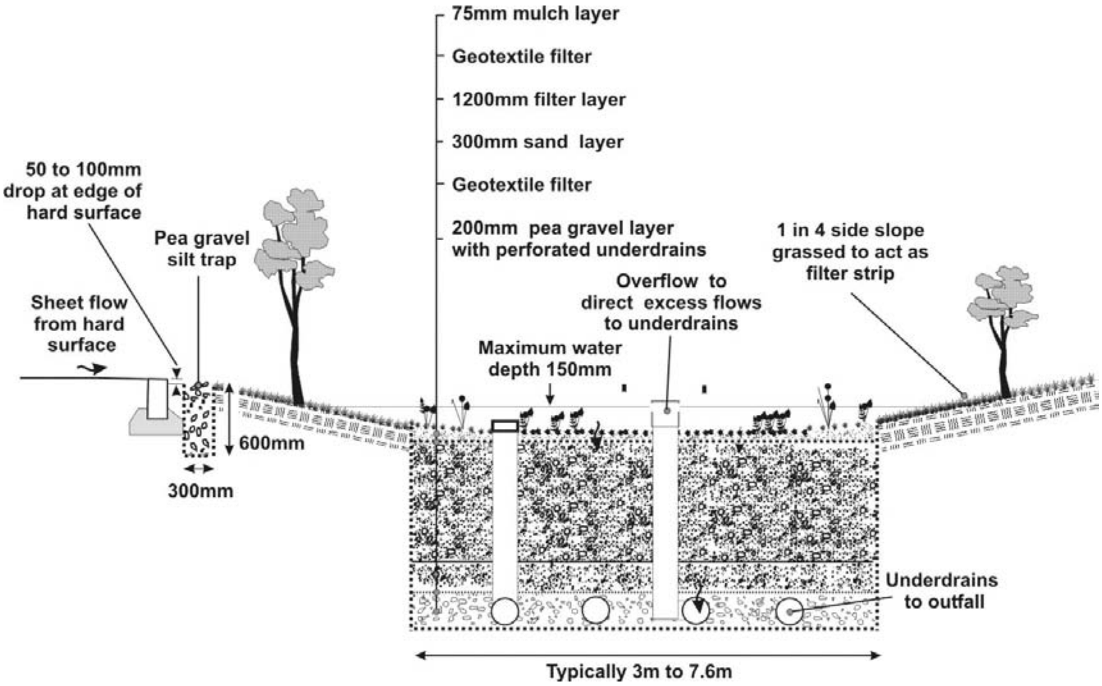

Figure 9.4.2 *Example detail of a bioretention area*

Various geotextile filters can be provided within the construction to stop the migration of fines between layers and to trap hydrocarbons. A shallow geotextile provided at 150 mm depth into the soil filter is useful to keep clogging and the retention of hydrocarbons as high in the system as possible to aid maintenance.

Various design guides for bioretention areas also specify minimum lengths, length/width ratios and other criteria to ensure that bioretention areas perform as required (Table 9.4.5).

Table 9.4.5 *Design criteria for bioretention areas*

Criteria	Claytor and Schueler (1996)	Bitter and Bowers (2000)	Winogradoff (2002)	Minnesota Metropolitan Council (2001)
Minimum length	4.6 m	12 m	—	12.2 m
Minimum width	3 m	4.6–7.6 m	—	4.6 m
Length/width	2:1 (for widths greater than 3 m)	—	—	—
Maximum slope	—	20% longitudinal	2–20% (use weep gardens design if steeper)	Less than 5%
Maximum entry velocity	—	0.91 m/s	—	—
Groundwater depth	Greater than 1 m below base of underdrain	—	Greater than 1 m below base of underdrain	Greater than 1 m below base of underdrain

Similar design requirements are also quoted in other guidance from the USA (New Jersey Department of Environmental Protection, 2000 and the United States Environmental Protection Agency, 1999a).

The minimum widths quoted allow random planting of trees, which increases the planting density and provides a more robust planting that can withstand pollutants. The 2:1 ratio of length to width maintains a longer flow path to promote settling of sediment from the runoff.

Inlets

The inlet to the bioretention area is required to divert the water quality treatment volume into it and then allow runoff in excess of this to flow to the normal drainage system. Various methods are available, as shown in Figure 9.4.3.

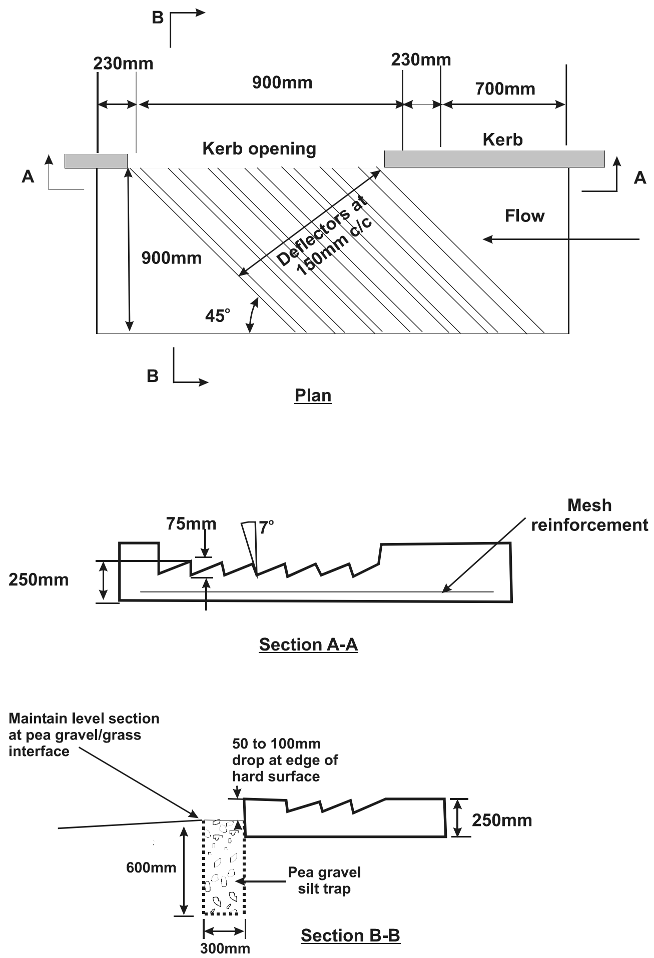

Figure 9.4.3 *Diversion structures to bioretention areas (Claytor and Schueler, 1996)*

A gravel filter is also provided where lateral flow from a car park occurs to act as a pre-treatment mechanism. Alternatively, a 3 m-wide grassed filter strip can provide pre-treatment. Providing pre-treatment is extremely important to prevent clogging by sediment. A permeable pavement could also outflow into a bioretention area and would provide adequate pre-treatment.

9.4.6 Construction

To minimise erosion and sediment generation, bioretention areas should ideally be constructed at the end of development. If this is impractical, they should be protected from silt-laden runoff using silt fences or straw bales as recommended in CIRIA C532 *Control of water pollution from construction sites* (Masters-Williams, 2001). If this is not done the bioretention area may silt up and require reconstruction (see Chapter 6).

The following watch points should be closely monitored during construction to minimise the risk of early failure of the system once it has been handed over to the client.

1 The filter and soil planting bed should not be compacted. The soil should be placed in 200–300 mm lifts to aid natural compaction.

2 The bioretention area should be excavated using a backhoe excavator and the construction plant should avoid running over the bioretention area, to minimise compaction of the natural soils.

3 Mulch should not be piled up around plants as this will cause disease and encourages pests.

4 Care should be taken to ensure geotextiles are not clogged or torn during construction. If they are damaged they must be repaired or replaced.

   Independent inspections combined with good site CQA procedures are essential to ensure that a reliable and durable bioretention area is produced (Chapter 6).

5 Testing of the imported soil for the filter layer should be carried out. One particle size distribution, pH and organic matter test should be undertaken per retention area.

9.4.7 Planting

Originally bioretention areas were designed to simulate a terrestrial forest community of native species dense and robust enough to withstand the stress of urban situations and pollution from runoff. Aesthetics and visual amenity are prime considerations in the choice of plants and the advice of a landscape architect will be necessary.

The same considerations apply as for a swale in Section 9.7 with the choice of planting based on the following three zones.

1 **Upland area**. Planted with trees along the boundary of bioretention area to form a canopy with an under-storey of trees, shrubs and herbaceous plants

2 **Lower layer**. Use plants adapted to standing and fluctuating water levels

3 **Middle layer**. Slightly drier area, but can still use plants that can tolerate fluctuating water levels.

The most recent US design guidance (Winogradoff, 2002) gives more flexibility in planting by allowing a wider range of species to be used. It still recognises that different areas of the facility will be subject to different zones of saturation. It allows plants that cannot tolerate saturated conditions to be placed around the outside at higher levels and where appropriate shade is provided by trees.

It is important to use native species in bioretention areas, as this helps to ensure development of a dense, durable cover of vegetation. A minimum of three tree and three shrub species should be used to give a diversity that protects against insect attack and disease. The planting will also give a more consistent rate of evapotranspiration and pollutant and nutrient uptake.

Perennials should be planted along the edge of the retention area, where colour and seasonal interest are required. Herbaceous ground cover should be provided to protect the mulch from erosion (three or four species at least). The ratio of shrubs to trees should be from 2:1 to 3:1 and the planting should have a random and natural layout.

Woody species should not be planted near to inlets and outlets as they cause blockage from falling debris and leaves. A list of suitable plants for use in bioretention areas is provided in Appendix 5.

Ornamental garden

Ornamental planting can also act as a bioretention area where aesthetics are of key importance. The retention area should be considered as a mass bed planting so that foliage will cover the entire area at the end of a second growing season.

A variety of species should be used to give year-round interest, with perennials giving colour from spring to autumn and ornamental grasses and evergreen or berry-producing shrubs ensuring that the area remains visually acceptable during the winter. Low-maintenance ornamental species are preferred.

Open space meadows

A useful technique is to use bioretention planted as meadows, which significantly reduces the maintenance requirements (Winogradoff, 2002). In this case, the planting is a variety of ornamental grasses interlaced with various wildflowers.

Table 9.4.6 *Maintenance requirements for bioretention areas (after USEPA, 2002)*

Operation	Frequency
Inspections to identify any areas that are not operating correctly, infiltration surfaces that have become compacted, silt-laden or ineffective for any reason. Record any areas that are ponding and where water is lying for more than 48 hours. Report to client.	Monthly
Collect and remove from site all extraneous rubbish that is detrimental to the operation of the SUDS and the appearance of the site, including paper, packaging materials, bottles, cans and similar debris.	Monthly
Mulching – remove and replace.	Annual
Reinstate design levels, restore or improve infiltration and remove silt by removing existing or damaged vegetation and reinstatement of surface to design levels. Remove damaged or silt covered vegetation to a depth 50 mm below the original design level and cultivate to a fine tilth. Returf using turf of a quality and appearance to match existing using additional fine-sieved topsoil to BS 3882:1994 to achieve final design levels. or: Reseed to BS 7370:Part 3:1991, Clause 12.6 using seed to match existing turf in appearance and quality. Supply and fix fully biodegradable coir blanket as supplier's instructions to protect seeded soil. Allow to top-dress with fine-sieved topsoil to BS 3882 to achieve final design levels. Provide protection and watering to promote successful germination and/or establishment.	As required – say 5 per cent of area annually
Treatment and restoration of eroded areas as above.	As required – say 5 per cent of area annually
Treatment of diseased trees.	As required
Weeding.	As required – say annually
Pruning and trimming of trees.	Every two years – recycle back into mulch
Spiking and scarifying to maintain filtration. Thatch is a tightly intermingled organic layer of dead and living shoots, stems and roots, developing between the zone of green vegetation and the soil surface. To improve infiltration performance, break up silt deposits. To prevent compaction of the soil surface it should be scarified with tractor-drawn or self-propelled equipment to a depth of 5 mm to relieve thatch conditions and remove dead grass and other organic matter. Thatch removal should be carried out in conditions that are dry and free from frost. Perforate the soil surface using tractor-drawn or self-propelled spiker to penetrate panned layers to a depth of 100 mm and allow water to percolate to the more open soil below. Follow by top dressing with a medium to fine sand. Spiking is particularly effective when the soil is moist.	Every three years when mulching

9.4.8 Operation and maintenance

The useful life of a bioretention area is directly related to the frequency of maintenance and effective operation is dependant on maintenance. If correctly designed and maintained bioretention areas can last indefinitely. The recommended maintenance schedule for bioretention areas is provided in Table 9.4.6.

All the maintenance for bioretention areas can be undertaken as part of landscape maintenance and therefore it will have marginal cost implications if the latter is already required. The nutrients in a bioretention area are normally elevated due to their presence in the runoff and the use of a mulch layer. There should be no need to apply additional fertiliser, which will increase pollution of runoff from the systems.

9.5 FILTRATION TECHNIQUES

Box 9.5.1 *Key considerations for filter design*

Description

Constructed tank or lagoon whose base contains a filter material through which water percolates, to promote pollution removal.

Design criteria

- Pre-treatment volume equal to 25–40 per cent of the water quality volume for the catchment
- provide sufficient surface area to store the water quality volume as a thin layer on the surface (maximum 150 mm deep)
- calculate infiltration time through filter based on permeability of filter and head of water. Minimum time of infiltration to be 40–48 hours
- combined sedimentation and filter chamber to provide a total volume greater than 75 per cent of the water treatment volume
- the maximum head of water that can develop in the sedimentation chamber must be greater than twice the average height of water above the filter device to prevent backflow of water in the system
- length to width ratio of the sedimentation chamber should be a minimum of 2:1.

Pollutant removal

Good when maintained.

Applications

Suitable for use on most commercial or institutional sites and in most ground conditions. Where surface space is restricted underground, perimeter and pocket filter systems are all ideal as they take up very little surface space.

Limiting factors

- Limited to a maximum catchment size of between 0.8 ha (perimeter or underground filters) and 4 ha for surface filters
- difficult to use on very flat sites with shallow outfalls because of the head drop required.

Maintenance

- Monthly inspections and blockage removal
- monthly litter removal
- monthly mowing or grass to maintain height
- replace sorbent pillows where provided as required (every six months)
- annually reinstate eroded areas or damaged vegetation
- annual removal of sediment.

9.5.1 Description

Filtration devices are used to treat the pollution in stormwater runoff. There are many different variations but the most common ones use a filter material to filter out and adsorb the pollutants. The filter material may be sand, gravel, peat or compost or a combination of these. Originally filters were developed as sand filters in Texas as most other types of treatment technique were unsuitable for the area, because of climatic, ground and groundwater conditions.

They usually comprise a two-chamber system in which the first chamber is a wet pool used to allow sedimentation of coarser solids within the runoff. Finer particles and other pollutants are removed as the water passes through the filter medium. Excess flows above the filter's capacity are diverted using an overflow. They can be installed as surface filters, underground filters and perimeter filters (Figure 9.5.1).

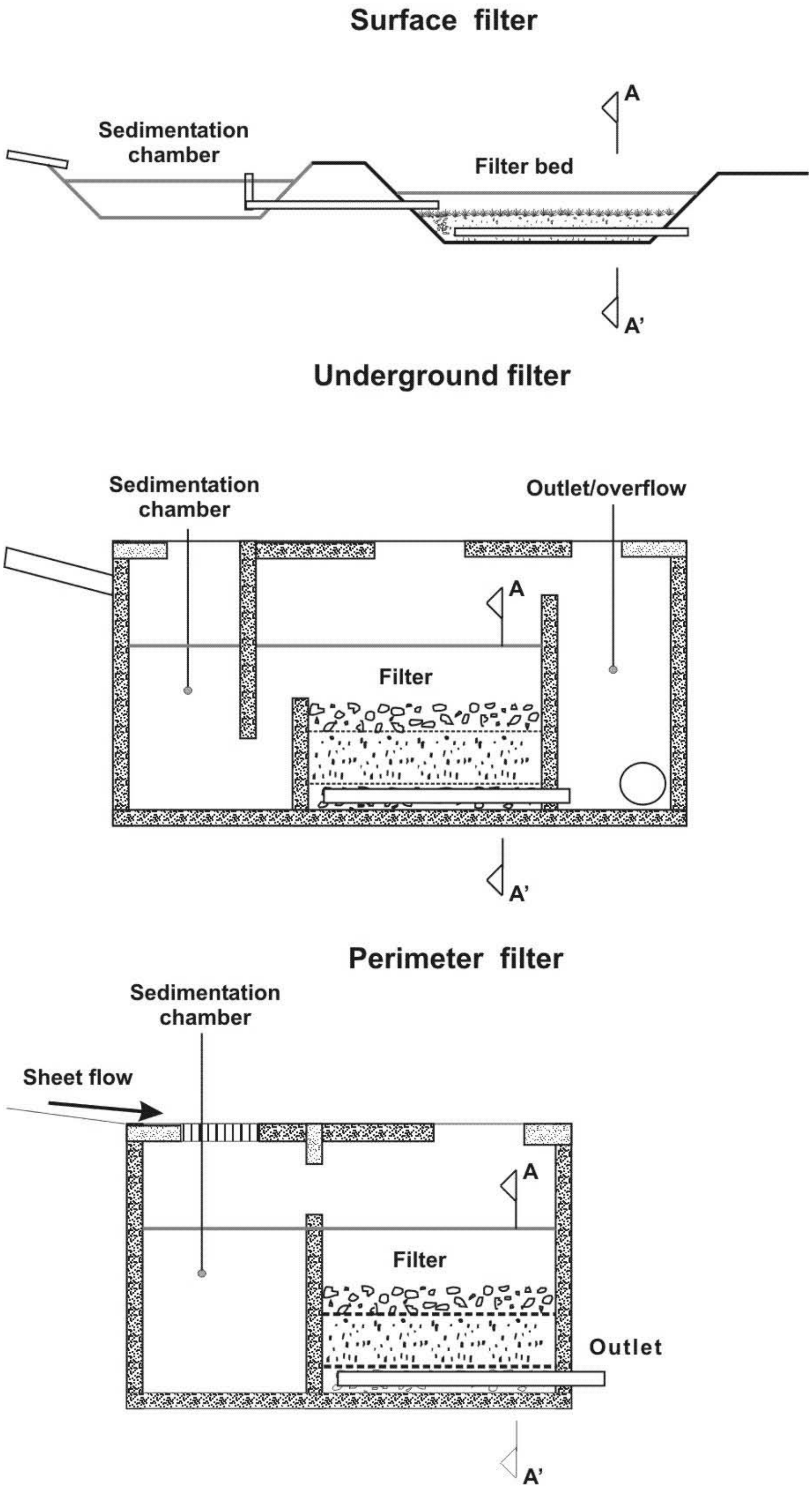

Figure 9.5.1 *Types of filtration device (after Claytor and Schueler, 1996)*

Surface and underground filters are usually constructed off-line to treat the water quality volume. Perimeter filters are located on-line (where they have to be designed to treat the full range of likely flows) and are provided with an overflow for larger storm events.

There are four basic elements to any filter design.

1. Flow diverter to divert water quality treatment volume into the filter.
2. Pre-treatment to remove coarse sediment from the runoff.
3. Filter medium.
4. Outflow mechanism to divert treated water back to the conveyance system.

The outflow from a filtration device can be either to a piped or other conveyance system or the treated runoff may be infiltrated to the ground if the soil and groundwater conditions are suitable. An overflow is also required to deal with excess flows that enter the filter. There are many different design variations and proprietary systems that have been developed to meet site-specific constraints and to improve pollutant removal. Filtration devices should not be confused with infiltration devices which are discussed in Section 9.8.

9.5.2 Suitable applications

Filters have very few limitations and constraints on use when compared with other SUDS techniques. Filtration devices are suitable for use on most commercial or institutional sites and in most ground conditions. On urban sites where surface space is restricted underground, perimeter and pocket filter systems are all ideal, as they take up very little surface space. Care is required when approving them for use in residential areas unless maintenance can be guaranteed, and they should not be used for individual houses because of the maintenance requirements (Schueler, 2000o).

Where the outfall from the filtration device is to a piped system, the sand filters may be used in stormwater hotspots. Surface filters should normally be lined with an impermeable geomembrane. If no lining is provided they should be located at least 1 m above the groundwater table to prevent contamination.

Filtration techniques are usually limited to a maximum catchment size of between 0.8 ha for perimeter or underground filters and 4 ha for surface filters (USEPA, 2002), although larger sites may be split into sub-catchments. The larger the area of the catchment the more intensive maintenance is required due to increased sediment loads.

Filters are more difficult to use on very flat sites with shallow outfalls because of the head drop required to drive flow through the system (typically 1.5–2.5 m head is required, although perimeter filters can operate with a driving head as low as 0.3 m).

9.5.3 Advantages and disadvantages

The advantages and disadvantages of filters are summarised in Table 9.5.1.

Table 9.5.1 *Advantages and disadvantages of filters*

Advantages	Disadvantages
Can be used on most sites to treat the water quality volume	Filters only deal with the water quality volume
Can be designed to take up little space so ideal in urban sites	High maintenance burden and quickly lose performance if not maintained
Versatile and adaptable	Cannot treat large catchment areas
Perimeter filters useful on sites such as lorry parks where there is limited landscaping	Out of sight – so may be forgotten
	Do not provide amenity and are not aesthetically pleasing
	Drainage levels must be able to provide a minimum head of 0.9 m between the inlet and outlet to provide gravity flow (0.3 m for perimeter filters)

9.5.4 Performance

Pollutant removal

Filtration devices are relatively good at removing most of the common pollutants in stormwater. Exceptions to this are nitrates, which appear to be exported from filtration systems (USEPA, 1999g). This may be due to mineralisation of organic nitrogen in the filter bed. Organic filters should, in theory, have greater removal rates than sand filters, but there is little evidence to prove this and their improved pollutant removal is generally gained at the expense of increased maintenance.

Filters provide excellent removal of suspended solids, which is to be expected as filtration is successful at removing particulates from stormwater (Claytor and Schueler, 1996). Much of the particulate load is removed by the initial sedimentation chamber (Schueler, 2000p), which is a vital feature of effective treatment. The removal of particulates also leads to good metal removal, since a large proportion of the metals present in runoff are attached to particulates. Filters are also good at removing hydrocarbons and their efficiency improves with increasing pollutant load.

They are only moderately successful at removing dissolved pollutants, and Schueler (2000o) found that removal efficiencies for bacteria, ammonia and orthophosphorous were variable. They also have modest phosphorous removal capability (Schueler, 2000p) and bacteria removal (Schueler, 2000q, reported that sand filters gave removal rates of 51 per cent for faecal coli form and 58 per cent for faecal streptococci).

If high levels of nutrient or bacteria removal are required then other techniques should be used, or the filter combined with other techniques. It was reported that the filters are most effective at pollutant removal when combined with a retention pond.

A study of sand filters in Austin, Texas, found that off-line systems provided higher pollutant removal efficiencies than on-line systems (Tenney *et al*, 1995). It noted that if sediment was left to build up on the surface of the filter bed drainage took several days.

The removal efficiencies for sand filters are provided in Table 9.5.2.

Table 9.5.2 *Pollutant removal efficiencies for filters*

	Removal efficiency (per cent)										
	USEPA, 1999g [2]	**USEPA, 1999g [2]**	**USEPA, 1999g [2]**	**USEPA, 1999g [2]**	**Claytor and Schueler, 1996 [3]**	**Claytor and Schueler, 1996 [3]**	**Claytor and Schueler, 1996 [3]**	**Schueler, 2000p**	**Tenney *et al*, 1995**	**Atlanta Regional Commission, 2001**	**Design values from Section 3.4.2 of this book [1]**
Type of filter	Peat/sand	Compost	Perimeter sand filter	Surface sand filter	Surface and under-ground filter	Perimeter sand filter	Organic sand filter	Compost	Off-line and on-line sand filter [4]	Sand	
Method of estimation	Unknown	Unknown	Unknown	Unknown	Mainly mass loading	Mainly mass loading	Mainly mass loading	EMC	Mass loading	Unknown	
Total suspended solids	66–95	85–95	8–83	75–92	85	80	95	43	70–87	80	80–90
Nitrate/nitrogen	47	–	47	27–71	35	45	35	–	18–32	25	25–40
Total phosphorous	51	4–41	20–65.5	19–80	55	65	40	-88	3–61	50	50–80
Hydrocarbons	–	–	–	–	55–84	80	90	20 [5]	–	–	50–80
Cadmium								–			
Copper	26–75	61–87	22–91	33–91	35–90	–	85	33	19–86	50	50–80
Lead								50			
Zinc								29			

Notes

1 Use lower values for sites where maintenance may not occur or to give increased confidence that design parameters will be met.

2 Includes some data from other references.

3 Averages of reported monitoring data and includes data from other references.

4 Lower values for on-line sand filter.

5 With low inflow concentration.

It is important to note that there is a limit to the concentrations of pollutants that SUDS techniques can remove from runoff. Once this level is reached no further improvement in quality is possible using SUDS techniques. The irreducible pollutant concentrations for sand and organic filters are provided in Table 9.5.3.

Table 9.5.3 *Irreducible pollutant concentrations for sand and organic filters (Claytor and Schueler, 1996)*

Parameter	Irreducible concentration (mg/l)
Total suspended solids	19.3 +/- 10.1
Total phosphorous	0.14 +/- 0.13
Total nitrogen	1.93 +/- 1.02

This was also demonstrated by a study of the performance of sand filters to remove phosphorous (Schueler, 2000r). As the phosphorous concentration in the inflow of stormwater reduces so does the removal efficiency of the sand filter (Figure 9.5.2).

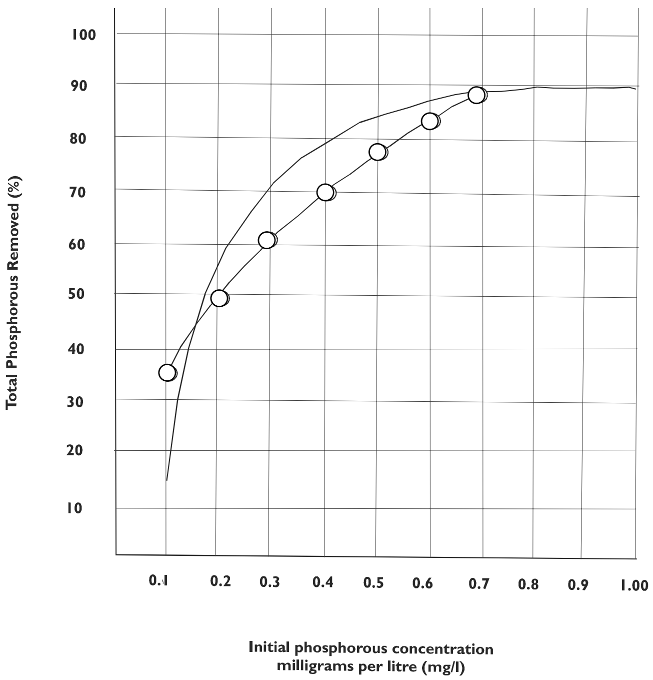

Figure 9.5.2 *Variation of phosphorous removal efficiency with inlet concentration (Schueler, 2000r)*

The performance of various filter media in laboratory tests (0.5 mm–1 m filter sand, zeolites, concrete aggregate sand, compost and pea gravel) was studied in the USA (Tenney *et al*, 1995). For all types of filter media tested, they found there was a trade-off between the hydraulic performance of the filter and the pollutant removal (Figure 9.5.3). They also found that compost quickly breaks down and requires frequent replacement. The most effective performance was provided by medium sand with a grain size between 0.5 mm and 1 mm. Pea gravel had no pollutant-removal capabilities.

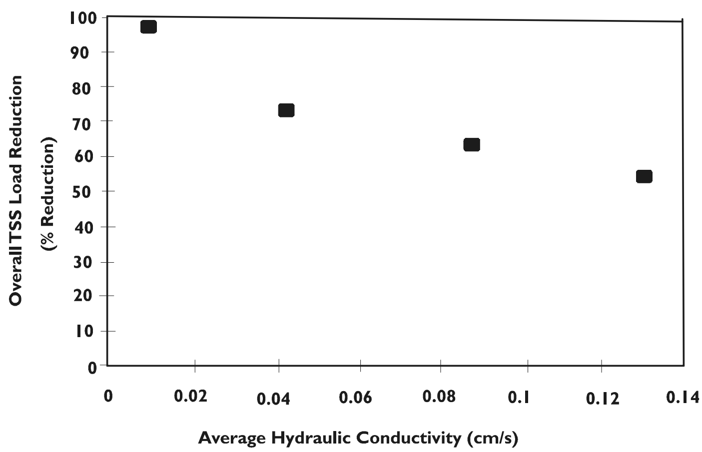

Figure 9.5.3 *TSS reduction and hydraulic conductivity (Tenney* et al*, 1995)*

Hydraulic performance

Filters are usually designed as a water quality technique and there is little available data on their hydraulic performance. The most important hydraulic aspect is clogging, which is a particular problem due to runoff from pervious areas (landscaping etc). To reduce the rate of clogging and associated maintenance, filters should only be used to treat runoff from impervious areas (Schueler, 2000r).

Monitoring of the performance of a sand filter in Denver found that as sediment built up on the surface of the filter, the hydraulic capacity reduced (Urbonas, 2000). Flow through the filter rapidly reduced from an initial rate of 7.3 m/day to 0.5 m/day and then stabilised at 0.37 m/day after a few storms. A layer of sediment some 1.6 mm thick caused this reduction and led to increased bypass flows and a lower overall TSS removal rate of 45 per cent (Figure 9.5.4).

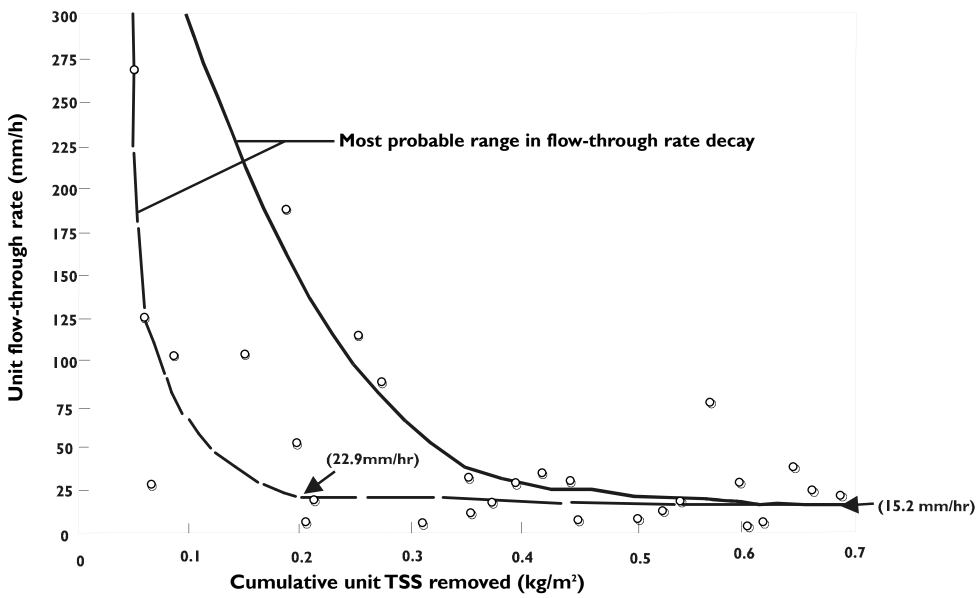

Figure 9.5.4 *Flow rate versus cumulative TSS removed (Urbonas, 2000)*

Standard sand filters seem to be less prone to clogging than compost or other special filter media (Schueler, 2000p).

9.5.5 Design criteria

Soil and groundwater requirements

Filters can be used in most ground conditions. They should normally be lined to prevent exfiltration unless specifically designed for this. If unlined they should be located at least 1 m above the groundwater table.

Hydraulic design

Pre-treatment is an extremely important and integral element of the filter operation. This should be achieved in a sedimentation chamber that precedes the filter bed. Pre-treatment improves pollutant removal and also reduces the maintenance requirements for the filter bed. Pre-treatment should be equal to 25 per cent of the water quality volume for the catchment (USEPA, 1999g and Maryland Department of the Environment, 2000). For areas with a high sediment load this should be increased to 40 per cent. For surface filters the sedimentation chamber can be wet or dry, and for the underground and perimeter filters it has a permanent wet pool.

The most common method of calculating the area of the sedimentation chamber is to use the Camp-Hazen equation:

$$A_s = (Q_o / W) \ln (1 - E) \qquad (9.5.1)$$

Where:

A_s = surface area (m^2)

Q_o = discharge rate from basin (water quality volume/detention time) (m^3/s)

W = particle settling velocity (m/s)

E = removal efficiency – typically assumed to be 90 per cent (0.9)

The minimum detention time in the filter system should be 24 hours.

The combined sedimentation and filter chamber should also provide a total volume equal to at least 75 per cent of the water treatment volume to allow temporary storage before it flows through the filter. This may be reduced if detailed analysis of the rainfall and outflow from the system shows a lower volume is acceptable.

An over-flow weir should be provided in the sedimentation chamber or filter chamber and should be set to operate if the design treatment volume is exceeded, it should also be sized to pass two thirds of peak flow associated with water quality volume.

Flow should be diverted into the filter chamber so that even flow occurs over the filter bed to prevent scour or erosion. The maximum head of water that can develop in the sedimentation chamber must be greater than twice the average height of water above the filter device to prevent backflow of water in the system.

The length-to-width ratio of the sedimentation chamber should ideally be a minimum of 2:1 (Maryland Department of the Environment, 2000) although this is usually only achievable for surface filters where there are no space constraints.

Other specific dimensions are quoted in many US design manuals, such as minimum depths for the sediment chamber. There is no clear reason for this, however, and justification is not provided, therefore it is recommended that the filters are designed on the basis of the preceding criteria only.

Pollutant removal

The design of filters to remove pollutants is the same as for the bioretention areas discussed in Section 9.4. The water that percolates through the filter should be retained within it for at least 40 hours in order to maximise filtration and adsorption (Claytor and Schueler, 1996). Other guidance proposes a similar requirement, recommending that a bioretention system should dewater within 48 hours of a design storm occurring (Winogradoff, 2002).

The surface area required to achieve this can be calculated using the following equation:

$$A_f = Q_{wq} \times d_f / [(k \times (h + d_f)(t_f)] \qquad (9.5.2)$$

Where:

A_f = surface area of filter bed (m^2)

Q_{wq} = water quality treatment volume (m^3)

d_f = filter bed depth (m)

k = coefficient of permeability of filter medium for water (m/s)

h = average height of water above filter bed (half maximum height) (m)

t_f = time required for water quality treatment volume to percolate through treatment bed (s)

It is important that the coefficient of permeability for the filter medium used in design allows for reduction due to clogging (see Figure 9.5.4).

Pollutant removal can be enhanced by including other treatment methods within the filter. One filter was provided with sorbent pillows in the sedimentation chamber to adsorb pollutants (especially hydrocarbons). Fine bubble aerators and inclined plate settlers may also be used (Center for Watershed Protection, 2000a).

It is possible to estimate the maximum capacity of filter materials to adsorb contaminants (and so estimate the likely replacement intervals) using techniques described in Section 9.4.

Erosion

Sheet flow must be developed over the filter bed to prevent erosion. For surface sand filters the inlet should also be designed to prevent erosion of the sides and base of the sedimentation chamber or basin.

Extreme events

The inlet to the filter system should be designed so that extreme events bypass the filter (filters are normally designed only to treat the water quality volume for a site).

Design details

Specific design details for filters are shown in Figures 9.5.5, 9.5.6 and 9.5.7. Specific requirements include the following based on guidance from the USA:

- the filter medium is typically 0.45–0.6 m thick or 0.6 m thick for a perimeter filter. The overlying topsoil or gravel layer should be around 75 mm thick
- the provision of a geotextile at the top of the filter, below a gravel or topsoil layer, will collect sediment and prevent clogging occurring deeper in the filter so that only the surface layer and geotextile needs to be removed to regenerate filter
- the minimum depth of permanent water in the sedimentation chamber for underground and perimeter filters is normally 0.6–0.9 m
- filters should be located where they can intercept as much of the runoff from the site impervious area as possible, and where they can be connected to the main conveyance and retention system of the site. Off-line systems are preferred as they avoid re-suspension of particles in heavy storms.
- filters must have an underdrain, which should be sized to carry the volume of water that will percolate through. They provide positive drainage through the filter and prevent dead spots, which may become anaerobic and release previously captured phosphorous. Inspection/cleanout wells should be provided to the underdrain. The underdrain should be laid in a gravel bed, which is normally a minimum of 150 mm thick and 10–20 mm grain size. Alternatively, geocellular units may be used for the underdrain. Underdrains should have a minimum gradient of 0.5–1 per cent. The minimum pipe size should be 150 mm.

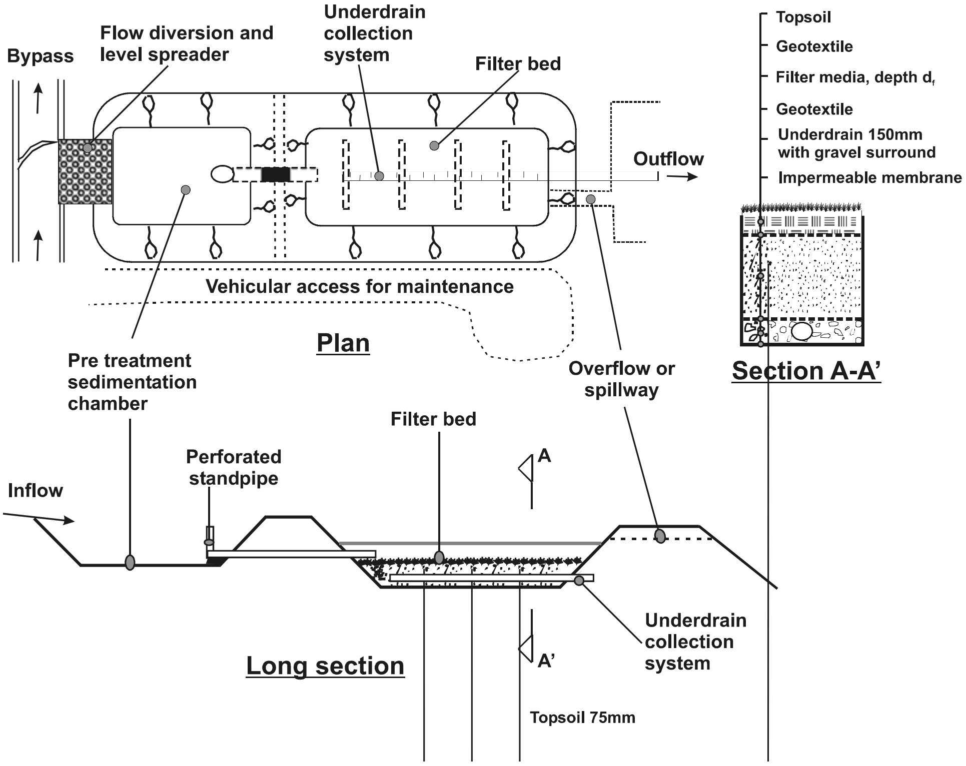

Figure 9.5.5 *Example details for surface sand filter (Maryland Department of the Environment, 2000)*

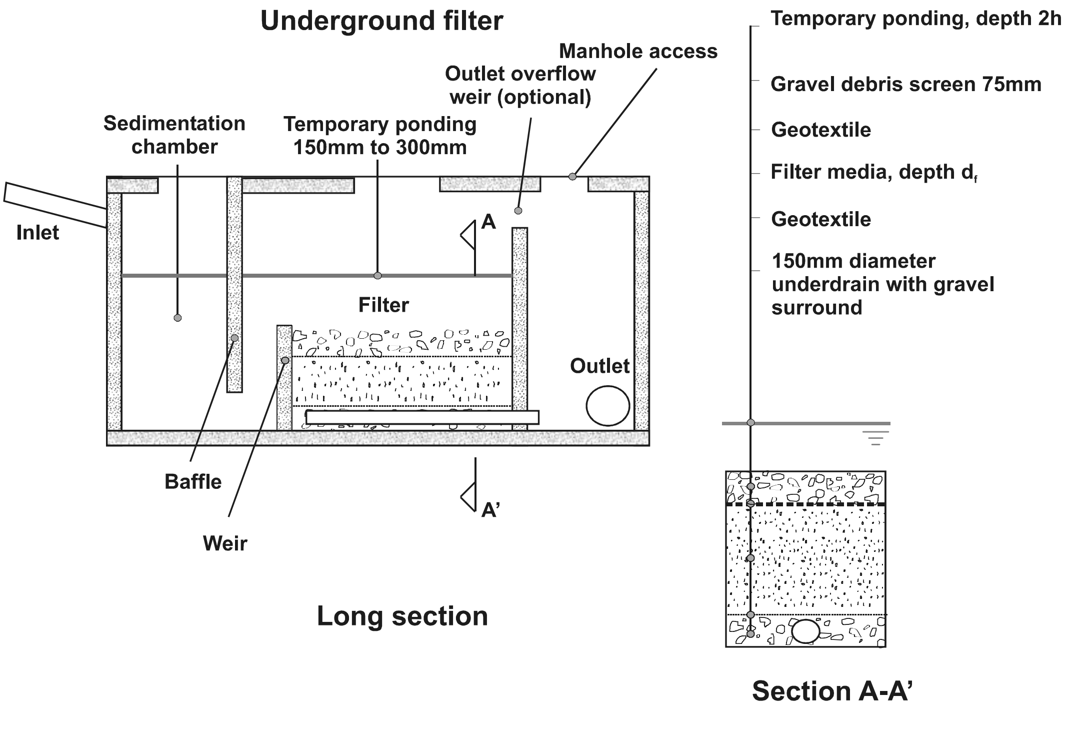

Figure 9.5.6 *Example details for underground sand filter (Atlanta Regional Commission, 2001)*

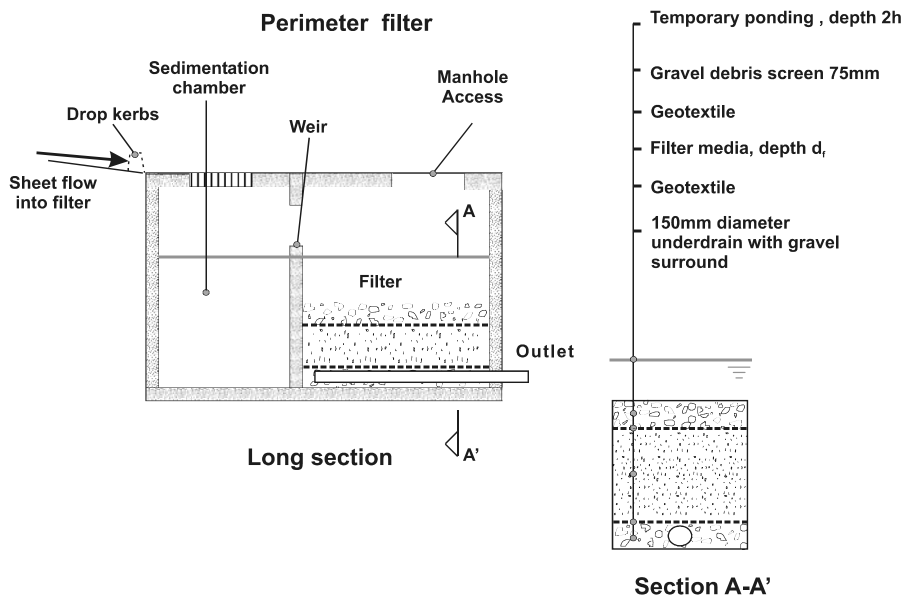

Figure 9.5.7 *Example details for perimeter sand filter (Claytor and Schueler, 1996)*

The sand provided in the filter should be specified to meet the required hydraulic criteria. A sand with grain sizes of 0.5–1 mm often gives the best balance between hydraulic capacity and pollutant removal.

However, other specifications have been used such as that provided in Table 9.5.4.

Table 9.5.4 *Specification of sand for sand filters (City of Portland Environmental Services, 2002)*

Sieve size (nearest UK equivalent)	Percentage passing by mass City of Portland Environmental Services (2002)
10 mm	100
5 mm	95–100
2.36 mm	80–100
1.18 mm	45–85
600 µm	15–60
300 µm	3–15
150 µm	< 4
75 µm	—

If geotextiles are used in the filter system the pore size and permeability should be specified to suit the flows required and the likely particle size that will require retention.

Wherever possible, filters should be visible and signed so that they are recognised as components of a SUDS scheme. The location should also be shown in the owner's manual (Section 7.2).

The design should allow easy access for maintenance. There is a need to remove heavy wet sand from the system, usually by hand, and access should be designed to allow this.

Inlets

The inlet to the filter is required to divert the water quality treatment volume into it and then allow runoff in excess of this to flow to the normal drainage system. A simple method is to provide an overflow weir in a manhole. The inlet to the filtration device is sized to carry the peak discharge for the water quality volume, and the flow over the weir and through the overflow pipe is designed to carry the flow from the maximum design storm for the site.

9.5.6 Construction

During construction, runoff should not be allowed to enter the filter as this will clog it before it becomes operational. It is important that the top of the filter bed is completely level otherwise filtration will be localised and early failure may occur. In areas where groundwater protection is a concern the completed tank structure (concrete or membrane) should be filled with water for 24 hours to allow leakages to be identified.

9.5.7 Planting

Where a surface filter is covered with topsoil, planting should be with species that will not inhibit infiltration and are low maintenance.

9.5.8 Operation and maintenance

The effective operation of filters is dependent on frequent maintenance. The design should allow easy access to all types of filters so that the filter medium can be replaced. For underground and perimeter filters, entry into confined spaces needs to be considered and the appropriate health and safety regime put in place. The recommended maintenance schedule for filtration devices is provided in Table 9.5.5.

Table 9.5.5 *Maintenance requirements for filters*

Operation	Frequency
Inspections to identify any areas that are not operating correctly, blockages to inlets and outlets, infiltration surfaces that have become compacted, silt-laden or ineffective for any reason. Record any areas that are ponding and where water is lying for more than 48 hours. Report to client.	Monthly
Collect and remove from site all extraneous rubbish that is detrimental to the operation of the SUDS and the appearance of the site, including paper, packaging materials, bottles, cans and similar debris.	Monthly
Check that the surface of filter bed is not blocked by algal matter, silts or organic matter, and remove and replace the surface filter medium as necessary. Also remove any weeds from surface filter.	Monthly (Schueler, 2000o reported that this is vital if filters are to continue functioning)
Maintain grass height within the specified range, where provided in surface filters. Ensure that soil and grass does not become compacted. Do not cut during periods of drought or when ground conditions or grass are wet, without prior agreement.	Monthly
Replace sorbent pillows where provided.	Six-monthly
Remove sediment (see Section 7.3 and 7.6 and below).	Annually or when exceeds 15 mm on filter bed or 300 mm in sedimentation basin
Reinstate design levels, repair eroded or damaged areas by returfing or reseeding, restore or improve infiltration and remove silt by removing existing or damaged vegetation and reinstatement of surface to design levels.	Annually

Testing of sediment from a sand filter found levels of contamination similar to ponds, so similar disposal regimes can be used (Schueler, 2000o). Disposal of sediment from SUDS systems is discussed in more detail in Section 7.3.

9.6 GRASSED FILTER STRIPS

Box 9.6.1 *Key considerations for grass filter strip design*

Description

Wide, relatively gently sloping areas of grass or other dense vegetation that treat runoff from adjacent impermeable areas.

Design criteria

- Max length of impermeable area flowing to strip is 23 m
- the flow across the filter strip can be determined using Manning's equation for overland sheet flow
- maintain sheet flow with water depths less than 50 mm
- minimum residence time of 5 minutes.

Pollutant removal

Moderate.

Applications

Most suited to small car parks, roads and similar areas.

Limiting factors

- Require a large amount of space
- should not be used to treat hotspot runoff if infiltration is likely.

Maintenance

- Monthly inspections
- monthly litter removal
- monthly mowing
- scarifying and spiking as required
- remove silt, replace damaged vegetation as required.

9.6.1 Description

Grassed filter strips are wide, gently sloping areas of grass or other dense vegetation that are designed to treat runoff from adjacent impermeable areas. The runoff is designed to sheet flow across the filter strip sufficiently slowly to filter out sediment and associated pollutants.

They were originally used as a treatment practice in the USA to deal with polluted runoff from agricultural areas but were developed for use in urban areas as well. They are often employed as a pre-treatment technique before other SUDS techniques to reduce the risk of silting.

Two filter strip designs are used. The first is simply a relatively flat area (Figure 9.6.1). A more complex design uses a grass berm at the toe of the filter strip slope to provide a small dam that holds the water and increases settling of sediment. The berm is constructed using permeable material so that the runoff slowly flows through it.

Figure 9.6.1 *Grassed filter strip*

9.6.2 Suitable applications

The main restriction to the use of filter strips is the amount of space they require. They are most suited to small car parks, roads and similar areas but are not generally suitable for use in dense urban developments unless the filter strip has a dual purpose – for example, as landscaping or as an open area. They can be used in any soil conditions but are not suitable for treating hotspot runoff if infiltration is likely to occur and the risks to groundwater are unacceptable.

Filter strips are designed to treat sheet flow from adjacent impermeable surfaces. They should not be used to treat runoff that has been collected via gullies or any other system that concentrates flows (New Jersey Department of Environmental Protection, 2000).

Filter strips should be used to treat only very small drainage areas. For a flow path longer than 23 m, flow over impervious surfaces changes from sheet flow to concentrated flow. Once flow is concentrated, the velocities are too great for filtration to be effective in removing sediment (USEPA, 2002).

9.6.3 Advantages and disadvantages

The advantages and disadvantages of filter strips are summarised in Table 9.6.1

Table 9.6.1 *Advantages and disadvantages of grassed filter strips*

Advantages	Disadvantages
Effective pre-treatment to help ensure long-term performance of other SUDS techniques	Require a large amount of space
Can encourage evaporation and, if soil conditions are suitable, infiltration	Care required to achieve even gradient in construction
Very low maintenance	Only moderate pollutant-removal efficiency
Easily integrated into landscaping	Limit to size of impermeable area they can serve

9.6.4 Performance

Pollutant removal

Pollutant removal in filter strips is highly variable (Atlanta Regional Commission, 2001) and depends on the soil and type of vegetation provided. Soluble pollutants may also be removed indirectly if the runoff infiltrates the soils and is adsorbed or taken up by vegetation. This removal mechanism depends on the type of soil and vegetation.

The results of studies into the performance of filter strips in the USA indicate that flow velocities need to be kept low (below 0.76 m/s) to promote pollutant removal and that a flow spreader should be used for distribution of runoff (Walsh *et al*, 1997).

Two filter strips next to highways in Texas with a treatment length of 7.5–8.8 m were also monitored. These had relatively high removal rates, probably because the strips were taking runoff from a relatively small impermeable area and had low flow velocities. The results of the study are summarised in Table 9.6.3. A sediment lip developed at the edge of the paved area where runoff ran into the filter strip, eventually preventing flow and causing it to concentrate in other areas. This can be prevented by providing a drop to the strip (Figure 9.6.2).

An assessment of the risks posed by the presence of retained pollutants in filter strips (especially the heavy metals) concluded that the rate of loading would give a design life of between 244 and 1202 years before the metals in the strip would be considered hazardous to health (Walsh *et al*, 1997). The loading rates are summarised in Table 9.6.2 and typical examples of pollutant-removal rates are provided in Table 9.6.3.

Table 9.6.2 *Annual loading rate of metals in filter strips (Walsh* et al*, 1997)*

Metal	USA 503 Regulations limit[1] Kg/ha/yr	US 183 filter strip Kg/ha/yr	Walnut Creek filter strip Kg/ha/yr
Zinc	140	4.9	9.2
Lead	15	1.2	0.25

1 Limit for metals in biosolids applied to cropland

Table 9.6.3 *Pollutant removal efficiencies for grassed filter strips*

	Removal efficiency (per cent)					
Reference	**USEPA, 2002**	**Atlanta Regional Commission, 2001**	**Walsh *et al*, 1997 (summary of literature)**	**Walsh *et al*, 1997 (monitoring of sites)**	**Claytor and Schueler, 1996**	**Design values from Section 3.4.2 of this book**[1]
Method of estimation	Unknown (for 23 m strip values in brackets for 46 m strip		Unknown	EMC (mass loading in brackets)	Various	
Total suspended solids	54 (84)	50	28–70	85–87 (87–89)	70	50–85
Nitrate/nitrogen	-27 (20)	20	—	33–44 (46–54)	30	10–20
Total phosphorous	-25 (40)	20	-21–40	34–44 (45–55)	10	10–20
Hydrocarbons	—	—	—	—	85	70–90
Cadmium	—	40	—	—	40–50	25–40
Copper	—		—	—		
Lead	-16 (50)		25	17–41 (31–52)		
Zinc	47 (55)		40–88	75–91 (79–93)		

1 Use lower values for sites where maintenance may not occur or to give increased confidence that design parameters will be met.

Hydraulic performance

Grassed filter strips are used as a treatment technique to remove sediment from runoff. They are not used to attenuate flow rates and there is no readily available information on the hydraulic performance, although the hydraulic behaviour does influence the level of pollutant removal that is achieved.

9.6.5 Design criteria

Grassed filter strips behave in a similar way to grassed channels and many of the design methods and criteria for swales (Section 9.7) can also be applied to filter strips.

Soil and groundwater requirements

Filter strips can be used in any soil conditions. They should be located at least 1 m above the water table if infiltration is likely to occur. They should not be used to treat runoff from hotspots if the risk of groundwater pollution due to infiltration is unacceptably high.

Hydraulic design

It is important to ensure that sheet flow occurs across the filter strip to encourage filtration by the vegetation. If flow velocities are too high then concentrated flow will occur and short-circuit the filter strip rendering it ineffective.

This requirement is achieved by ensuring that filter strips only deal with runoff from small areas (Claytor and Schueler, 1996). A flow spreader should be provided at the edge of the impermeable area where it discharges runoff on to the filter strip, such as a gravel diaphragm (Figure 9.6.2). The maximum length of impermeable area flowing on to a filter strip should be about 23 m, although this is dependent upon the slope. More detailed guidance on the maximum lengths that should drain to a filter strip, based on the maximum lengths over which it is possible to maintain sheet flow on the impermeable surface, is provided in Table 9.6.4.

Table 9.6.4 *Maximum drainage length possible to maintain sheet flow (New Jersey Department for Environmental Protection, 2000)*

Slope	Kinematic n value for contributing drainage area	
	0.05 (pavement flow > 6 mm)	0.1 (pavement flow < 6 mm)
0.005	43 m	22 m
0.01	61 m	30 m
0.02	86 m	43 m
0.04	122 m	61 m

Guidance in the USA generally requires that the slope of the filter strip is between 2 per cent and 6 per cent. Lower gradients cause ponding of water and greater slopes increase flow velocities and cause concentrated flow in rivulets so that no filtration occurs. Filter strips are typically 7.5–15 m wide to be effective. A lower slope angle and denser vegetation reduces the width of filter strip required.

The flow across the filter strip can be determined using Manning's equation (see Section 9.7.5) as described in CIRIA C522 (Martin *et al*, 2000b).

Pollutant removal

Grassed filter strips are effective at removing pollutants associated with sediment particles (Novotny and Olem, 1994). To achieve the pollutant removal levels quoted in Table 9.6.3 the flow should be lower than the height of the vegetation in the strip and typically be limited to 50 mm depth to maintain filtration. The residence time of runoff in the strip should be designed to be at least 5 minutes (Atlanta Regional Commission 2001). In the UK a maximum flow velocity of 0.3 m/s is recommended to promote sedimentation (Kellagher, 2004). This can be estimated using the methods described in the previous section.

For filter strips with a berm the ponded area at the lower end of the slope should be designed to half-empty in 24 hours, either by water infiltrating through the berm or via appropriately sized outlet pipes. The wedge of water behind the berm should be sized to hold the water quality treatment volume. Volumes from more extreme events should be allowed to overflow the berm.

More complex methods of analysis based on the settling velocity of particles are available (for example, Novotny and Olem, 1994), but for the majority of SUDS schemes the criteria quoted above should provide a reasonable estimate of performance.

Erosion

The top and bottom of the slope should be at the lower end of the allowable slope range to decrease flow velocities and reduce the risk of erosion. If a toe berm is provided the crest should be protected against erosion during overtopping during extreme events.

Flow velocities should be designed to prevent erosion using the guidance provided for swales in Section 9.7.5. In the UK, a maximum flow velocity of 1.5 m/s is suggested to prevent erosion for extreme conditions (Kellagher, 2004). Erosion protection should be provided to the filter strip until the vegetation has become well established.

Extreme events

Filter strips are normally on-line treatment systems and need to be able to convey flows from the full range of design storm events. Flows from extreme events beyond this must be routed safely overland across the site.

Design details

The filter strip must be constructed to provide an even and consistent slope with no severe undulations that will cause localised ponding or promote flow in channels. A gravel diaphragm should be provided at the edge of the impermeable area to act as level spreader and promote sheet flow. The diaphragm should be around 300 mm wide and 600 mm deep and filled with 20 mm single-size gravel. There should be a drop of at least 50 mm from the pavement edge to the filter strip to prevent the formation of a sediment lip which will concentrate flow to other areas.

The filter strip should cover the length of the area being drained. Details are provided in Figure 9.6.2.

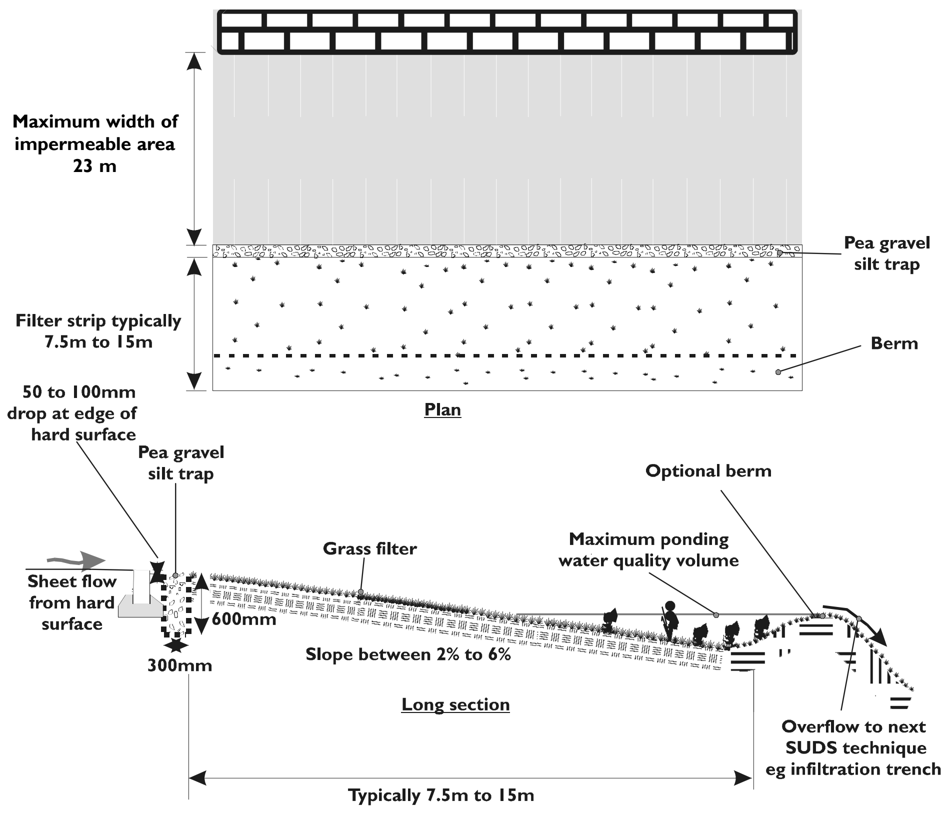

Figure 9.6.2 *Example details of a filter strip*

9.1 9.2 9.3 9.4 9.5 9.6 9.7 9.8 9.9 9.10 9.11 9.12 9.13 9.14 9.15

The underside of the filter strip should be located at least 1.0 m above the water table if infiltration is likely to occur.

Inlets

As discussed above the flow to the filter strip should be sheet flow from adjacent impermeable areas. A gravel diaphragm as discussed above should be provided. Flow from a kerb and gully system should not be directed to filter strips.

9.6.6 Construction

The filter strip must be graded evenly and with great care using experienced plant operators. Construction runoff should not be allowed to flow across grassed filter strips. One full growing season should be allowed for vegetation to establish before runoff is directed across the filter strip. Alternatively, erosion protection should be provided.

9.6.7 Planting

The graas should be able to withstand wet and dry and quite high flow velocities. The criteria that apply to planting for swales also apply to grassed filter strips (Section 9.7.7).

9.6.8 Operation and maintenance

Grassed filter strips are a relatively low-maintenance SUDS technique. However, the continued operation does depend on maintenance being undertaken.

The recommended maintenance schedule for grassed filter strips is provided in Table 9.6.5.

Table 9.6.5 *Maintenance requirements for grassed filter strips*

Operation	Frequency
Inspections to identify any areas that are not operating correctly, eroded areas, infiltration surfaces that have become compacted, silt-laden or ineffective for any reason. Record any areas that are ponding and where water is lying for more than 48 hours. Report to client.	Monthly
Collect and remove from site all extraneous rubbish that is detrimental to the operation of the SUDS and the appearance of the site, including paper, packaging materials, bottles, cans and similar debris.	Monthly
Maintain grass height within the specified range (100 mm typically). Ensure that soil and grass does not become compacted. Do not cut during periods of drought or when ground conditions or grass are wet, without prior agreement.	As required (but typically monthly)
Scarifying and spiking. Thatch is a tightly intermingled organic layer of dead and living shoots, stems and roots, developing between the zone of green vegetation and the soil surface. To improve infiltration performance, break up silt deposits and prevent compaction of the soil surface it should be scarified with tractor-drawn or self-propelled equipment to a depth of 5 mm to relieve thatch conditions and remove dead grass and other organic matter. Thatch removal should be carried out in dry conditions free from frost. Spiking. Perforate the soil surface using tractor-drawn or self-propelled spiker to penetrate panned layers to 100 mm depth and allow water to percolate to more open soil below. Follow by top-dressing with a medium to fine sand. Spiking is particularly effective when the soil is moist.	As required
Reinstate design levels, repair eroded or damaged areas by returfing or reseeding, restore or improve infiltration and remove silt by removing existing or damaged vegetation and reinstatement of surface to design levels.	As required
Seed or sods bare areas (see above).	As required

9.7 SWALES

Box 9.7.1 *Key considerations for swale design*

Description

Swales are shallow channels that are designed to convey runoff and remove pollutants.

Design criteria

- Use Manning's equation
- limit velocities to prevent erosion (typically 1–2 m/s depending on soil type
- maintain flow height of water below vegetation (typically 100 mm)
- minimum length of 30–60 m with a residence time greater than 10 minutes
- minimum base width 0.6 m
- maximum side slope 1:4.

Pollutant removal

Moderate to good (very good for enhanced dry swale).

Applications

Wide variety of situations within the landscaping of projects. Relatively easy to design and incorporate into landscaping areas. Used in locations such as highway edges (including residential streets), car parks, office developments, schools and retail developments.

Limiting factors

- Not usually practical in very flat or very steeply sloping sites, or where groundwater is very close to surface
- land may not be available for them, especially in high-density developments with little landscaping.

Maintenance

- Monthly inspections
- monthly removal of litter
- mowing as required, but at least twice a year
- scarifying and spiking as required
- repair damaged vegetation and silt as required.

9.7.1 Description

Swales are shallow channels designed to store and/or convey runoff and remove pollutants. They may be used as conveyance structures to pass the runoff to the next stage of the treatment train or they can infiltrate it into the ground, depending on soil and groundwater conditions.

The swale channel is broad and shallow and covered by grass or other suitable vegetation to slow down flows and trap particulate pollutants (Figure 9.7.1). They are typically located next to highways but can also be constructed in landscaped areas within car parks and elsewhere. They can replace conventional piped drainage and should remove the need for kerbs and gullies.

Figure 9.7.1 *Swale in a housing development, Scotland*

There are three kinds of swale with varying pollutant removal efficiency.

1 **Swale**.

2 **Enhanced dry swale**. A filter layer of soil over an underdrain keeps the swale dry most of the time. In places such as hotspots (see Section 3.2) they may have to be lined to prevent infiltration. Their dryness means they are the preferred option in most locations, as they do not become unsightly or generate odours.

3 **Wet swale**. Where underlying soils are poorly drained and underdrains are not provided, standing water is retained in the swale and acts as a linear wetland. As they are wet and boggy in the base they may be unsuitable for residential settings.

Swales that are simple shallow grass channels are not engineered to provide the same pollutant-removal capability as either dry swales with a filter medium or wet swales that act as linear wetlands (Claytor and Schueler, 1996). The three types of swale are shown in Figure 9.7.2.

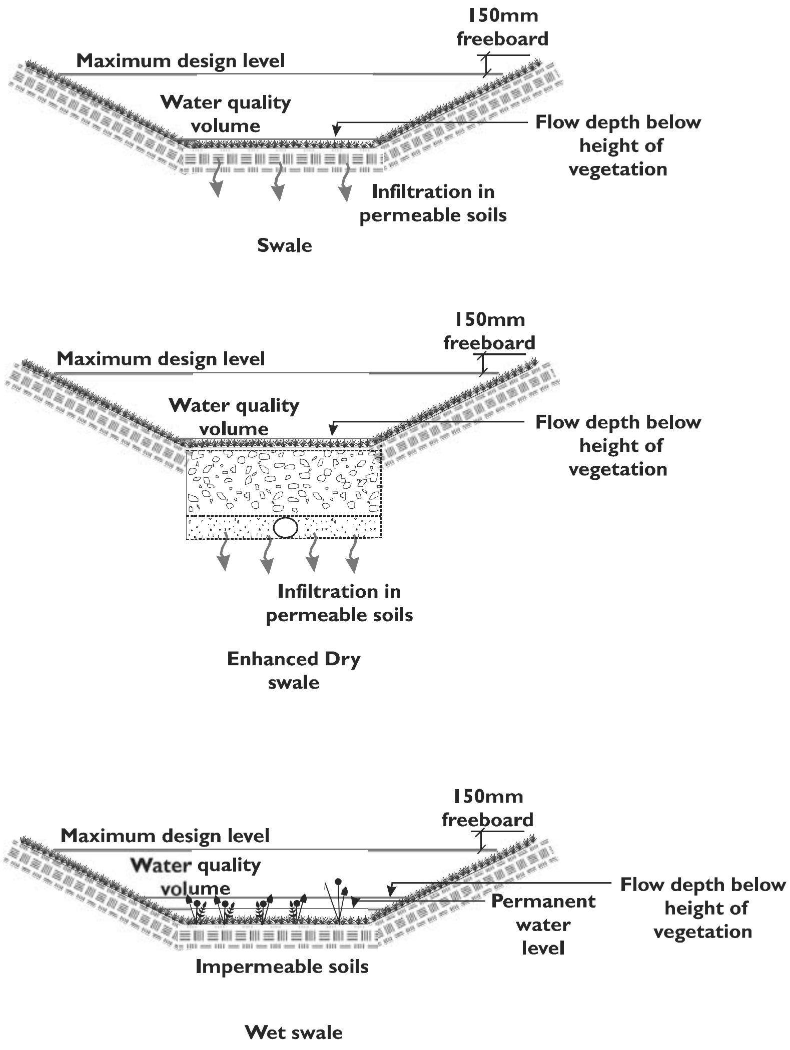

Figure 9.7.2 *Types of swale (Claytor and Schueler, 1996)*

Swales generally remove pollutants for frequent small storm events (Ellis, 1991). For larger, less frequent storms of between a 50 and 10 per cent annual probability (1 in 2 and 1 in 10 year return period), they can act as a storage and conveyance mechanism. For larger storms with an annual probability of less than 10 per cent (return periods greater than 1 in 10 years), providing storage in swales may become impractical as catchment size increases and they are often used in conjunction with other techniques.

Properly designed and maintained swales pose a negligible safety risk. Drowning is unlikely because of the limited depth of water. Shallow side slopes mean that the risk of someone tripping is negligible and the risk of overturning vehicles is much less than from normal roadside ditches in the UK.

The performance of swales can be enhanced by providing vegetated filter strips before runoff enters the swale and by providing check dams within them.

9.7.2 Suitable applications

Swales can be used in a wide variety of situations within the landscaping of projects. They are relatively easy to design and incorporate into landscaping areas. They have been used along highway edges (including residential streets), in car parks, and within office developments, schools and retail developments.

They are less appropriate in private gardens where excess fertiliser and weedkiller application can pollute the runoff, while excessive mowing keeps the grass too short to be an effective filter.

They are generally used for subcatchments with small impermeable areas. The maximum impermeable catchment for which swales are practical is between 2 ha and 4 ha.

The ground and groundwater conditions need to be suitable for swales. The soils should provide a stable and vegetated bed and sides, and the groundwater must be more than 1 m below the base of the swale (see Section 3.2) if infiltration is required.

Swales need a relatively slow flow of water over them to remove pollutants, so they are restricted to sites without steep ground slopes unless they can be placed parallel to the contours. They are practical in sites with a maximum slope of less than 10 per cent. On very flat sites swales can become waterlogged if gradients are insufficient to allow a significant flow of water, although this can be prevented by the provision of underdrains (Richman *et al*, 1998). Underdrains are especially useful in residential areas to prevent the swales becoming unsightly.

It may be difficult to incorporate swales in:

- dense urban developments where landscaping and space for swales may be limited
- steeply sloping sites where it is difficult to retard flow rates
- over made ground, unless infiltration can be prevented
- sites with clean coarse sandy soils, where it may be difficult to establish dense vegetation and prevent erosion even under very low flows.

Swales can be used as a standalone SUDS technique where suitable. They may have limited storage volume and may not be able to store water for storms with an annual probability of less than 10 per cent (return period greater than 1 in 10 years) other than for very small impermeable areas. They work best when incorporated into a treatment train with other techniques (Section 2.2). They should not be used at the end of piped systems due to the high flows and risk of erosion (Martin *et al*, 2000a and b).

Swales are ideal for use as drainage on industrial estates (provided infiltration is prevented), because any pollution that occurs is visible and is more likely to be dealt with before it causes damage to watercourses (D'Arcy, 1998).

9.7.3 Advantages and disadvantages

The advantages and disadvantages of swales are summarised in Table 9.7.1.

Table 9.7.1 *Advantages and disadvantages of swales*

Advantages	Disadvantages
Easy to incorporate into landscaping (if care is taken, land take required may be minimal especially if the subcatchments are kept small)	Vulnerable to runoff from large storms which can erode vegetation
Reduce peak flows	Large size required to deal with runoff from less frequent storm events
Filter pollutants	Not practical in very flat or very steeply sloping sites, or where groundwater is very close to surface
Can promote infiltration where ground conditions are suitable	If not correctly designed can cause aesthetic or nuisance problems
Low capital cost (excluding cost of land take) and remove need for kerbs and gullies	Land may not be available for them, especially in high-density developments with little landscaping
Maintenance can be incorporated into landscaping maintenance regime	Impractical in sandy soils where erosion is difficult to prevent
Pollution and blockage is visible and easily dealt with	

9.7.4 Performance

Pollutant removal

Properly designed, constructed and maintained swales can have a design life of 20 years or more (Barrett, 1998). Factors that reduce the performance of swales include compacted soils, short runoff contact time, large storm events, frozen ground, large grass height, steep slopes, and high runoff velocities and discharge rates (USEPA, 1999k). Providing the design maintenance is undertaken correctly these can be avoided and pollutant removal should be as specified in Section 9.7.4.

Generally, the performance data shows that well-designed and well-maintained swales are good at removing TSS, metals and hydrocarbons. They are less successful in removing nutrients and do not remove bacteria. Some studies have reported very poor pollutant removal for swales – one quoted a removal efficiency for TSS in swales on an Illinois site that was as low as 25 per cent (Apfelbaum *et al*, 1994).

Low removal efficiencies often the result of the poor design of the swales that have been studied (Barrett, 1998). An assessment of the performance of swales in the USA found that many were just grass channels with poor pollutant removal. Those that had been designed either with underdrains or as linear wetlands had greater and more consistent removal efficiencies (Claytor and Schueler, 1996). Other studies report that swales are very good at removing TSS (80 per cent) when correctly designed but less so if undersized. No pollution was removed from runoff due to the poor design and construction of a swale investigated in one study (USEPA, 2002). The importance of good design, construction and maintenance cannot be overstated.

Swales are not very effective at removing dissolved pollutants and very low removal rates (of less than 10 per cent) can be expected (USEPA, 2002). Bacteria are not effectively removed by swales (Schueler, 2000q).

Runoff from two swales in Dundee, Scotland, showed an overall improvement in quality when compared with road runoff (Jefferies, 2001 and Macdonald and Jefferies, 2003). Performance for some pollutants was poor (mainly metals, although they were monitored during only one event in one swale). This may have been because the swale was carrying runoff from a construction site that had a very heavy sediment load. The monitoring suggested that providing a granular underdrain layer, shallower slopes and raised outlets improved swale performance.

Swale length and water depth are significant factors that affect pollutant removal. On the basis of results from a trial swale in the USA it was determined that residence time is crucial to pollutant removal. If residence is greater than 9 minutes the TSS removal should be more than than 83 per cent (Walsh *et al*, 1997). It was found that confidence in removal efficiency fell with lower residence times. The distance water travelled along a swale had a strong influence on pollutant removal (Figure 9.7.3), and increased travel along the swale improved removal of TSS. Similarly, water depth also affected removal rates. A greater depth resulted in less effective removal of TSS, because the water flowed over the vegetation rather than being filtered through it. The same effect was noted for metals, as would be expected, since metals in runoff are generally attached to sediment. The correlations for nutrients were less clear.

The Center for Watershed Protection (2000r) studied removal performance for different lengths of swale; the results are shown in Table 9.7.2. The swale was underlain by Glacial Till, which allowed very little infiltration and was fed by a pipe. Six samples from each length were taken.

Table 9.7.2 *Pollutant removal of 30 m and 60 m swales (Center for Watershed Protection, 2000r)*

Pollutant	Pollutant removal (per cent) 30 m swale	60 m swale
Total suspended solids	60	83
Total phosphorous	45	29
Nitrate	Negative	Negative
Bacteria	Negative	Negative
Total petroleum hydrocarbons	49	75
Total zinc	16	63
Dissolved zinc	Negative	30
Total lead	15	67
Total copper	2	46

The swale was effective in removing many pollutants but less so for dissolved pollutants and nutrients. The 60 m filter was more effective than the 30 m one and it was more consistent in performance. The negative removal for bacteria was attributed to pet droppings in the swale. The study concluded that swales should be at least 30 m long and have a 5–10-minute residence time. However, the results suggest the minimum length should be 60 m, with a residence time of at least 10 minutes.

Many references quote a minimum residence time within the swale to achieve effective pollutant removal. In one study, a minimum residence time of 9 minutes was needed to provide significant pollution removal (Colwell *et al*, 2000b). US design guidance suggests a minimum of 10 minutes' residence time (Claytor and Schueler, 1996) – with lower residence times, confidence in the performance of the swale drops (Walsh *et al*, 1997). Extending residence time from 4.5 minutes to 9 minutes improved hydrocarbon removal efficiency from 49 to 75 per cent in one study (Richman *et al*, 1998).

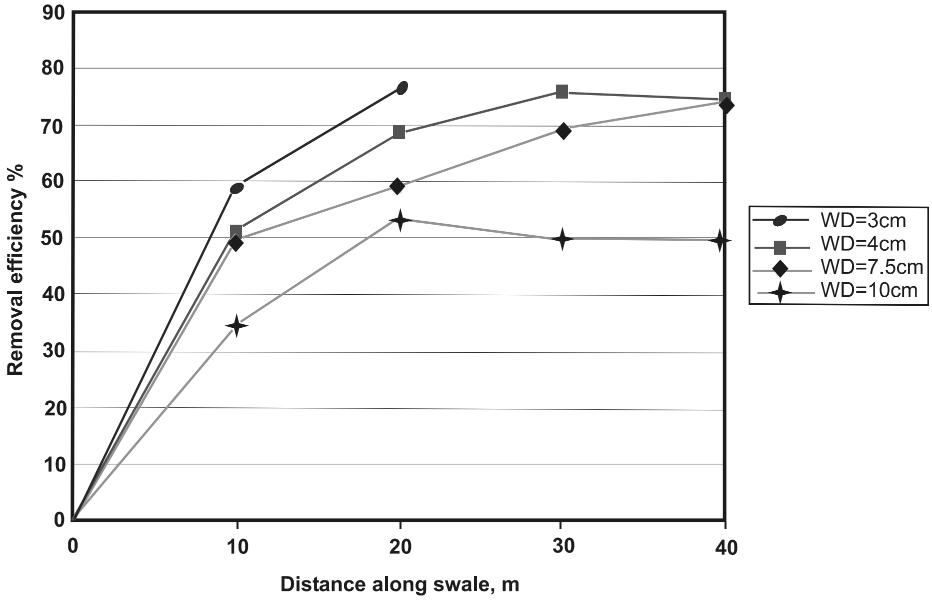

Figure 9.7.3 *Effect of water depth and swale length on TSS removal efficiency (Walsh* et al*, 1997)*

Seasonal variations in vegetation can affect pollutant removal in swales if drought causes vegetation to die so that the filtering effects are lost. TSS removal has also been found to be slightly greater (10 per cent) in the growing season.

Check dams are often used in swales to reduce the slope of swales, which slows flows and extends residence times. This results in increased pollutant removal and probably limits the washing-out of sediment in extreme events (Jan-Tai Kuo *et al*, 2001).

Pollutant removal rates for swales are summarised in Table 9.7.3.

There is a limit to the amount of pollution that any SUDS technique can remove from runoff and the lower the concentration the harder it is to remove. Irreducible concentrations for swales (the concentration in the runoff that cannot be reduced) are shown in Table 9.7.4. These should be considered the best water quality that can be expected from swales when used as a standalone technique.

Any pollution that is removed from runoff remains in the swale, which will exhibit elevated levels of cadmium, nickel lead and zinc. However, metals held in swales tend to be in an insoluble form and pose negligible risk of harm to plants, animals that eat plants or groundwater (Walsh *et al*, 1997). Hydrocarbons quickly biodegrade in swales and nutrients are taken up by plants.

Studies of swales in the USA from residential areas and from next to a busy four-lane highway found that although accumulation of metals did occur in the swales the levels were far below the concentrations that would classify the soils as hazardous waste in the USA (Richman *et al*, 1999).

A useful study of the effects of swale length and water depths on TSS removal was reported in the USA (Walsh *et al*, 1997). The results can be used to compare likely TSS removal for various swale layouts, when water depths have been determined using Manning's equation (Figure 9.7.3). It is also useful to compare the efficiency of swales in different design storms with different water heights, for example to see what proportion of pollution is likely to be captured in an extreme event (Table 9.7.5).

Table 9.7.3 *Pollutant removal efficiencies for swales*

	Removal efficiency (per cent)											
Reference	**Median efficiency quoted by USEPA, 2002**	**Atlanta Regional Commission, 2001 (quoted as conservative averages)**	**Barrett, 1998**	**Claytor and Schueler, 1996**	**Walsh et *al*, 1997 (summary from other sources)**	**Roesner et *al*, 1999 Also quoted by D'Arcy, 1998**	**Highways Agency et *al*, 1998b**	**Macdonald and Jefferies, 2003** [2]	**Luker and Montague, 1994**	**Winer, 2000**	**Schueler, 2000s**	**Design values from Section 3.4.2 of this book** [1]
Method of estimation	Unknown	Unknown	Mass load	Various pre-dominantly mass loading	Unknown	Mass loading	Unknown	EMC	Unknown	Various	Unknown	
Total suspended solids	81	80	70	80 wet/ 90 dry	60–83	80	60–90	55–72	—	38	81	60–80 wet/ 70–90 dry
Nitrate/ nitrogen	38	40 wet/ 50 dry	—	40 wet/ 50 dry	25	40	—	45	41–51	—	84	30–40 wet/ 50–90 dry
Total phosphorous	9	25 wet/ 50 dry	—	20 wet/ 65 dry	30	40	—	7.7 increase to 100 (ortho-P)	42–63	14	34	25–35 wet/ 30–80 dry
Hydrocarbons	62	—	—	—-		—	70–90	36	—	62	62	70–90 (wet and dry)
Cadmium	42					65	nd	423 increase See notes	63	nd	42	
Copper	51	20 wet/ 40 dry	—	40–70 wet/ 80–90 dry	50–90	50	50–70	85 increase See notes	49–70	32	51	40–70 wet/ 80–90 dry
Lead	67					75	80–90	43 See notes	56–76	35	67	
Zinc	71					50	70–90	14 increase See notes	77–93	28	71	

1 Use lowest values for simple swales without underdrains or for sites where maintenance may not occur or to give increased confidence that design parameters will be met.

2 Results for metals in Macdonald and Jefferies, 2003 are for one event from a swale without an underdrain.

Table 9.7.4 *Irreducible concentrations for swales (Claytor and Schueler, 1996)*

Pollutant	**Irreducible concentration mg/l**
TSS	43.4 +/- 47.0
TP	0.33 +/- 0.15
TN	1.74 +/- 0.71

Table 9.7.5 *Required swale length for TSS removal (Walsh* et al*, 1997)*

Water depth in swale	**Desired TSS removal** 30%	40%	50%	55%	60%	65%	70%	75%	80%
30 mm	10 m	10 m	10 m	10 m	20 m	20 m	20 m	20 m	> 20 m
40 mm	10 m	10 m	10 m	20 m	20 m	20 m	30 m	30 m	> 40 m
75 mm	10 m	10 m	10 m	20 m	20m	30 m	40 m	> 40 m	> 40 m
100 mm	10 m	20 m	20 m	> 40 m	> 40 m	> 40 m	> 40 m	> 40 m	> 40 m

Hydraulic performance

The only reported hydraulic monitoring of swales in the UK has been in Scotland (Macdonald and Jefferies, 2003). Monitoring of two swales in Dundee identified increased performance obtained from a swale with a 300 mm gravel underdrain. One of the swales was not finished when the monitoring was undertaken and as a result natural vegetation became established in the swales and no maintenance was carried out. The swales were set with base slopes of 2–5 per cent and flow into them was via drainage inlets in the kerb.

Mean reductions in peak flows were 1.2 per cent for one swale and 52 per cent for the other. Lag times were slightly longer for the swales compared with the road; mean lag times were 12–14 minutes. Runoff was prevented from 24–50 per cent of all storms.

9.7.5 Design criteria

Soil and groundwater requirements

Grassed swales should not be constructed in coarse sandy soils that cannot support the dense vegetation required to prevent erosion. If infiltration is required, the infiltration rate should be greater than 10^{-6} m/s, based on the information in CIRIA Project Report 21 (Watkins, 1995) and Report 156 (Bettess, 1996). Clay soils are not generally suitable for infiltration, therefore. Infiltration tests should be in accordance with BRE Digest 365 (BRE, 1991); see Section 9.8. Care should be taken not to compact soils below swales during construction, as this will reduce the infiltration capacity.

Groundwater must be at least 1 m below the base of a swale. If infiltration is likely to occur the design must comply with the regulator's policy on soakaways (Section 3.2).

Unlined swales should not be used in locations where infiltrating water may cause slope stability or foundation problems (eg in areas of landslides, at the top of cutting or embankment slopes, or close to building foundations), unless a chartered geotechnical engineer or engineering geologist has carried out a full assessment of the risks.

Unlined swales should not be used on contaminated sites unless it has been clearly demonstrated that the risk posed by leaching of contaminants is acceptable (see Section 2.6).

Hydraulic design

The hydraulic design of the swale should ensure it can:

- maintain flow height for the water quality treatment volume below the height of the vegetation (to ensure filtration occurs)
- provide required residence time and storage for the water quality treatment volume
- provide additional storage as required
- convey the storm runoff that needs to be attenuated for channel protection, site level of service etc (and that it cannot store) to the next element of the treatment train or provide controlled overflow to prevent flooding of critical areas. Swales are normally combined with other practices to achieve other criteria.

Manning's equation can be used to calculate the average velocity of water in a channel. The velocity is a function of the channel slope, roughness and shape.

$$V = \frac{1}{n} R^{\frac{2}{3}} S_o^{\frac{1}{2}} \tag{9.7.1}$$

Where:

V = mean cross-sectional flow velocity (m/s)

n = Manning's roughness coefficient (note this coefficient is often given as dimensionless, but it is not and in this case is $m^{-1/3}$ s)

R = hydraulic radius of channel (m) = A/P_w

A = cross-sectional area through which water is running (m^2)

P_w = wetted perimeter of channel (cross-sectional length of channel in contact with the water) (m)

S_o = channel slope

The roughness coefficient indicates how much the sides of the swale will resist flow and it is critical in sizing swales. If the n value is underestimated the flow velocities may be too great and cause erosion. If it is overestimated then flooding may occur more frequently than anticipated in the design. From a water quality perspective it is better to use a value of n that overestimates the swale width (up to a maximum value of 3 m) thus producing shallower flow (Colwell *et al*, 2000a).

There are many references that quote Manning's roughness coefficients for various surfaces (eg Richman *et al*, 1998). The most appropriate advice for swales in the UK is provided by Escarameia *et al*, 2002. Quoted values are summarised in Table 9.7.6. The value of n is affected by choice of vegetation (Section 9.7.7).

Table 9.7.6 *Roughness coefficients, n, for grass swales*

Reference	Surface and vegetation	n value ($m^{-1/3}$ s)
Colwell *et al* (2000a)	Grass swale	0.3
City of Eugene Stormwater Management Program (2002)	Grass swale	0.3
Escarameia *et al* (2002)	Grass swale	$n = 0.05 + 0.0048(1 + \alpha)H/VR$ (9.7.2) Where: H = height of grass (m) α = 0 for perennial rye grass when 0.0029 < VR < 0.029 m^2/s and 0.0.04 m < H < 0.15 m α = 1 for fescues when 0.0017 < VR < 0.0495 m^2/s and 0.04 m < H < 0.06 m For perennial rye grass greater with H between 0.15 m and 0.4 m take n = 0.5 V = mean cross-sectional flow velocity (m/s) R = hydraulic radius of channel (m)
Center for Watershed Protection (2000r)	Grassed swale	0.2 (0.24 for unmowed taller grasses)

The swale should be designed so that flows:

- treat the water quality volume to remove pollution (see Section 4.3)
- provide storage as necessary to achieve other design criteria
- half empty within 24 hours (Martin *et al*, 2000a and 2000b) so that storage and treatment is available for following events and vegetation is not damaged by saturated conditions (unless it is a wet swale)
- convey runoff from extreme events through the swale without causing erosion.

Pollutant removal

The principal pollutant-removal mechanisms are (City of Eugene Stormwater Management Program, 2002):

- settling and trapping of sediment in vegetation
- adhesion of sediment and pollutants to plants
- filtering and adsorption in the underlying soils (dry swales only)
- nutrient uptake by plants.

In order to treat the water quality volume the runoff must be retained in the swale for a specified time to allow settling and filtration to occur (ie a minimum residence time). Filtration by the vegetation in a swale is important, and this requires a sheet flow of water at a lower height than the grass or other planting. Pollution removal also depends on the length of swale, as a large proportion of pollution in runoff is attached to the sediment and is filtered out in the first 10 m of swale where it becomes attached to blades of grass. More soluble constituents and those attached to smaller particles do not settle out as quickly and so are not removed until after the first 20 m of swale (Walsh *et al*, 1997).

As discussed in Section 9.7.4, residence time is the main criterion for achieving good pollutant removal in swales. A residence time greater than 10 minutes should provide an acceptable level of removal. Another method of achieving the residence time is to specify a maximum flow velocity for the water quality treatment volume. The most common value is 0.3 m/s, although the range is up to 0.45 m/s. In the UK, CIRIA C521 and C522 (Martin *et al*, 2000a and 2000b) also quote 0.3 m/s as the maximum velocity for the water treatment volume.

To provide effective filtration the flow height of water in the swale must be kept below the height of vegetation for the water quality volume, otherwise the water flows over the top of it and the filtration effect is lost. Typically if grass is maintained at 150 mm height then a flow depth of 100 mm is specified (USEPA, 1999k). This also prevents the grass being pushed over by water flows, which again reduces the filtration effect.

Some studies have quoted minimum lengths for swales (assuming that water is collected so that it flows into the head of the swale) of 30–60 m. The required length is a function of the site constraints and hydraulic properties of the swale, so caution should be applied when considering these general guidance values in swale design.

Erosion

To prevent erosion, flow velocities must be kept below a critical value for runoff that is greater than the water quality treatment volume. Quoted values range from a maximum velocity of 1 m/s (City of Eugene Stormwater Management Program, 2002) to 2 m/s (Richman *et al*, 1998). The critical velocity at which erosion occurs depends on the soil and vegetation type (Table 9.7.7).

Table 9.7.7 *Maximum allowable flow velocities based on soil type (New Jersey Department of Environmental Protection, 2000)*

Soil type	Maximum allowable velocity m/s	
	Seeded	**Turfed**
Sand	0.6	0.91
Silt loam, sandy loam, loamy sand	0.6	0.91
Silty clay loam, sandy clay loam	0.76	1.2
Clay, clay loam, sandy clay silty clay	0.91	1.5

If erosion is likely to be a problem then erosion-control fabrics or geotextiles may be used to limit the effects (see Section 5.12).

Extreme events

Typically swales cannot provide storage for events greater than a 1 in 10-year return period even for small catchments, so often they are used in conjunction with other SUDS techniques to provide the required runoff control. The swale should be designed to divert excess runoff from storm events greater than those it was designed. The water should be directed to suitable locations such as landscaping areas, roads and, where acceptable, parking areas (Richman *et al*, 1998).

Design details

The following design details are based on the information provided in both UK and US design guidance (Martin *et al*, 2000a and 2000b; Richman *et al*, 1998; City of Eugene Stormwater Management Program, 2002; USEPA, 1999k; Minnesota Metropolitan Council, 2001; Claytor and Schueler, 1996; Barrett, 1998 and Colwell *et al*, 2000a).

Swales should be sited so that channel slope can be maintained at a desired level and the swales fit in aesthetically with landscaping and other site features. Ideally, they should be placed where water can flow into them laterally from impermeable areas, as this promotes pre-treatment. They should also be in locations that have easy access for maintenance.

Swales should have a trapezoidal or parabolic cross-section (see Figure 9.7.4), as these are easier to construct and maintain and offer good hydraulic performance.

The side slopes should be no greater than 1:4 to promote sheet flow, maximise the wetted perimeter of the swale, promote filtration and minimise erosion. This also promotes pre-treatment, enhances safety and allows easier access for mowing. Where detailed calculations are provided to demonstrate the required performance and stability of slopes they may be increased to a maximum of 1:3.

A gravel filter at the edge of the impervious surface is also useful as pre-treatment to runoff entering swales.

A flat, wide base promotes sheet flow and also makes maintenance easier. If the swale is to be mowed the base should be at least 0.6 m, as specified in many US stormwater manuals and swale design guidance. If the base of the swale is too wide, flows tend to concentrate along specific lines and cause gullying, so base width should be limited to 2.5–3 m maximum, unless a flow divider is provided to split the channel into two.

Many US stormwater management manuals specify maximum channel slopes for swales to avoid the risk of flows causing erosion and to ensure adequate filtration. They also quote minimum slopes to prevent persistent saturation, which causes poor vegetation cover unless tolerant species are planted.

The channel slope should preferably be designed using Manning's equation to ensure that flow velocities are low enough to prevent erosion and to keep the depth of flow for the water quality treatment volume, Q_{wq}, below the height of the vegetation, as well as to provide sufficient residence time for settling of sediment (see above).

A study of 14 swales in USA found that to achieve a residence time of greater than 9 minutes the swale's channel slope needed to be greater than 1 per cent. Where slopes exceeded 3.5 per cent, erosion had occurred. The study found that slopes between 1.5 and 2.5 per cent maintained the best vegetation cover.

In the absence of detailed design the criteria in Table 9.7.8 may be used.

Table 9.7.8 *Limits on channel slopes in swales*

Limits on channel slope	References
Normal channel slopes specified between 1 per cent and 4 per cent (some guidance suggests 1–2 per cent)	Ellis, 1991; Maryland Department of the Environment, 2000; USEPA, 2002; Richman *et al*, 1998; Atlanta Regional Commission, 2001; Claytor and Schueler, 1996; Martin *et al*, 2000a and 2000b; City of Eugene Stormwater Management Program, 2002; Minnesota Metropolitan Council, 2001
For slopes less than 1–1.5 per cent, poor drainage is likely; use of an underdrain will prevent a muddy base	City of Eugene Stormwater Management Program, 2002; Richman *et al*, 1998
For slopes greater than 2–4 per cent, use check dams	Ellis, 1991; Claytor and Schueler, 1996; Martin *et al*, 2000a and 2000b; Minnesota Metropolitan Council, 2001; Richman *et al*, 1998
Maximum slope with check dams 6–10 per cent	Richman *et al*, 1998; Barrett, 1998; New Jersey Department of Environmental Protection, 2000

Some form of physical barrier, such as bollards, may be required to prevent vehicles parking on the swale edges and causing damage. The use of very frequent drop kerbs may be considered as inlets, but it is important to make sure the vegetation level behind the kerbs is low enough not to obstruct the flow of water.

Alternatively, the edge of the swale may be reinforced to prevent damage from occasional vehicle overrun (Figure 9.7.6).

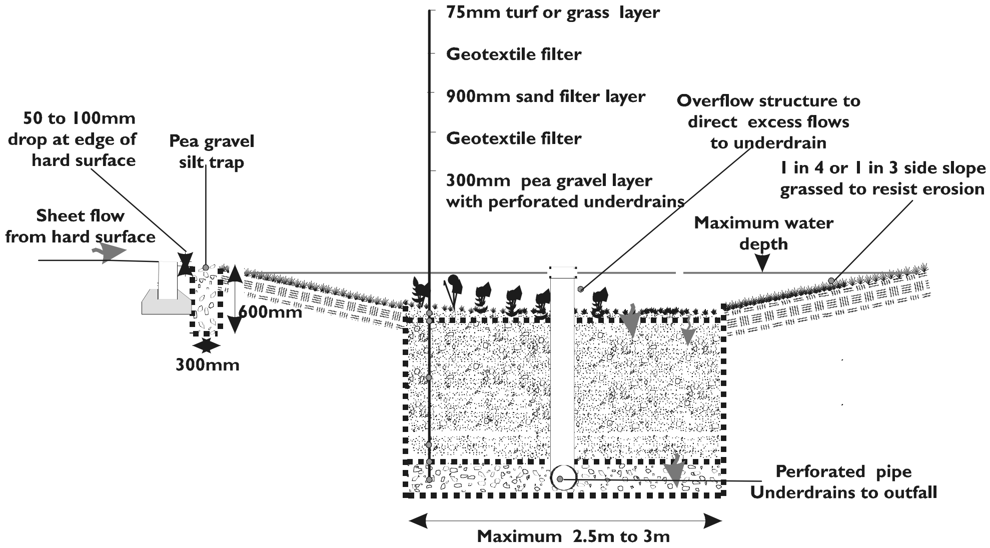

Figure 9.7.4 *Example details for a dry swale*

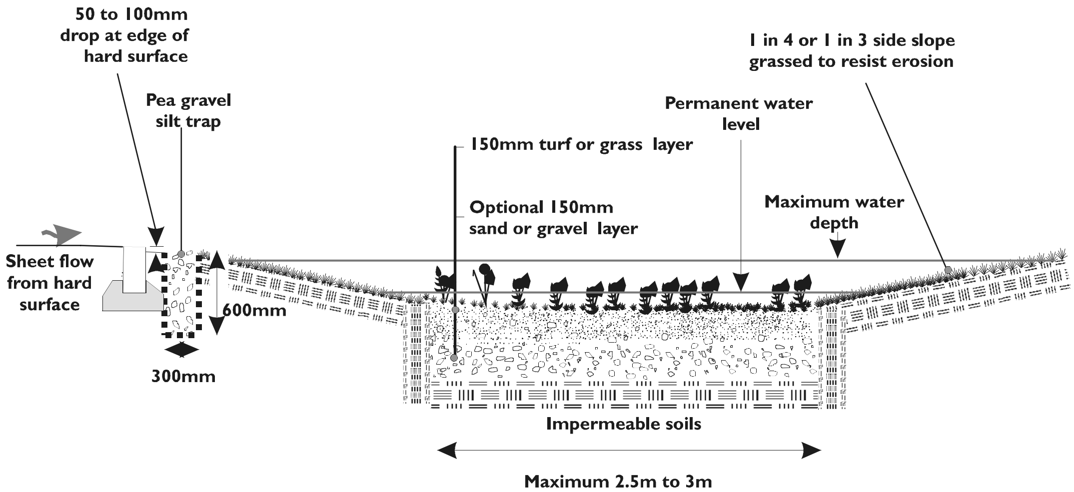

Figure 9.7.5 *Example details for a wet swale*

Figure 9.7.6 *Reinforcing the road edge in Holland (Drain Products Benelux)*

Inlets

The preferred way of directing water into a swale is continuously along its length by removing kerbs. This spreads the runoff laterally over a wider area, minimises erosion and disperses pollution widely in the surface vegetation. Shallow side slopes and a gravel diagram provide pre-treatment for lateral flows.

An alternative is to use a series of drop kerbs. The drop kerbs should be located as frequently as possible to encourage sheet flow off the impermeable surface at the drop points. If runoff from surfaces is directed into a swale via devices such as gullies or pipes that concentrate flow then the risk of erosion and silting is increased. Mitigation measures include flow spreaders and erosion control at the inlets. Pre-treatment should also be provided at the inlet using a sediment forebay.

Check dams

Check dams may be incorporated to reduce flow velocities and increase residence time, increase infiltration, or increase storage (Figure 9.7.7). Earth check dams should not be used unless they are provided with adequate protection against erosion (using geotextiles, geogrids or other appropriate methods) They are typically provided at 15 m centres.

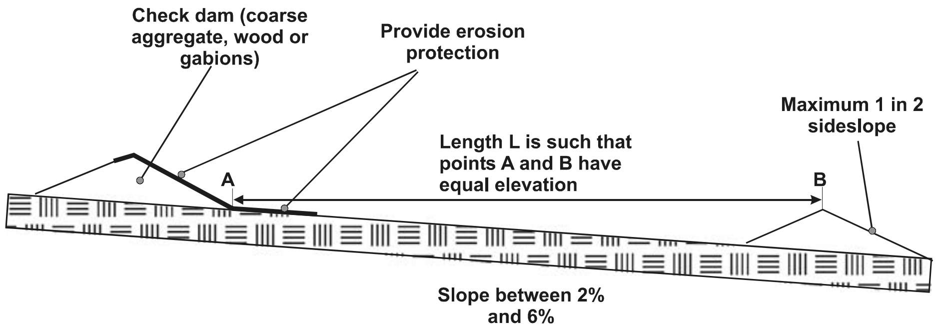

Figure 9.7.7 *Check dams*

Check dams should include a small orifice or pipe at the base to cater for low flows. They should prevent re-suspension of sediment. Erosion protection and an energy dissipater such as cobbles or boulders (100–150 mm diameter) should be provided downstream (extending 1.2–1.8 m) of the dam to both the base and sides of the swale. The dam should be built into the swale sides to ensure that water does not bypass it.

The water level at the crest of a downstream dam should be the same level as the toe of the upstream dam. The dams may be constructed using coarse aggregate (100–600 mm), such as Class 6B material specified in the *Specification for highway works* (Highways Agency *et al*, 1998a), wooden boards, gabions or earth (protected against erosion).

9.7.6 Construction

Attention to detail during construction of swales is vital if they are to perform as designed (Macdonald and Jefferies, 2003). Reasons for construction-related problems with swales include:

- construction workers who are unfamiliar with the technique
- poor timing of swale construction so that it becomes inundated with construction runoff and associated sediment
- poor finishing of the swale (for example, tarmac levels causing flow to bypass the swale inlets, turf laid too high so that it prevents water entering the swale, and inlets positioned so that parts of it do not receive runoff).

Construction of swales should avoid compacting the soil below, as this will reduce infiltration. The swales should not be used to convey runoff until construction of the site has reached a state where sediment from the site will not cause silting of the swale (Chapter 6). Indeed, many references (for example, Barrett, 1998) state that no construction runoff should be allowed into swales. If sediment from the construction site does accumulate, the swales should be cleaned before the contractor hands them over to the owner or operators.

Runoff should not be allowed into the swale until the vegetation is sufficiently established to prevent erosion of soils from the sides and base. If necessary, erosion control should be provided until vegetation becomes established using proprietary systems such as jute, straw or geosynthetic mats.

9.7.7 Planting

Planting is provided in swales to:

- provide dense cover and dense root structure to resist erosion
- slow flows and increase residence time and filtering of pollutants.

It is best to use a variety of planting to suit the aesthetics of a site and to use swales to enhance the visual landscape design (Figure 9.7.8).

Figure 9.7.8 *Swale integrated into landscape and retention pond*

A mixture of plants should be provided, including wet and dry area grasses that can grow through silt to give the best chance of dense vegetation developing. Native species should be used, as they will provide year-round cover without the need for irrigation or fertilisation and will provide habitat for indigenous species (Richman *et al*, 1998). Fine-growing grasses maximise filtration (City of Eugene Stormwater Management Program, 2002, specifies grass with a density of 600–1600 blades of grass per 0.09 m^2).

Factors affecting the choice of plants in the UK include salt tolerance, growth rate and tolerance to wet conditions encountered in drainage channels (Escarameia *et al*, 2002).

Two grass mixtures are most suitable for use in swales in the UK:

- perennial ryegrass
- fescues.

Plants can be placed as either turf, seeds or less commonly from potted plants.

Turf provides immediate protection provided the seams are protected. This can be achieved by laying the strips perpendicular to the flow of water and hand-tamping them after laying. Where high flow velocities are expected or slopes are at 1:3, the turf should be secured with pegs.

Seeds can be scarified into the soil or hydroseeded. Woody plants, such as willows, bunch grasses or rushes, can be planted from containers or cuttings.

The planting choice should be based on the flow velocities within the swale. Larger swales can be divided into three zones – lower, middle and higher – as shown in Figure 9.7.9.

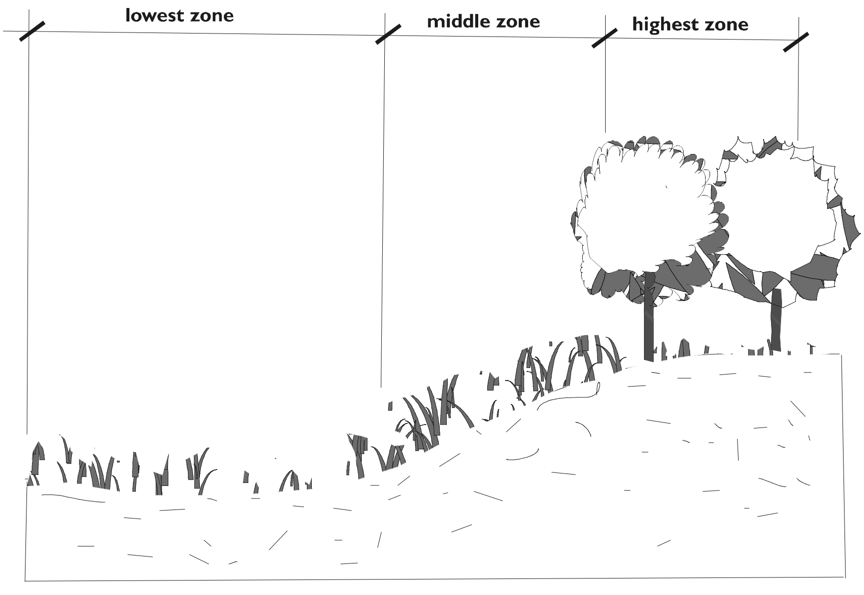

Figure 9.7.9 *Planting zones for swales (Richman* et al*, 1998)*

The general aim is to mimic natural vegetation to a watercourse. This means planting trees in the higher zone, complemented by an under-storey of shrubs and grasses below the trees in the middle and lower zones. Woody plants should be avoided near inlets and outlets, as debris snags on them and causes blockages.

The zones are:

- lower – plants that tolerate standing water and varying water levels
- middle – plants that can tolerate drier conditions but periodic inundation
- highest – plants that are adapted to drier conditions.

Although the intention is to mimic natural vegetation, care should be taken when locating trees near swales, as excessive leaf fall may cause blockages. The selection of turf or woody plants depends on the residence time required and affects the value of Manning's roughness coefficient used in design (Section 9.7.5).

9.7.8 Operation and maintenance

The useful life of a swale is directly related to the frequency of maintenance, and effective operation is dependent on maintenance. A US study found that only 50 per cent of swales had been maintained (Center for Watershed Protection 2000b).

If correctly designed and maintained swales can last indefinitely. The recommended maintenance schedule for swales is provided in Table 9.7.9. All the maintenance for swales can be undertaken as part of landscape maintenance and therefore will have marginal cost implications if the latter was already required.

Table 9.7.9 *Maintenance requirements for swales*

Operation	Frequency
Inspections to identify any areas not operating correctly, eroded areas, infiltration surfaces that have become compacted, silt-laden or ineffective for any reason. Record any areas that are ponding and where water is lying for more than 48 hours. Report to client.	Monthly
Maintain grass height within the specified range (50 mm above specified design water depth: Barrett, 1998). Ensure that soil and grass does not become compacted. Do not cut during periods of drought or when ground conditions or grass are wet, without prior agreement (Maryland Department of the Environment, 2000). Remove cuttings from swale to dispose of pollutants and reduce nutrient load in swale. Grass cuttings have been shown to increase nutrient load in swales (Jan-Tai Kuo *et al*, 2001).	As required, but at least twice a year
Collect and remove from site all extraneous rubbish that interferes with the operation of the SUDS and is detrimental to the appearance of the site, including paper, packaging materials, bottles, cans and similar debris.	Monthly
Scarifying and spiking. Thatch is a tightly intermingled organic layer of dead and living shoots, stems and roots, developing between the zone of green vegetation and the soil surface. To improve infiltration performance, break up silt deposits and prevent compaction of the soil surface it should be scarified with tractor-drawn or self-propelled equipment to a depth of 5 mm to relieve thatch conditions and remove dead grass and other organic matter. Thatch removal should be carried out in dry conditions free from frost. Spiking. Perforation of the soil surface using tractor-drawn or self-propelled spiker to penetrate panned layers to 100 mm depth and allow water to percolate to more open soil below. Follow by top-dressing with a medium-to-fine sand. Spiking is particularly effective when the soil is moist.	As required
Reinstate design levels, repair eroded or damaged areas by returfing or reseeding, restore or improve infiltration and remove silt by removing existing or damaged vegetation and reinstatement of surface to design levels.	As required
Seed or sod bare eroded areas (see above).	As required

9.8 INFILTRATION DEVICES

Box 9.8.1 *Key considerations for design of infiltration devices*

Description

Takes runoff, temporarily stores it and allows it percolate into the ground.

Design criteria

Base on full site investigation data including infiltration tests in accordance with BRE 365 or CIRIA Report 156.

Use design method from CIRIA Report 156 (Bettess, 1996).

Pollutant removal

Moderate.

Applications

Most suited to areas where runoff is relatively unpolluted and sediment loads are low (eg roofs or small car parks). Preferred method of drainage in Building Regulations if conditions are suitable.

Limiting factors

- Should not normally be used in stormwater hotspots
- on sloping sites, ensure that infiltrating water will not cause rises in groundwater and surface issues of water further downslope
- should not be used to drain landscaped areas.

Maintenance

- Six-monthly inspections of silt traps, pre-treatment devices and removal of sediment
- annual check of observation well to ensure emptying and no clogging
- remove sediment as required.

9.8.1 Description

An infiltration device takes runoff from a development and allows it to percolate into the ground. The device has a storage volume so that the runoff may be allowed to empty from the device into the ground over a period of time (usually a maximum of 24 hours to half empty) to provide storage for runoff from any following storms (Figure 9.8.1).

Figure 9.8.1 *Infiltration trench*

Infiltration devices include soakaways and infiltration trenches. Infiltration can also be used to release water from below other SUDS techniques such as pervious pavements (Section 9.2), swales (Section 9.7) and basins (Section 9.9).

They reduce the volume of water that has to be disposed of through sewers and provide recharge of groundwater that may maintain water levels in local watercourses. Soakaways are the most commonly used type of infiltration device in the UK. An example soakaway used in the UK is shown in Figure 9.8.2. The use of plastic geo-cellular units to construct infiltration devices is well established in the UK and Europe.

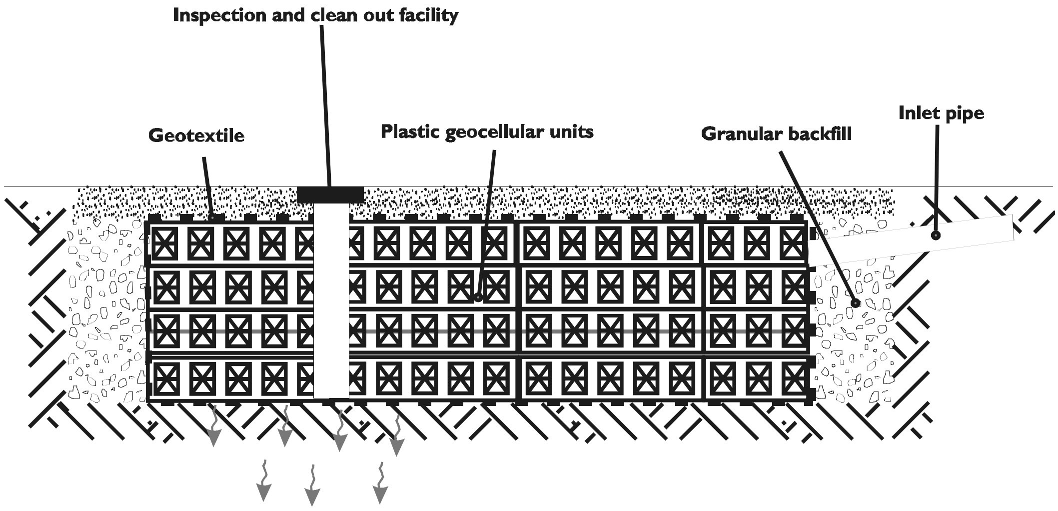

Figure 9.8.2 *Example soakaway construction*

9.8.2 Suitable applications

Infiltration devices are most suited to areas where runoff is relatively unpolluted and sediment loads are low (eg roofs). They should be designed to take runoff from relatively small catchments to reduce risk of clogging (2–10 ha maximum – USEPA, 2002). If larger areas are to be drained they should be split into smaller sub-catchments.

They should be preceded by some other form of treatment to remove sediment and treat pollutants to acceptable levels before entering the infiltration device, for example a sediment trap or oil separator. Where infiltration is used below another technique, such as a pervious pavement, the pre-treatment will be provided by the SUDS technique itself.

Part H of the Building Regulations (DTLR, 2002) requires consideration of infiltration before any other method of dealing with stormwater runoff. Soil and groundwater conditions are crucial to their successful use and soils must be sufficiently permeable to accept infiltration (Section 9.8.5). In many areas of the UK, clay soils or high groundwater levels limit the use of infiltration devices.

They can be used in urban areas, providing the infiltrating water does not affect building foundations and other infrastructure. The Building Regulations normally require a minimum of 5 m from any building or structure to an infiltration device; in some cases this may be reduced on the basis of specialist advice (Section 9.8.5).

Infiltration should not be used in stormwater hotspots unless pollution in the runoff has been pre-treated to acceptable levels using other techniques. On sloping sites, an assessment should be made to ensure that infiltrating water will not cause rises in groundwater and surface issues of water further downslope. They should not be used to drain landscaped or similar areas due to risk of sediment causing clogging.

Soakaways are usually designed to accept the runoff to meet site level of service criteria (if surcharging within the pipework cannot be proved to provide additional storage) as defined in Section 4.3. They can be designed to meet the other criteria if required.

9.8.3 Advantages and disadvantages

The advantages and disadvantages of infiltration devices are summarised in Table 9.8.1.

Table 9.8.1 *Advantages and disadvantages of infiltration devices*

Advantages	Disadvantages
Reduce volume of water running directly to watercourses and recharge groundwater	Cannot be used in hotspots without prior treatment of runoff
Do not take up surface space	Cannot be used unless soil and groundwater conditions are suitable
Can be used where there is no outfall for surface water such as a suitable watercourse or sewer	Do not provide amenity benefits
Construction is understood, simple and rapid	Statutory sewerage undertakers will not currently adopt infiltration devices
	There may be a legal liability to the owner if groundwater pollution occurs (Newman, 2001)

9.8.4 Performance

Pollutant removal

Infiltration devices will remove pollutants from stormwater if a geotextile or other filter layer is provided around the outside to trap sediment and hydrocarbons before they enter the ground. Without this layer the infiltration device itself will not remove pollutants (although the unsaturated ground around it will act as a filter layer). Infiltration of the runoff through the surrounding and underlying ground also removes pollutants, mainly by filtering and adsorption.

The removal efficiencies quoted in the literature are provided in Table 9.8.2. It should be noted that these appear to include the removal achieved by the ground surrounding the soakaway and therefore assume there is sufficient depth of unsaturated soil below the infiltration device and that the runoff does not enter directly to groundwater.

Table 9.8.2 *Pollutant-removal efficiencies for infiltration devices*

	Removal efficiency (per cent)		
Reference	USEPA, 2002	Winer, 2000	Design values from Section 3.4.2 of this book [1]
Method	Unknown	Combination	
Pollutant			
Total suspended solids	75	—	70–80
Nitrate/nitrogen	55–60	42	25–60
Total phosphorous	60–70	100	60–80
Hydrocarbons	—	—	—
Cadmium	85–90	—	60–90
Copper		—	
Lead		—	
Zinc		—	

1 Use lowest values for sites where maintenance may not occur or to give increased confidence that design parameters will be met.

A two-year-old soakaway and one 30 years old, each serving a similar type of catchment area, inflow and outflow, were monitored in France from February to November 1996 (Barraud *et al*, 1999). The soil around the 30-year old soakaway was also tested for pollutants. The soakaways were located very close to the water table. Heavy metals were retained in the soils below the soakaway (Table 9.8.3), but Kjeldahl nitrogen, chemical oxygen demand and total organic carbon were high and sometimes greater than the inflow concentrations. The concentrations of all the pollutants were reported to be below the permissible levels in the drinking water standards (this is assumed to refer to European Union drinking water standards). The concentrations of zinc and lead found in the groundwater below the site were reported to be lower than the inflow concentrations by 74 and 98.5 per cent respectively, but a major part of this reduction may have been due to dilution.

Table 9.8.3 *Percentage retention of pollutants in soils and sludge at base of soakaways (Barraud* et al*, 1999)*

Pollutant	Percentage retained in soil below soakaway	
	30 years old	Two years old
Zinc	—	54–88
Lead	31	98
Cadmium	29.5	—

The majority of the heavy metals were retained in the first 100 mm of soil below the base of the soakaway with reducing concentrations thereafter. Slightly elevated concentrations did persist until 1 m depth below the base. Hydrocarbons were also present to 1 m depth. All pollutant levels were low with the exception of cadmium which is elevated throughout the soil profile below the base of the soakaway (Figure 9.8.3).

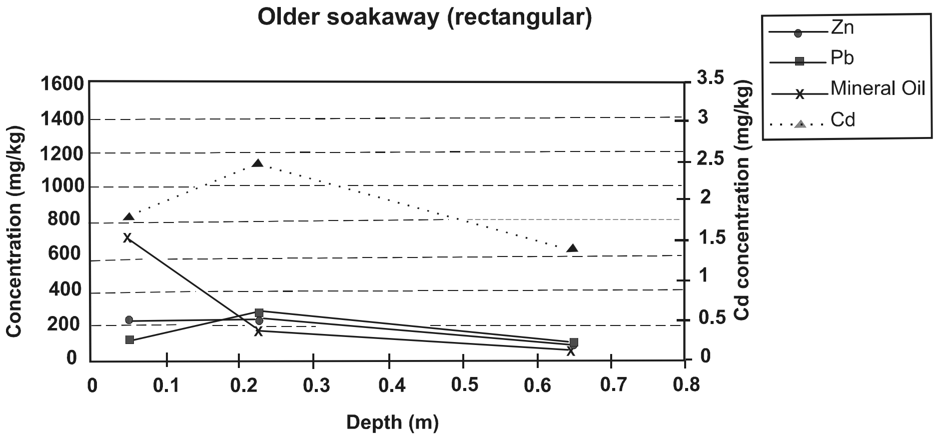

Figure 9.8.3 *Contamination below base of 30-year-old soakaway (Barraud* et al*, 1999).*

Hydraulic performance

Infiltration has been used in the UK to deal with runoff from roofs for at least a century with no widespread problems reported. It is estimated that at least 65 000 infiltration devices are installed in the UK each year (Bettess, 1996). A high failure rate for infiltration devices has been reported in the USA (USEPA, 2002), where one study suggested that less than 33 per cent were operating correctly after five years. However, many did not incorporate pre-treatment to remove solids. A study of more than 200 infiltration devices in Maryland, USA, that were constructed between 1984 and 1986 found that the most commonly used practice was infiltration (45 per cent of projects). It was estimated that 80 per cent of the trenches were working as designed, although in 50 per cent of those studied water levels could not be confirmed because of a lack of observation wells (Harrington, 1989).

It was also noted that of those not working correctly, 85 per cent did not have filter strips to remove sediment, 50 per cent did not have the benefit of a site investigation for design and 70 per cent had failed as a result of silting that had occurred during construction.

Consequently, it was recommended that runoff should be filtered before entering an infiltration device and construction runoff should be prevented from entering.

In designing infiltration devices, careful consideration should be paid to how the water behaves and where it is likely to flow to once it is in the ground. A bulb of saturation develops in the soil around a working infiltration device and in this area the water flows under the influence of the hydraulic pressure gradient. As water seeps out, the flow area expands outwards and saturated conditions can be maintained for longer, then the saturated zone retreats back when all the water has infiltrated. Outside the saturated zone the water flow is driven by capillary forces and gravity.

The water generally flows downwards through the unsaturated zone although preferential pathways may be followed in locations such as solution features. When the infiltrating water reaches the groundwater table it will move sub-horizontally in the direction of groundwater flow.

Detailed monitoring of a soakaway constructed at a school in Wallingford, Oxfordshire, found that the soakaway performance was predicted with reasonable accuracy using the design method proposed in CIRIA Report 156 (Bettess, 1996) to determine storage volume and time to empty. It also found that soakage of water does occur out of the base of soakaways and the factors of safety used in the CIRIA report give a reasonable degree of protection against the risk of failure (Abbott, 2000).

The results did not give any evidence of deterioration of infiltration over time (the soakaway was tested in the third and fourth years after construction). It also found that the infiltration rate varied with depth of water, which is not taken into account in design. An important conclusion reached from the study was that extrapolation of infiltration test results lead to a serious underestimation of the infiltration capacity (by an order of magnitude).

Figure 9.8.4 shows the response of water levels within the soakaway to rainfall events.

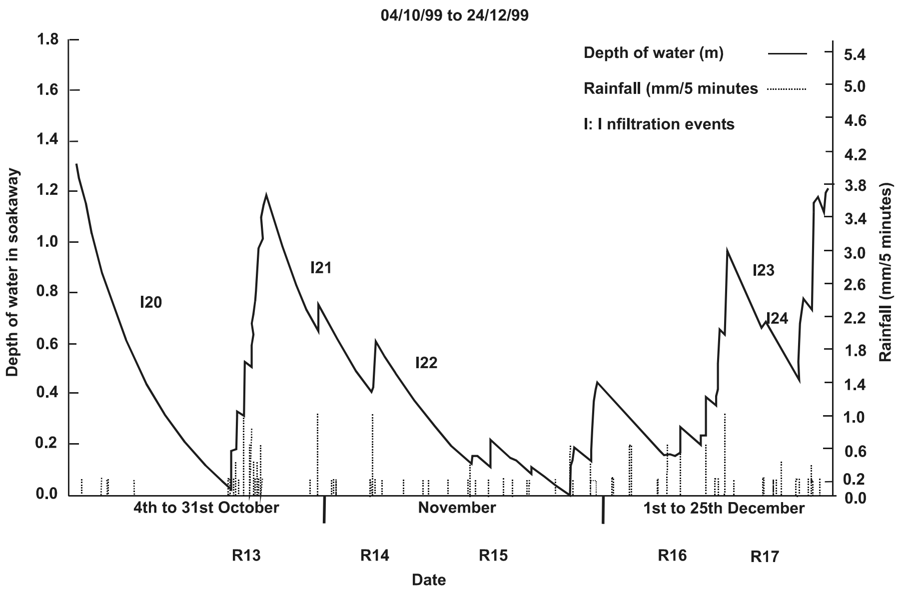

Figure 9.8.4 *Response of soakaway to rainfall events (Abbott* et al*, 2000)*

A soakaway was constructed at Aberdeen University in December 1998 and monitored from January 1999 to January 2000 (Kelso *et al*, 2000, and Pokrajac and Deletic, 2000). It was designed in accordance with the guidelines given in CIRIA Report 156 (Bettess, 1996) and the infiltration of the soils around the soakaway (made ground) varied from 2.8×10^{-6} m/s to 3.2×10^{-8} m/s. This is a very low infiltration rate and is either close to or below the limit of acceptability for soakaway drainage.

Tests to determine the level of clogging were undertaken one month and six months after commissioning and it was concluded that no clogging had occurred. Clogging will be less noticeable where very low permeability soils surround the soakaway (since the permeability of silt may be similar to the permeability of the surrounding soils) and construction sediment is unlikely to have been an issue for this trial project.

Groundwater was present at between 0.5 m and 1.5 m below the base of the soakaway and it was reported that the soakaway never emptied of water during the monitoring. It was concluded that infiltration through the base was negligible (not surprising given the low permeability of the soils) and that the infiltration rate varies with head of water in the soakaway.

9.8.5 Design criteria

Soil and groundwater requirements

A qualified geotechnical specialist should advise on the suitability of soil and groundwater conditions to accept infiltration drainage. The most important aspect of design is that the soil has sufficient capacity to accept infiltration of stormwater runoff.

Infiltration cannot normally be used in clay soils and soils used to accept infiltration of runoff should have a clay content of less than 20 per cent and a clay/silt content of less than 40 per cent. The soils must have an infiltration rate greater than 1×10^{-6} m/s. The permeable layer must be sufficiently thick and have sufficient lateral extent to allow dispersal of water through it.

The infiltration rate of the soils must be tested using large-scale tests at the location and depth of the proposed infiltration device. Small-scale tests using small (eg 300 mm × 300 mm × 300 mm) pits and small volumes of water are not representative and will not give a reliable estimation of the infiltration capacity of the ground. The test should be undertaken in accordance with the protocol described in BRE Digest 365 and CIRIA Report 156 (Bettess, 1996) using at least the minimum volumes of water or trial pit dimensions quoted in the documents. The results of the test should be accompanied by detailed soil descriptions made in accordance with British Standard BS 5930:1999. Tests should be undertaken until water levels drop below the level equivalent to 25 per cent of the starting volume remaining in the pit and extrapolation should not be used to determine the infiltration rate (Abbott *et al*, 2000). BRE Digest 151 has been withdrawn, so testing and design using this method is no longer acceptable.

The base of the infiltration device must be at least 1 m above the seasonally high groundwater table so that the storage capacity is not reduced during times of high groundwater levels and to prevent direct discharge to groundwater. If an aquifer is especially sensitive the Environment Agency or SEPA may require 3 m clearance.

Hydraulic design

Detailed guidance on the hydraulic design of infiltration devices is given in CIRIA Report 156 (Bettess, 1996) and BRE Digest 365 (BRE, 1991). The method in CIRIA Report 156 is summarised here. The design method provided in CIRIA 156 is usually more suitable for SUDS as it allows for infiltration through the base of systems and has been shown to given a reasonable estimation of performance (Abbott *et al*, 2000). For most SUDS systems infiltration through the base is an important route, since the systems tend to be wide and flat (for example, pervious pavements and infiltration basins). The increased use of soakaways and infiltration trenches in a wider range of situations with depth limitations due to groundwater levels and using geo-cellular structures also requires shallow systems in which base infiltration is important.

For an infiltration system to work satisfactorily it must have sufficient surface area to infiltrate water. Normally the infiltration rate is lower than the rainfall rate and sufficient volume must be provided to store excess water from a design storm that does not infiltrate during the storm. The size depends on:

- the hydraulic properties of the ground (see previous section)
- the catchment area
- rainfall characteristics.

Infiltration devices may be used to achieve all the design criteria discussed in Section 4.3.

Infiltration devices can be classified as one of two types.

1 **Plane infiltration system**. In this, the outflow is predominantly through the base (for example, pervious pavements).

2 **3D infiltration system**. A significant proportion of the outflow occurs through the sides.

In any design the parameters will vary and there will be some risk that the design parameters will be exceeded. The ground is a naturally variable material and infiltration capacity is likely to vary significantly across a site, even in relatively homogeneous soils. In addition, the infiltration capacity can reduce over time if the infiltration device is not maintained. A factor of safety is therefore applied to the infiltration rate (Bettess, 1996). The factor takes account of the consequences of failure and the risk of reduced infiltration rates occurring (Table 9.8.4).

The drainage area served by an infiltration device should be kept to a minimum to prevent excess silt loading and to limit the risk of groundwater mounding (localised raising of the groundwater levels due to the concentrated infiltration at a point).

Table 9.8.4 *Factors of safety for infiltration design (Bettess, 1996)*

	Consequences of failure		
Catchment area	**No damage or inconvenience**	**Minor inconvenience eg surface water on car park**	**Damage to buildings or structures or major inconvenience**
Less than 100 m^2	1.5	2	10
100–1000 m^2	1.5	3	10
Greater than 1000 m^2	1.5	5	10

The design methods from CIRIA Report 156 are summarised in Box 9.8.2.

Box 9.8.2 *Infiltration design (Bettess, 1996)*

Parameters

The required inputs for infiltration design are:

q = infiltration coefficient from percolation tests (m/h) – determined following procedure in CIRIA Report 156
A_d = total area to be drained including any adjacent impermeable areas (m^2) = $A_I + A_p$
n = porosity of soakaway fill material (voids volume/total volume)
i = rainfall intensity (m/h)
D = rainfall duration (h)
A_b = base area of infiltration system (m^2)

Plane infiltration systems

For plane infiltration systems (outflow from base only) for a given rainfall event discharging to the infiltration device of a given plan area the maximum depth of water that will occur in the device, h_{max}, is based on:

$$h_{max} = (D/n).(Ri - q) \quad (9.8.1)$$

Where R = ratio of drained area to base area of pervious surface, A_d/A_b

The calculation is carried out for a range of rainfall durations to determine the maximum value of h_{max}.

Time for half emptying is given by:

$$t = nh_{max}/2q \quad (9.8.2)$$

3-D infiltration systems

For 3-D infiltration systems (outflow from base and sides for a given rainfall event discharging to the infiltration device of a given plan area the maximum depth of water that will occur in the device, h_{max}, is based on:

$$h_{max} = a(e^{(-bD)} - 1) \quad (9.8.3)$$

Where:
$a = (A_b/P) - (iA_d/Pq)$
$b = Pq/nA_b$
P = perimeter of infiltration system (m).

The calculation is carried out for a range of rainfall durations to determine the maximum value of h_{max}.

Time for half emptying is given by:

$$T = (nA_b/qP)\log_e[(h_{max} + A_b/P)/(h_{max}/2 + A_b/P)] \quad (9.8.4)$$

Pollutant removal

The base of an infiltration device should have sufficient unsaturated soils below it so that filtration of the stormwater can occur before it reaches the groundwater table. Normally a minimum depth of 1 m is required, but this may be greater in particularly sensitive locations.

A sediment trap is always required before an infiltration device and this will remove a significant amount of pollution from runoff.

Erosion

Erosion of fines from the soil surrounding the infiltration device should be prevented. Where this is a design consideration, infiltration devices should be designed to take runoff from the smallest practical catchment areas so that the volumes of water infiltrating are small.

Geotechnical assessment

Infiltration devices introduce water to the ground that may, in some circumstances, adversely affect the load capacity or stability of the ground. This can cause instability in buildings or other structures.

The following factors should be considered when locating infiltration devices in a site:

- do not locate close to the top of slopes
- do not locate close to buildings (the Building Regulations specify a minimum distance of 5 m but this may be relaxed if a soakaway located closer can be demonstrated to have a negligible risk of affecting the foundations to the building)
- do not allow infiltration into deep deposits of made ground as this may cause inundation settlement
- assess the ground conditions to ensure that loss of fines is unlikely to occur
- do not use infiltration if dissolution of the ground may occur.

The ground slope downstream of the infiltration device (based on the direction of groundwater flow) should not be greater than 1:5 to prevent problems with water issuing at the surface (Harrington, 1989). The use of soakaways should be assessed by a geotechnical engineer to ensure that the ground conditions are acceptable and that percolating water will not cause undue problems (see Section 5.1.1).

Extreme events

Extreme events above the capacity of the infiltration device should be routed over the site surface along acceptable flood routes. Infiltration devices can be sized to cope with storms up to 1 in 200 years or greater. An overflow may be provided if necessary.

Design details

An example detail for an infiltration trench constructed using plastic geocellular units is provided in Figure 9.8.5. They can also be constructed using an open aggregate with a large void space (in excess of 30 per cent voids).

All infiltration devices should be provided with observation and clear-out wells/pipes to allow inspection and maintenance to be undertaken. The sides and base should be wrapped in a geotextile. If water is allowed to infiltrate through the top surface a geotextile should be located at 150–300 mm depth to trap sediment and hydrocarbons close to the surface to make maintenance easier.

The use of plastic geocellular units can reduce the volume of excavation and disposal of surplus soils from infiltration devices. The units typically have up to 95 per cent porosity compared to the 30 per cent for aggregates, thus reducing excavation volumes to provide the same amount of storage.

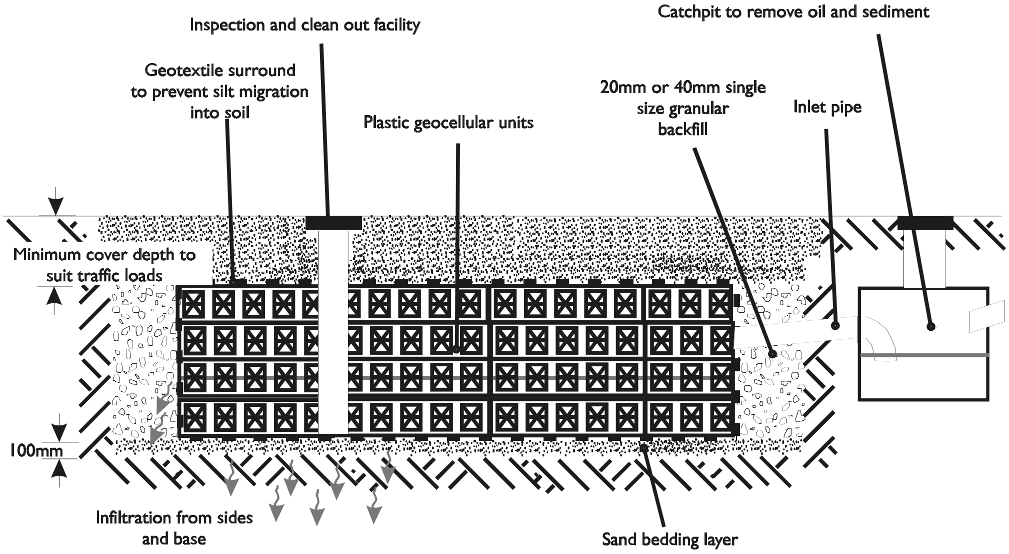

Figure 9.8.5 *Example infiltration device details*

Inlets

Infiltration devices should be provided with a sediment trap in the upstream pipework. This should be able to treat 25 per cent of the water quality volume to remove sediment (Maryland Department of the Environment, 2000).

9.8.6 Construction

Construction runoff should not be allowed to enter into soakaways or into excavations for soakaways as this will cause silting. The soils around the sides and base of the infiltration device should not be allowed to become smeared or compacted as this will reduce the permeability.

9.8.7 Operation and maintenance

The useful life and effective operation of an infiltration device is directly related to the frequency of maintenance. If correctly designed and maintained, infiltration devices can last in excess of 30 years. The recommended maintenance schedule for infiltration devices is provided in Table 9.8.5.

Table 9.8.5 *Maintenance requirements for infiltration devices*

Operation	Frequency
Inspect silt traps and note rate of sediment accumulation.	Monthly in first year and then six-monthly
Remove sediment from pre-treatment devices (eg catchpits) either by hand or using gully-emptying tanker with suction pump. See Section 7.3 for disposal requirements.	Depends on rate of accumulation, but at least six-monthly
Check observation well following three days of dry weather to ensure emptying is occurring.	Annually
Inspect observation well for clogging.	Annually
Reconstruct or remove sediment from storage area when failure occurs (sediment can be removed using a gully-cleaning tanker with suction pump).	As necessary

9.9 INFILTRATION BASIN

Box 9.9.1 *Key considerations for infiltration basin design*

Description

Depressions designed to store runoff and infiltrate it into the ground.

Design criteria

Base on full-site investigation data including infiltration tests in accordance with BRE 365 or CIRIA Report 156.

Use design method from CIRIA R156.

Pollutant removal

Moderate.

Applications

Most suited to small catchments with light sediment loads.

Limiting factors

Require a large area which reduces their applicability in urban areas.

Maintenance

- Monthly inspections
- monthly litter and blockage removal
- monthly mowing
- sediment removal from pre-treatment device
- repair damaged vegetation annually or as required
- scarify and spike annually or as required
- sediment removal as required (typically every five years).

9.9.1 Description

Infiltration basins are designed to store runoff and infiltrate it into the ground. They operate in the same way as the infiltration devices described in Section 9.8 except that they are open, uncovered areas of land.

Figure 9.9.1 *Infiltration basin*

Basins can be formed by excavating depressions into the ground or by forming an embankment to impound the stored runoff water. Infiltration basins do appear to have had a higher rate of failure in the USA than other infiltration methods (USEPA, 2002). This was attributed to the fact that, in many cases, they have been used as regional controls, which has increased sediment loads and caused early clogging in the bottom of the basin.

In the past, infiltration basins have not been designed with an attractive appearance particularly in mind. Nevertheless, they can be landscaped (Figure 9.9.1) or combined with the principles of bioretention (Section 9.4) to provide added aesthetic and amenity value.

9.9.2 Suitable applications

The restraints on the use of infiltration basins are the same as those discussed for infiltration devices in Section 9.8.2. An extra limitation is the space required for infiltration basins, which limits their application in dense urban developments. They should be restricted to a maximum catchment area of 4 ha (and ideally around 1 ha) to reduce the risk and consequences of premature clogging.

9.9.3 Advantages and disadvantages

The advantages and disadvantages of infiltration basins are summarised in Table 9.9.1.

Table 9.9.1 *Advantages and disadvantages of infiltration basins*

Advantages	Disadvantages
Reduce volume of water running directly to watercourses and recharge groundwater	Cannot be used in hotspots without prior treatment of runoff
Can be used where there is no outfall for surface water such as a suitable watercourse or sewer	Cannot be used unless soil and groundwater conditions are suitable
Simple and cheap to construct	Do not normally provide amenity benefits (but can be combined with bioretention principles to increase aesthetic and amenity provision)
When clogging occurs it is visible and so can be easily dealt with	Statutory sewerage undertakers will not currently adopt infiltration devices
	There may be a legal liability to owner if groundwater pollution occurs (Newman, 2001)
	Require a large area, which reduces their applicability in urban areas

9.9.4 Performance

Pollutant removal

Removal of pollutants occurs on the infiltration device's base and also in the underlying soils where pollutants are filtered and adsorbed on to soil particles in the unsaturated zone. The pollutant-removal efficiencies quoted all include some element of removal in the soils beneath the devices, although the proportion cannot be quantified.

There is a very wide variation in reported performance of infiltration basins, but most of the basins studied appeared to be failing due to silting (Urbonas, 1994). At that time it is also likely that they were constructed without pre-treatment facilities.

The removal efficiencies are provided in Table 9.9.2.

9.1 9.2 9.3 9.4 9.5 9.6 9.7 9.8 9.9 9.10 9.11 9.12 9.13 9.14 9.15

Table 9.9.2 *Pollutant removal efficiencies for infiltration basins*

Pollutant	Removal efficiency (per cent)		
Reference	**USEPA, 2002**	**Urbonas, 1994**	**Design values from Section 3.4.2 of this book** [1,2]
Method	Unknown	Unknown	
Total suspended solids	75	0–99	45–75
Nitrate/nitrogen	55–60	0–70	55–60
Total phosphorous	60–70	0–75	60–70
Hydrocarbons	—	—	—
Cadmium	85–90	—	85–90
Copper		—	
Lead		0–99	
Zinc		0–99	

Notes

1 Use lower values for sites where maintenance may not occur or to give increased confidence that design parameters will be met.

2 The values assume that a sediment or forebay or stilling chamber is provided and that the inlet from the chamber to the basin is designed as a filter strip.

Hydraulic performance

A high failure rate of infiltration basins has been reported in the USA (Hilding, 2000). This was reported to be in areas where the soils had a high clay content and a correspondingly low infiltration rate. To investigate this further, a study of 23 infiltration basins in the Pacific North West of the USA was undertaken. The study found that the infiltration basins had been constructed in permeable soils (clay content was a maximum of 13 per cent, with infiltration rates between 7.8×10^{-6} and 2.5×10^{-4} m/s).

The majority of the basins were still working after 10 years, but some problems had been encountered. There was standing water in 26 per cent, but in every case this was because of a high water table. Sediment was noticeable in 35 per cent of basins, but none had been provided with pre-treatment.

The difficulty of sustaining grass growth on the basin floor was reported as a frequent maintenance problem, but this is not surprising if the floor was below the water table level.

9.9.5 Design criteria

Soil and groundwater requirements

The soil and groundwater requirements for infiltration basins are the same as for the other infiltration devices discussed in Section 9.8.5.

Hydraulic design

The hydraulic design requirements are similar to those for other infiltration devices and the same design methods provided in Section 9.8 may be used. The maximum storage depth should be limited to 0.8 m to limit the effects of water pressure on the vegetation in the basin and it should be designed to half empty within 24 hours, again to avoid distress to the vegetation.

Pollutant removal

Pollutant removal from runoff by infiltration basins occurs by surface filtration and by filtration and adsorption into the soils underlying the basin. Pre-treatment to remove sediment is an important element of infiltration basin operation, because it can markedly improve pollutant removal. Pre-treatment is usually effected by means of a sediment forebay or stilling basin and by designing the outlet from the forebay to the pond as a grassed filter strip for further removal of sediment. Incorporating these two elements into the design should also significantly lower the rate of clogging.

The stilling basin should have a volume equal to 25 per cent of the water quality treatment volume. The design requirements for the stilling or sediment forebay are the same as for ponds (Section 9.11). A vertical staff gauge should be provided to allow the depth of sediment accumulation to be monitored.

Erosion

Erosion protection should be provided around the inlets to the infiltration basin. The protection can take the form of gabions, rip rap or reinforced soil solutions.

Extreme events

Infiltration basins should incorporate an overflow weir and emergency spillway (or other overflow arrangement) to deal with runoff from events that exceed the design capacity.

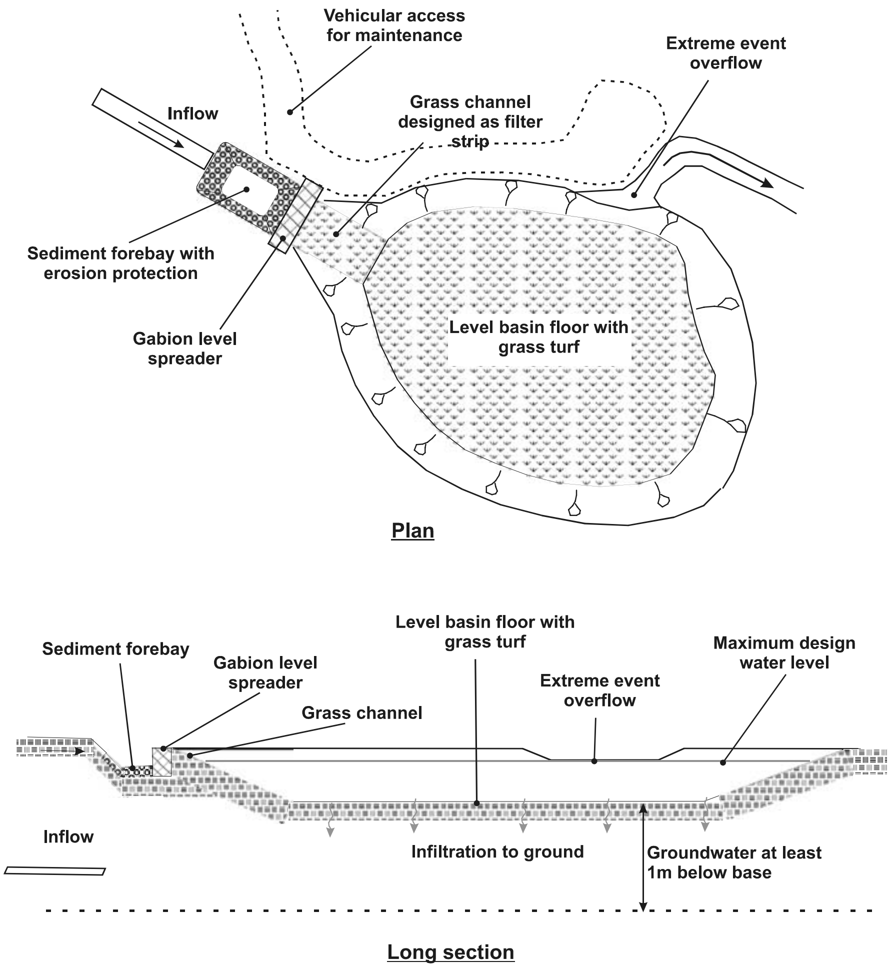

Figure 9.9.2 *Example details of an infiltration basin*

Design details

Infiltration basins should be designed with two things in mind.

1 Prevent heavy sediment loads getting into the basin.

2 Provide easy access for maintenance.

The base of the infiltration basin should be level and even, to promote even infiltration, and should be at least 1 m above the water table. A level spreader should be provided at the inlet to the basin from the stilling basin to promote shallow sheet flow into the basin, to maximise pollutant removal. For safety reasons, the side slopes to an infiltration basin should be no greater than 1:3. The rate of inflow and rise in water levels should slow enough to obviate any hazard.

Inlets

A sediment forebay should be provided. The inlet to the basin from the forebay should be via a level spreader to encourage even shallow flow into the basin.

9.9.6 Construction

The base of the infiltration basin must be constructed to an even grade with no significant undulations. This is required to promote even infiltration across the whole base of the system.

The soils in the base and sides of the infiltration basin should not be smeared or compacted during construction. Light construction plant should be used, and after completion the base should be rotavated. The soils in the base of the basin should be inspected by a geotechnical engineer to confirm they are suitable for infiltration.

The base and sides of the basin should be stabilised before runoff is allowed to enter it. Construction runoff should not be allowed to enter the infiltration basin. If the basin is required to deal with construction runoff a sacrificial layer should be left in the basin. This layer, which will become clogged, can be removed at the end of construction. Typically, a 450 mm-thick layer should be acceptable.

9.9.7 Planting

Planting in an infiltration basin should be able to withstand both wet and dry periods. The same criteria that apply to planting in bioretention areas and swales should be applied in infiltration basins (Section 9.4 and 9.7).

Deep-rooted plants are preferable, as these will improve infiltration by creating small conduits within the soil. Low-maintenance, rapidly germinating grasses are preferred, because these will stabilise the sides and base of the basin quickly.

To reduce the maintenance requirements, planting with wildflower meadows may be considered (see Planting in Section 9.11.2).

9.9.8 Operation and maintenance

The useful life of an infiltration basin is directly related to the frequency of maintenance, and effective operation is dependant on maintenance. If correctly designed and maintained, infiltration basins can last up to 30 years.

The recommended maintenance schedule for infiltration basins is provided in Table 9.9.3.

Table 9.9.3 *Maintenance requirements for infiltration basins*

Operation	Frequency
Inspections to identify any areas not operating correctly and infiltration surfaces that have become compacted, silt-laden or ineffective for any reason. Areas that are ponding or where water is lying for more than 48 hours should be noted.	Monthly
Collect and remove from site all extraneous rubbish that is detrimental to the SUDS operation and the appearance of the site, including paper, packaging materials, bottles, cans and similar debris.	Monthly
Maintain grass height within the specified range. Ensure that soil and grass does not become compacted. Do not cut during periods of drought or when ground conditions or grass are wet, without prior agreement.	Monthly
Remove sediment from pre-treatment devices (eg catchpits or forebays).	As required based on rate of accumulation
Repair grassed areas damaged by trampling, abrasion or scalping during mowing. Maintain turf or vegetation in a manner appropriate to the intended use and replace eroded areas when necessary.	Annually or as required
Scarifying and spiking. Thatch is a tightly intermingled organic layer of dead and living shoots, stems and roots, developing between the zone of green vegetation and the soil surface. To improve infiltration performance, break up silt deposits and prevent compaction of the soil surface it should be scarified with tractor-drawn or self-propelled equipment to a depth of 5 mm to relieve thatch conditions and remove dead grass and other organic matter. Thatch removal should be carried out in dry conditions free from frost. Perforation of the soil surface using tractor-drawn or self-propelled spiker to penetrate panned layers to 100 mm depth and allow water to percolate to more open soil below. Follow by top-dressing with a medium-to-fine sand. Spiking is particularly effective when the soil is moist.	Annually or as required
Remove sediment when failure occurs, spike and replace vegetation (see above).	As necessary (typically every five years)

9.10 FILTER DRAINS

Box 9.10.1 *Key considerations for filter drain design*

Description

Trenches filled with a permeable material into which runoff is collected from the edge of paved areas, then stored and conveyed.

Design criteria

Rate of percolation of water through filter material estimated using Darcy's law. The rate of percolation should be sufficient to meet the design criteria.

Storage of water is dependent on the void ratio of the aggregate.

Design of slotted pipe is normally based on conventional piped drainage methods to achieve the required flow to meet the site-specific design criteria.

Pollutant removal

Moderate to good.

Applications

Normally used next to roads and in parking areas.

Limiting factors

- Only suitable for small catchments.

Maintenance

- Monthly inspections
- monthly weed control
- annual sediment removal and vegetation build-up
- replace clogged filter material (as required – typically 10 years or more).

9.10.1 Description

Filter drains are trenches filled with a permeable material into which runoff is collected from the edge of paved areas, then stored and conveyed (Figure 9.10.1). A slotted pipe is incorporated in the base of the trench to collect and convey filtered water. A filter drain behaves in a similar way to a sand filter (Section 9.5). The residence time is lower, however, because the gravel infill has a higher permeability than sand. They are also known as French drains.

Figure 9.10.1 *Filter drain*

9.10.2 Suitable applications

Filter drains are normally used next to roads and in parking areas to take runoff from the adjacent paved area. Runoff enters the filter drain by flowing over the pavement's edge into the filter material.

9.10.3 Advantages and disadvantages

The advantages and disadvantages of filter drains are summarised in Table 9.10.1.

Table 9.10.1 *Advantages and disadvantages of filter drains*

Advantages	Disadvantages
Conventional technique that is simple to construct and well understood	Filter material can be prone to clogging as it is not usually feasible to provide pre-treatment
Very little land take	Frequent maintenance is required to prevent build-up of a grass lip at the road's edge that prevents runoff flowing into the drain
	Stone scatter can occur (this can be prevented by binding the surface layer of filter material with bitumen)
	If not lined, it can leak water into the road pavement

9.10.4 Performance

Pollutant removal

The presence of pollutants in runoff from a filter drain in Aberdeen, located next to a highway, has been monitored by the University of Abertay, Dundee (Wigham, 2000). The results are summarised in Table 9.10.2, although the removal efficiency was not determined.

Table 9.10.2 *Pollutant concentrations in outflow from a filter drain (Wigham, 2000)*

Pollutant	Concentration in runoff (mg/l unless stated) 21 Feb 2000	3 April 2000
pH	6.9	7.0
Conductivity	15 700 µs/cm	16 800 µs/cm
Total suspended solids	531	251
Biochemical oxygen demand	13	8.2
Ammoniacal nitrogen	2.5	2.65
Chloride	5940	5983
Aluminium	4.43	4.65
Cadmium	2.72 µg/l	0.62 µg/l
Lead	736 µg/l	81.5 µg/l
Chromium	90.3 µg/l	13.6 µg/l
Copper	366 µg/l	11.1 µg/l
Nickel	47.2 µg/l	9.25 µg/l
Zinc	1670 µg/l	298 µg/l
Hydrocarbons	5.51	5.65

The high levels of chloride and conductivity were attributed to winter salting of the road; suspended solids were also high. The type of filter material is not known, but if coarser material allowing fast percolation of water is used the pollutant removal will be reduced. The levels of metals and hydrocarbons in the runoff were reported to be relatively low.

Testing of a filter drain on the M1 motorway in the UK determined the pollutant removal efficiencies given in Table 9.10.3. In the absence of other data, these values may be used as upper limits to assess the effects of filter drains within SUDS schemes.

Table 9.10.3 *Mean annual removal efficiencies for filter drains (Luker and Montague, 1994)*

Pollutant	Mean annual removal efficiency (per cent)
TSS	85
Total lead	83
Total zinc	81
Solid associated zinc	84
Dissolved zinc	56
Chemical oxygen demand	59
Oil	70*
Polycyclic aromatic hydrocarbons	70*

* Estimated value

Hydraulic performance

The filter drain alongside a road in Aberdeen discussed in the previous section was also monitored to assess its hydraulic performance (Jefferies, 2001). The drain is 750 m long and takes runoff from the road and footways. The trench was designed as an infiltration device but acted as a filter drain due to the low permeability of the surrounding soils (1×10^{-10} m/s).

The outflow from the filter drain was highly variable, ranging from 0.8 per cent to 196 per cent and averaging 41.6 per cent (Figure 9.10.2).

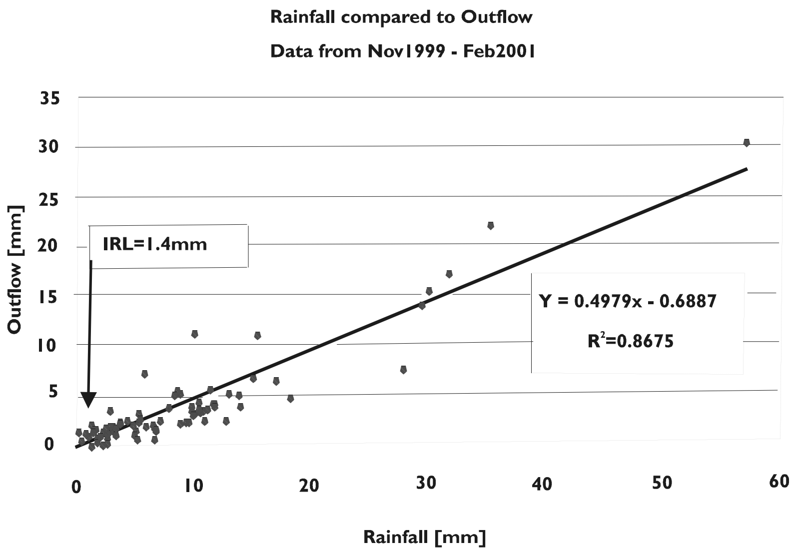

Figure 9.10.2 *Rainfall compared to outfall from a filter drain (Jefferies, 2001)*

Another study of the same filter drain found that as the depth of rain for any event increased, the percentage reduction in outflow decreased. The performance in very wet antecedent conditions lead to a drop in attenuation performance (Wigham, 2000).

9.10.5 Design criteria

Soil and groundwater requirements

Filter drains may be used in any ground conditions. They will require lining in permeable soils if infiltration is not desirable (for example, if the risk of groundwater pollution is unacceptable).

Hydraulic design

There are three elements to the design of filter drains.

1. Design of filter material to percolate water. The rate of percolation is a compromise between pollutant removal and the need to restrict the risk of flooding in the catchment to the design storm event.
2. Design of filter material to store water. The greater the void ratio, the more storage is available in the trench.
3. Design of the pipe system to convey water.

The rate of percolation of water through the drain filter material can be estimated using Darcy's law. The rate of percolation should be sufficient to meet the design criteria.

The storage of water within the trench and aggregate is dependent on the void ratio of the aggregate.

The slotted pipe in the base of the filter drain should be designed using conventional pipe design methods to achieve flows required to meet the site-specific design criteria.

Pollutant removal

Pollutant removal depends on the residence time to allow adsorption of pollution to the aggregate. It also depends on the grading of filter material in respect to the solids in runoff, which determines the amount of filtration that will occur. The level of TSS removal in filter drains can be estimated by calculating the flow through time for runoff to percolate to the perforated drain and also the hydraulic conductivity of the filter material. These values can be compared to the values of TSS removal given for sand filters in Section 9.5 (Figures 9.5.4 and 9.5.5).

Erosion

The main cause of filter drain erosion is from vehicles running off the carriageway and scattering the filter material. This can create a hazard to vehicles on the carriageway as well. To avoid this, the top 200 mm layer of filter material can be bound with bitumen or reinforced with geo grids or cellular systems (Highways Agency *et al*, 1996).

Extreme events

The surface of the filter drain should be dished to form a channel shape to carry runoff from extreme events. Overflows into the slotted pipe within the drain should be provided at the necessary intervals.

Design details

An example detail is provided in Figure 9.10.3.

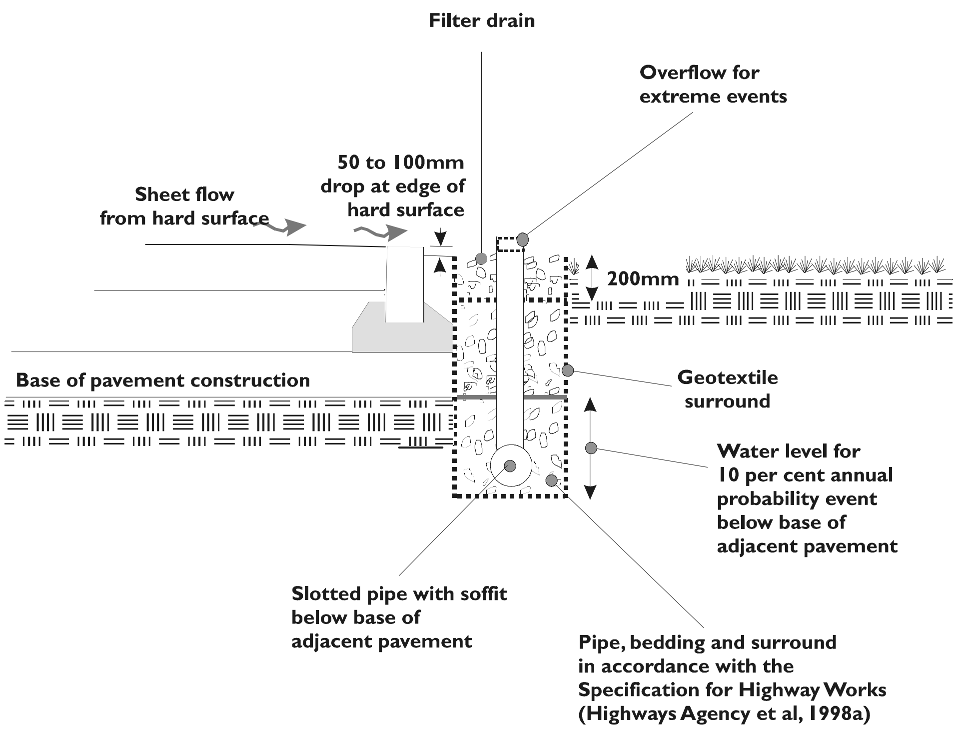

Figure 9.10.3 *Example details of a filter drain*

A geotextile should be provided around the outside of the filter drain. If a geotextile is placed over the top of the filter material at 200 mm depth it will collect sediment and prevent blockage of the whole depth of filter, thus minimising the volume of material requiring replacement when the filter eventually clogs.

Inlets

Flow into a filter drain is normally via runoff direct from the edge of the adjacent pavement. A drop of 50 mm to the filter drain should be provided to reduce the risk of sediment and vegetation build up blocking flow. Alternatively, runoff can be collected from gullies and be piped into the top of the filter drain.

9.10.6 Construction

Construction runoff should not be allowed to enter filter drains as it will cause clogging due to the high sediment loads.

9.10.7 Operation and maintenance

The recommended maintenance schedule for filter drains is provided in Table 9.10.4.

Table 9.10.4 *Maintenance requirements for filter drain*

Operation	Frequency
Inspections to identify any areas not operating correctly, infiltration surfaces that have become compacted, silt-laden or ineffective for any reason. Record any areas that are ponding and where water is lying for more than 48 hours. Report to client.	Monthly
Weed control to prevent accumulation of silt and ensure a neat appearance. Weed growth on filter drains is often temporary due to lack of soil, and drying of the trench will kill most weed growth during summer. Hand-pull, or spot treat with Glyphosphate or similar approved herbicide, perennial weeds such as nettles, docks, thistle and ragwort that have become established in the gravel surfaces. Avoid blanket spraying of weedkiller, which may inhibit bioremediation of organic pollutants and contribute to pollution load.	Monthly
Remove any sediment or vegetation build-up at edge of carriageway.	Annually
Remove clogged filter material and geotextiles and replace. This can be minimised by placing geotextiles close to surface to prevent silt migration into the filter aggregate.	As necessary (typically every 10 years next to highways but may be longer where silt loads are lower)

9.11 PONDS AND DETENTION BASINS

9.11.1 Wet ponds

Box 9.11.1 *Key considerations for wet pond design*

Description

Basins that have a permanent pool of water and provide temporary storage above it.

Design criteria

- Pond shape irregular with islands and bars
- length:width 1.5:1 to 4:1
- inlet velocity 0.3–0.5 m/s
- sediment forebay = 20 per cent of permanent pool volume
- side slopes 1:3 maximum
- space above permanent pool for temporary storage
- pond area = 150–250 m^2/impermeable ha
- volume of permanent pool = V_t (exceptionally = $4V_t$).

Pollutant removal

Very good.

Applications

Can be used in most sites, the only restriction being space.

Limiting factors

- Space required
- needs a large enough catchment to maintain a permanent pool.

Maintenance

- Monthly inspections
- monthly litter removal
- mow side slopes as required (typically monthly)
- bank clearance annually or every three years
- manage wetland plants (annually or every three years)
- remove sediment in forebay as required (typically three to seven years)
- repair damaged vegetation
- remove sediment in main pond (25 years or greater).

Description

Wet ponds are basins with a permanent pool of water in the base (Figure 9.11.1). Temporary storage is provided above the level of the permanent pool and the primary pollutant removal mechanisms are the settling out of solids and biological activity in the pond (which removes nutrients). Temporary storage is usually designed to promote pollutant removal, with the residence time being the key factor in the level of treatment obtained. Typically a residence time of 24–48 hours gives a reasonable balance between pond size and treatment level.

Figure 9.11.1 *Wet pond*

9.1 9.2 9.3 9.4 9.5 9.6 9.7 9.8 9.9 9.10 9.11 9.12 9.13 9.14 9.15

Wet ponds – also known as stormwater ponds, retention ponds and wet extended detention ponds – are widely used as a SUDS technique, largely because they are cost-effective and can be applied as a site or regional control.

Wherever possible, wet ponds should be designed to provide enhanced amenity and wildlife benefits, provided the alternative uses are compatible with the primary function as part of a stormwater management system (Section 9.11.1.5). They are constructed by excavating a depression in the ground or constructing an embankment to retain the stored water.

Suitable applications

Wet ponds can be used in most sites. The only restriction is the space required, which limits their use in constricted city-centre or other urban sites. They can accept runoff from hotspots if they are lined or located on impermeable soils. If the soils below the pond are highly permeable a liner will be required to maintain the wet pool.

They also require sufficient catchment area to maintain the wet pool and experience in the USA suggests a minimum catchment area of around 4 ha and preferably 10 ha (Maryland Department of the Environment, 2000, and USEPA, 2002, among others), although others suggest a minimum catchment as low as 2 ha. Ponds are most often used as a site or regional control.

Advantages and disadvantages

The advantages and disadvantages of wet ponds are summarised in Table 9.11.1.

Table 9.11.1 *Advantages and disadvantages of wet ponds*

Advantages	Disadvantages
Can be used in most ground conditions	Land take limits use in congested sites
Can be used in hotspots if lined	Perceived safety hazard
Provide aesthetic, amenity and wildlife benefits	
Well-designed ponds can increase the value of properties located around them	

Performance

Pollutant removal

SUDS ponds have been used widely in Scotland since the mid-1980s (Heal, 2000), where a comprehensive study of the pollutant removal from ponds was carried out. The study is discussed in detail in Case Study 2 presented in Appendix 4. The results show that the ponds are effective in removing pollutants from stormwater runoff; removal levels are comparable to those reported in the US studies discussed below (Jefferies, 2001).

Monitoring of two wet detention ponds was undertaken in Washington State, USA, to determine their pollutant removal performance (Comings *et al*, 1998). One of the ponds was designed to treat pollution and improve water quality (area equal to 5 per cent of the catchment and a detention time of one week) and the second was also designed to attenuate flows (1 per cent of the catchment area with a detention time of one day, though there was evidence of short-circuiting). The results showed good removal of all the pollutants tested over a one-year period, with the pond designed purely to improve water quality performing better than the one that was used for both water quality and attenuation.

Another study of two wet ponds was undertaken to assess the effects of pool size and volume on pollutant removal performance (Schueler, 2000h). Lakeside Pond had a pool volume some seven to 15 times greater than that usually specified. The Runaway Bay pond was 20 times smaller than Lakeside Pond. The pollutant-removal characteristics are summarised in Table 9.11.2.

Table 9.11.2 *Effect of pond dimensions on pollutant removal (Schueler 2000h)*

	Lakeside Pond	Runaway Bay
Characteristics		
Drainage area (ha)	26	177
Pond area (ha)	1.9	1.3
Mean depth (m)	2.4 m	1.2 m
Pool volume	Equivalent to 180 mm rainfall on catchment	Equivalent to 8.4 mm rainfall on catchment
Pollutant removal		
Total suspended solids	93	62
Total phosphorous	45	36
Kjeldahl nitrogen	32	21
Extractable zinc	80	32
Extractable iron	87	52

The larger pond was more effective in removing pollutants although the difference in performance between the two was not as great as expected, given the difference in size. This was attributed to short-circuiting in the larger pond, causing the detention time to reduce to only a few hours.

Monitoring results from ponds designed in accordance with the most recent US guidelines show they work better and give pollutant-removal efficiencies above the average national values from the USA (Schueler, 2000g). The results of monitoring are summarised in Table 9.11.3. The study demonstrated the importance of providing ponds with sufficient size and detention time (the ponds had detention times of between two and 70 days), aquatic benches and well-established vegetation.

It was also reported that in arid climates evaporation played a key role in the removal of pollutants. Similar findings were also reported for ponds in Canada (Schueler, 2000k) that had similar good design features and large volumes (designed to store a water quality volume based on 13–17 mm of rainfall) – see Table 9.11.3.

A study of pond performance in Minnesota found that their performance reduces in winter (Oberts, 2000). The reasons cited were reduced biological activity and a reduced pool volume because of the formation of an ice layer on the water surface. The ice layer can also force inflow under it, so that it scours the base and re-suspends sediment. The results indicate there is a 50 per cent drop in removal efficiency during snowmelt conditions. If snowmelt is significant, pre-treatment of runoff will be needed before it reaches the pond (in a filter strip or swale, for example).

Another study in Canada found that winter removal of pollutants from three ponds was only slightly lower than during the growing season (Schueler, 2000k).

The removal efficiencies quoted in the literature are summarised in Table 9.11.3.

Table 9.11.3 *Pollutant removal efficiencies for wet ponds*

Pollutant / Reference	USEPA, 2002[1]	Atlanta Regional Commission, 2001 (median values)	Comings et al, 1998[2]	Schueler, 2000f	Schueler, 2000g	Schueler, 2000k	D'Arcy, 1998[3]	Jefferies, 2001	<www. bmpdatabase. org>	Winer, 2000	Yousef et al, 1986[4]	Mikkelsen et al, 2001	Design values from Section 3.4.2 of this book[5]
	Removal efficiency (per cent)												
Method of estimation	Unknown	Unknown	Mass load	Unknown	EMC	EMC	Unknown	EMC	EMC	Various	EMC	Unknown	
Total suspended solids	67 (20–99)	80	61–81	78	83–93	75–86	90	+0.3	4–99	80	—	70–84	75–90
Nitrate/ nitrogen	31 (-12–85)	30	—	-12	50–55	-1–18	—	—	-1–64	33	86.5	7–33	30–50
Total phosphorous	48 (12–91)	50	19–46	49	52–87	56–67	50	—	-60–88	51	11.4 (90.1)	40–74	30–50
Hydrocarbons	—	—	—	—	—	29–51	—	80	32–66	—	—	—	30–60
Cadmium			52–68	—	—	49–80	80	65	-10–67	—	—	11–50	
Copper	24–73 (-25–99)	50	37–47	57	—	22–65	70	77–84	-40–89	57	77 (50)	30–75	50–80
Lead			73–76	—	39–90	11–73	80	58–75	-21–93	—	95 (55)	48–82	
Zinc			45–72	51	27–86	25–72	50	42–68	-54–93	66	96 (88)	30–82	

Notes

1 Typical design range of values from literature quoted in brackets.
2 Lower values for quality/attenuation design, higher for quality only, except for cadmium.
3 Assumes permanent pool designed for at least two-week residence time.
4 Particulate, dissolved in brackets.
5 Use lowest values for sites where maintenance may not occur or to give increased confidence that design parameters will be met.

Wet ponds, in common with all other SUDS techniques, cannot remove *all* pollution from runoff. The irreducible concentrations (levels that cannot be reduced by further treatment) for various SUDS techniques, including ponds, have been estimated in the USA (Schueler, 2000b). These irreducible levels exist because internal biological processes within ponds produce nutrients and there are limits to the degree of sedimentation that can occur. Removal rates become asymptotic as the detention time in the pond increases and so further retention time beyond 24 hours does not provide significant improvement in quality (Figure 9.11.2).

Sedimentation is the major pollutant removal mechanism in ponds , so the sediment collected in the base of ponds can be expected to be contaminated. This has been confirmed by various studies in the UK and the USA. Phosphorous collects in sediments, but nitrogen is removed by denitrification (Yousef *et al*, 1986).

The sediment load into two ponds has been studied in Scotland. The sediment volume entering the ponds was estimated to be between 124 m^3/yr and 501m^3/yr (Heal, 2000). This gave an estimated life for the ponds of 31–37 years. The sediment depth was monitored over the area of one pond and as shown in Figure 9.11.3, the majority of sediment is deposited close to inlets in the primary basin.

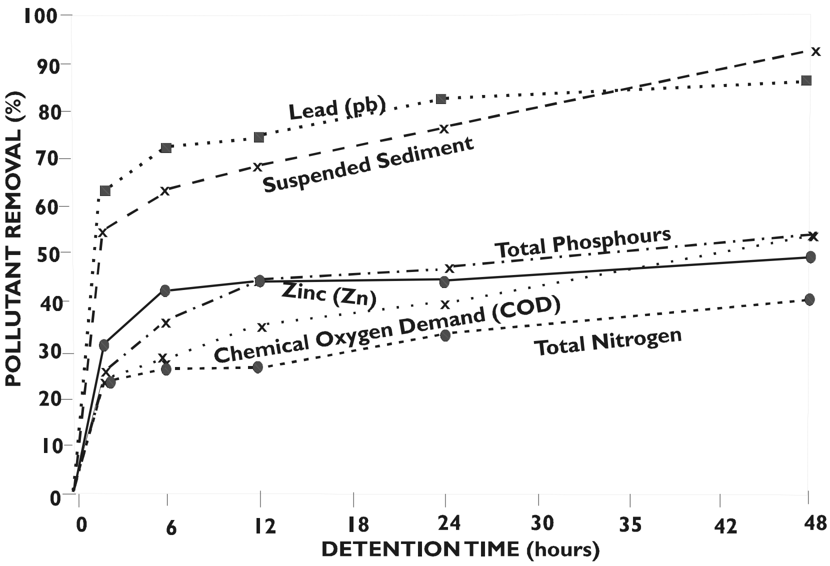

Figure 9.11.2 *Removal rate versus detention time for wetlands (Grizzard* et al*, 1986, quoted from Schueler 2000b)*

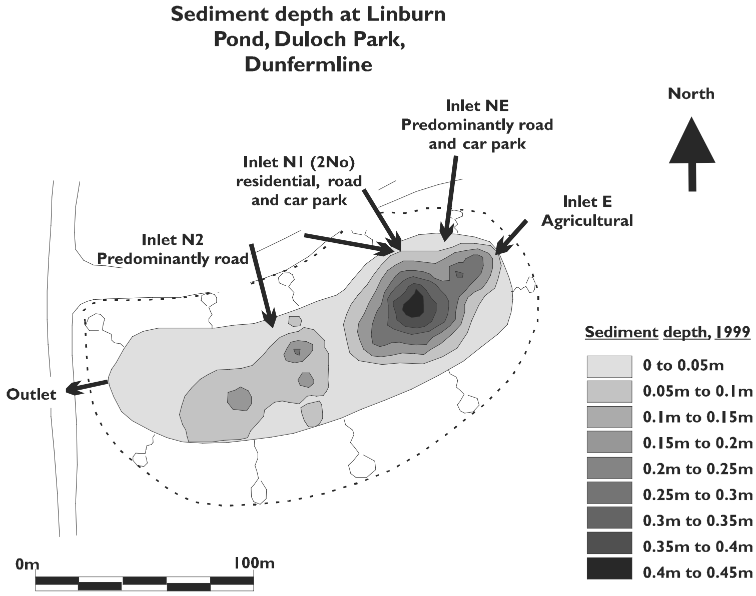

Figure 9.11.3 *Sediment depth, Linburn Pond, Scotland, 1999 (Heal, 2000)*

The pollutant concentrations in the sediment are summarised in Table 9.11.4. However, pollutants are not just trapped in the sediment. As the layer builds up it becomes dynamic and various processes can occur within it (Schueler, 2000j and 2000g). Pollutants can thus be removed from the sediment by plant uptake or biodegradation. Metals were fixed in the sediment and less than 10 per cent of cadmium and zinc were leachable. Negligible leaching of copper and lead occurred. Sedimentation rates were reported to be between 2.5 mm and 25.4 mm per year, with the larger values applicable to ponds that were small in relation to their catchment. Sediment deposition was found to be irregular, with the greatest amounts being placed near to inlets, as would be expected. The pollutant levels from this study are also provided in Table 9.11.4. It was concluded that the sediment in the USA studies was not a toxic hazard (it could be land-applied in USA) and that pond clean-out was likely to be required every 25 years (every five to seven years for the forebays).

Table 9.11.4 *Pollutant concentrations in pond sediment*

Pollutant	Concentration in sediment mg/kg		
	Schueler, 2000g	Schueler, 2000j	Heal, 2000*
Total phosphorous	—	292–3863	50–2200
Total kjeldahl nitrogen	—	219–11 200	—
Cadmium	—	0.4–15	—
Lead	21.5	11–620	—
Zinc	471	6–3171	15–155
Copper	46.7	2–173	—
Petroleum hydrocarbons	5202	474–12 892	—
PAH	10 210	—	—

* Values from Heal, 2000 estimated from graphs.

A Scottish study suggested that 69 per cent of sediment from Scottish ponds would be classified as uncontaminated using the British Waterways system for classifying dredging arisings for disposal (Heal and Drain, nd). The conclusion was that, based on the British Waterways system, sediment from the majority of SUDS ponds in Scotland would be suitable for disposal on adjacent land within the boundaries of the SUDS. Only 2 per cent was classified as highly contaminated material that required disposal to a landfill site. Conversely, other studies have found high levels of toxic metals in pond sediment (Mikklesen *et al*, 2001) and levels of PAH and TPH that would classify it as special waste in the UK under current legislation (Schueler, 2000g).

The approach to waste disposal of dredgings from SUDS ponds taken by the Environment Agency in England and Wales is provided in the draft *Framework for sustainable drainage systems (SUDS) in England and Wale*s (National SUDS Working Group, 2003). This states that:

> *As part of routine maintenance in the case where an authorisation is not normally required ... operators of SUDS can deposit removed sediment at a point within the site near its point of removal, and not more than 10m from the edge of the structure. For SUDS that are authorised, the Agency will place conditions on the authorisation to control the deposit of sediment removed as part of maintenance.*

Hydraulic performance

The hydraulic performance of ponds in Scotland suggests a typical hydraulic response with a lag time of four hours, which reduced to around two hours as the catchment developed, demonstrating the attenuation of peak flows through the ponds (Spitzer, 2000a). Studies of other ponds in Scotland have demonstrated attenuation of flows with reductions in peak flows of up to 57 per cent (Jefferies, 2001). Further details of the hydraulic performance are provided in Case Study No 2 in Appendix 4.

The studies also demonstrated the reduction in volume of flow from a pond in Scotland as shown in Figure 9.11.4 (Jefferies *et al*, 2001).

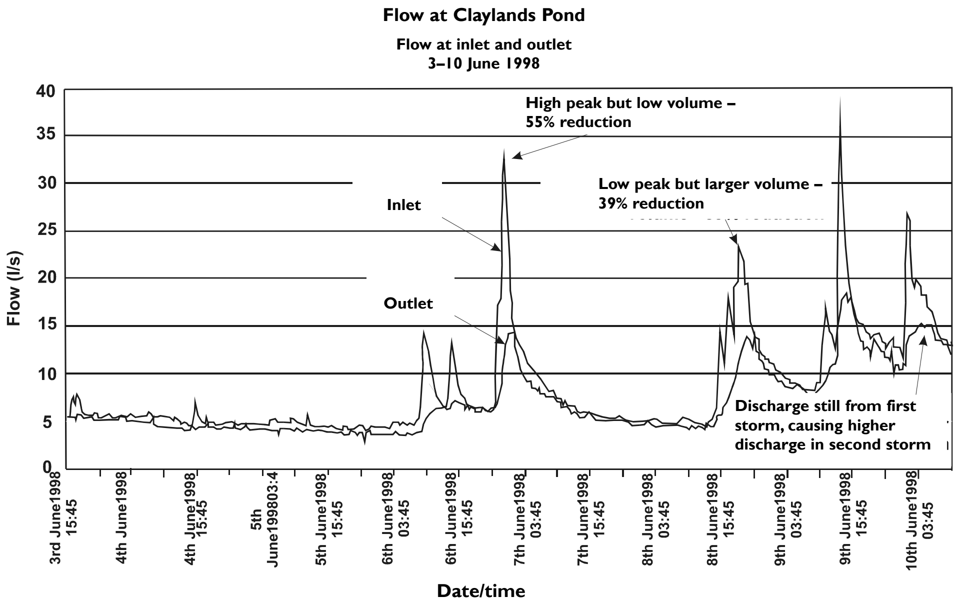

Figure 9.11.4 *Peak flow attenuation at Claylands Pond, Scotland (Jefferies* et al*, 2001)*

Design criteria

Soil and groundwater requirements

The soil below a wet pond must be sufficiently impermeable to maintain the required water levels within the permanent pool. In highly permeable strata such as chalk, a liner may be required to prevent water leaking out of the pond.

There is some evidence that the pollutant-removal performance of ponds is impaired if they intersect the water table, so ideally ponds should be located above it. If a pond is taking runoff from a stormwater hotspot and there is a risk of polluted water infiltrating to the water table, the pond must be lined.

Soil and groundwater conditions should be assessed in relation to the stability of side slopes and any embankment that may be required to impound the pond.

Geotechnical design

If a dam structure is required to form the pond it should be designed by a qualified geotechnical engineer with suitable experience. Any dam impounding a volume of water greater than 25 000 m^3 is subject to the provisions of the Reservoirs Act 1975 (see Section 5.10.3). The Health and Safety Executive may also require similar precautions with smaller reservoirs if they are situated where a breach could cause loss of life (see Section 5.10).

A detailed slope stability assessment of the side slopes and dam structure will be required, taking the phreatic surface within the dam or slope into account. For dams a seepage analysis may be required to identify seepage pathways through and below the dam structure. Generally the side slopes to embankments should be no greater than 1:3 on both the upstream and downstream face (for safety reasons).

Hydraulic design

Wet ponds should be designed with the following three key features.

1 Sediment forebay to remove sediment from runoff entering the pond.

2 Permanent pool of water to encourage biological treatment of runoff.

3 Space above the permanent pool to store the water quality volume temporarily during the required retention time and to meet any attenuation requirements.

A detailed discussion on flood routeing into ponds and their hydraulic design is provided in CIRIA Book 14, *Design of flood storage reservoirs* (Hall *et al*, 1993).

Prevention of short-circuiting of flow through the pond is essential to ensure good pollutant-removal performance (Section 9.11.1). There are two aspects that affect this (Hall *et al*, 1993).

1 Inlet flow conditions.

2 Pond shape.

Inlet velocities should be maintained at 0.3–0.5 m/s, which minimises resuspension of sediment in the pond (Hall *et al*, 1993).

Good inlet design is also important. To promote good distributed flow across the pond, strategically placed islands should be used where necessary to direct flows and the pond shape should be irregular. The distance between inlet and outlet should be maximised.

Wind-induced currents that may occur in large ponds can be avoided by aligning the length with the prevailing wind direction (Ellis, 1989).

Design for amenity and habitat

Ponds and wetlands are probably the most important SUDS technique in terms of providing amenity and wildlife habitat. Ponds designed for flood attenuation have been used very successfully to provide amenity, wildlife and recreational sites in the UK. (Hall *et al*, 1993 and Ellis, 1989). Ponds provide a very rich habitat and are important for aquatic invertebrates, wetland plants and amphibians. They are also used by mammals, birds and fish.

If ponds are well managed and maintained they can be a valuable community asset. For example, Bracknell Forest Borough Council has countryside rangers that look after 16 storage reservoirs in open spaces around the town (Hall *et al*, 1993). Aztec West Commercial Development near Bristol has attractively landscaped ponds that provide valuable landscaping and wildlife opportunities.

To provide the greatest amenity and wildlife benefits, it is important to integrate these requirements into the design at an early stage. It is much more difficult and costly to provide them as a bolt-on extra to a pond designed purely for drainage. Many of the requirements complement the other roles – for example, shallow planting around the pond margins for wildlife also aids pollutant removal.

Accumulation of sediment in shoals or bars provides valuable habitats to wading birds and other wildlife (Hall *et al*, 1993) and the sediment forebay can be provided with shallow marshland plants. Islands break up the flow of water, thereby enhancing pollutant removal, and also provide valuable habitat. Ideally, they should be planted with a dense tangle of shrub on the north and east sides and a shallow shelving beach on the south side. Planting with bramble and wild rose encourages wading birds. Construction of shallow promontories breaks up a pond's lines and provides territorial shelter, seclusion and feeding grounds for a wide variety of species and can split the pond up into different areas for recreational use.

Between 50 and 70 per cent of a pond should have water greater than 1–1.5 m deep in order to encourage oxygenation. Deeper fish pools need to be at least 2.5 m deep. A shallow bench should be provided over 25 per cent of the pond surface. The areas should be randomly distributed around the pond and avoid providing concentric rings of zones around the pond (SEPA, 2000) as shown in Figure 9.11.5.

The Scottish Environmental Protection Agency (SEPA, 2000) provides a list of ways in which SUDS ponds can be improved to provide nature conservation (Box 9.11.2).

Box 9.11.2 *Ways to maximise the nature conservation value of SUDS ponds (SEPA, 2000)*

There are many ways to maximise the nature conservation value of new SUDS ponds and wetlands.The functions and constraints of SUDS schemes vary, and not all of the features will be appropriate in all schemes, but as many as possible should be included.

- Maximise water quality reaching pond basins by fully implementing SUDS treatment sequences to prevent or ameliorate the export of pollutants into pond basins.
- Where possible, locate SUDS basins in, or adjacent to, non-intensively managed landscapes where natural sources of native species are likely to be good.
- Locate water treatment ponds near to (but not directly connected to) other wetland areas such as natural ponds, lakes and river floodplains. Plants and animals from these environments will be able to colonise the new ponds and potentially recolonise them after pollutant influx events.
- Create habitat mosaics with sub-basins of permanent, temporary and semi-permanent ponds; vary these in size (from 10 000 m^2 down to 1 m^2) and depth (1000 mm down to 50 mm).
- Ensure that some ponds, or parts of basins, are not exposed to the main pollutant burden and so allow many more sensitive animals and plants to exploit some parts of the site.
- Create small pools around the margins of larger ponds that are fed by clean surface runoff from non-intensively managed grassland, scrub or woodland on the basin sides.
- Create shallow grassy ponds along swales and floodways, particularly towards their cleanest ends – pools just one or two metres across and only 100 mm deep will be valuable for wildlife.
- Maximise the area of shallow and seasonally inundated ground dominated by emergent plants, which generally are more tolerant of pollutants than submerged aquatic plants.To do this, create very low slopes at the water's edge (eg 1:50) and try to avoid fixing pond levels at a predetermined height.
- Create undulating "hummocky margins" in shallow water; these mimic the natural physical diversity of semi-natural habitats.
- Avoid smoothly finished surfaces as traditionally used in ditch, drain and river engineering.Although they give an impression of tidiness, they provide less physical habitat diversity for plants and animals.
- Plant trees, scrub and wet woodland around ponds.They provide a valuable habitat for amphibians, a food source for invertebrates and tannins from decaying bark to help to prevent algal blooms.
- Encourage development of open, lightly shaded and densely shaded areas or pools; this will add to the diversity of habitats available.
- Encourage or install dead wood in ponds (anchor securely where necessary). Dead wood provides firm substrates for pond animals and can provide egg-laying sites for dragonflies and other animals.
- Encourage the development of mosaics of marginal plants (rather than single-species stands) to maximise habitat structural diversity.
- Avoid artificial planting-up ponds and allow natural colonisation (other than the plants needed for the water treatment function of the pond or the creation of safety barriers).
- Check planting schemes one and two years after establishment to ensure that specifications have been carried out and undertake immediate remedial action if invasive alien species are found.
- Consider whether grazing livestock can be given access to ponds; grazing has been shown to be a viable and effective way of managing some SUDS schemes in agreement with conservation organisations or farmers.
- Wherever possible include a brief post-implementation stage about a year after SUDS creation. Use this to (i) fine-tune the pond design and (ii) capitalise on new opportunities that have arisen (for example, pooling of natural areas of standing waters or natural seepage areas). Fine-tuning of this sort costs very little but will often greatly increase the biodiversity value of a SUDS scheme.

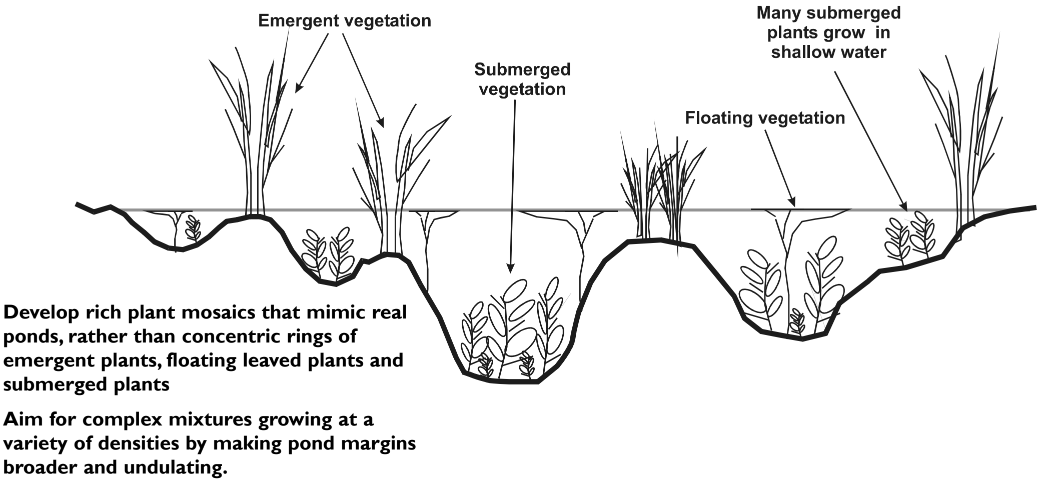

Figure 9.11.5 *Mixed pond vegetation zones (SEPA, 2000)*

Ponds should also be managed in a way that does not degrade the habitat (SEPA, 2000).

In summary the main requirements are as follows.

1. Identify all the species and habitat types in a pond and make sure none are eliminated during maintenance.
2 Only remove sediment or planting from 25 per cent of the pond area at any one time.
3 Pre-treat runoff water before it enters the pond (for example, use source control).
4 Do not remove marginal or aquatic vegetation unless there is a clear objective and reason for it.
5 Only remove 1 m^3 of sediment a year for every 100 m^2 of pond area.
6 Do not worry if shallow ponds dry out occasionally, as this happens in nature.

Ponds can also be used for wide variety of recreational purposes including angling, canoeing, rowing, sailing, wind surfing, subaqua diving and model boats. To use a pond for recreation the water quality should be of an acceptable level to prevent adverse effects on health; be especially aware of bacteria and viruses. Pollution from boats can also affect outflow. Again, consideration must be made at an early stage of design. Factors that affect recreational use include depth, shape and the need for buildings around the edge. More details on the provision of recreational facilities are given in CIRIA Book 14 (Hall *et al*, 1993).

Pollutant removal

Pollutant removal is mainly achieved by sedimentation in the pond forebay and to a lesser extent within the pond itself (USEPA, 2002).

Various criteria are quoted to determine the size of the sediment forebay varying from a volume equal to 10 per cent of the volume of the permanent pool (USEPA, 2002 and Maryland Department of the Environment, 2000) up to 20 per cent of the permanent pool volume, with extra 150 mm of dead space to allow for sediment accumulation (City of Portland Environmental Services, 2002).

Biological activity in the pond also removes pollutants such as nutrients. The key factor is to provide sufficient residence time for runoff in the pond to achieve sufficient removal of pollutants. Design of ponds for pollutant removal has developed based on the particle settling velocities and hydraulic residence time. A detention time of two to three weeks is required to remove nutrients and six to 12 hours is required for TSS removal. However, other studies question the effectiveness of providing detention times longer than 24 hours (Urbonas, 1997).

As discussed, it is also important to prevent short-circuiting, which can lead to retention times as low as three hours (Hall *et al*, 1993). Turbulent flow also causes scouring on the base of the pond and re-suspends sediment.

The most important factor contributing to good pollutant removal is the size of the permanent pool in relation to the catchment area. The larger the pool the better its performance, until a limiting size is reached. CIRIA Book 14 suggests that ponds should be sized so that the surface area of the permanent pool is equal to 1 per cent of the catchment area to achieve 80–90 per cent removal of TSS. A pond area of 150–250 m^2 pond area per impervious hectare of catchment will give a 50–60 per cent removal of nutrients.

Various US stormwater design manuals and technical papers also provide rules of thumb for sizing the volume of ponds. These range from providing a pond volume equal to the water quality treatment volume to a pond volume up to four times this. The most commonly used criteria is to make the volume of ponds equal the water quality volume of runoff from the catchment (commonly known as V_t).

There has been some confusion in the UK about the use of criteria such as sizing the pool to four times water quality volume (sometimes referred to as $4V_t$). Some references suggest this as a method of increasing residence time and thus pollutant removal (for example to increase phosphorous removal). The use of $4V_t$ should not be considered a baseline and the appropriate criteria for a particular site depends on the level of pollutant removal required (V_t is adequate in many cases, especially where other SUDS techniques precede the pond).

CIRIA Book 14 (Hall *et al*, 1993) agrees with this and recommends that the minimum volume of the permanent pool for flood storage reservoirs should be based on one of following criteria.

1. 12–15 mm of runoff distributed over the catchment.
2. 12–15 mm of runoff distributed over the impervious area of the catchment.
3. two and a half times runoff volume generated from mean annual storm.
4. four times the volume generated by the mean annual flood ($4V_t$) if maximum pollutant removal is required. This has a major impact on the size of pond and its use should be carefully considered. In most cases, design to provide temporary storage of V_t provides a sufficient level of removal.

The first three are based on the use of sedimentation as the primary pollutant removal mechanism and the fourth is used to maximise biological uptake so that the pollutant removal becomes more effective. It should also be noted that a small pond with a well-designed shape and form and no short-circuiting will perform better than a large, poorly designed pond.

Various residence time criteria have also been quoted for pond design to achieve effective pollutant removal and these are summarised in Table 9.11.5.

Table 9.11.5 *Pollutant removal design criteria for ponds*

	Brown, 2000	Livingstone, 1989a	USEPA, 2002	Hall *et al*, 1993
Residence time of runoff in pond	2–6 h	120 h	24–48 h	15–24 h (and 5–6 h for smaller storms)

Typically a residence time of 24 hours is most common. One study (Brown, 2000) suggests that the majority of settling takes place in the first six hours and there are limited improvements to pollutant removal with greater times. It recommends that the extra storage above the permanent pool should hold flows for between two and six hours for larger storm events. This is consistent with performance observed in other studies (Schueler, 2000b) as shown in Figure 9.11.2. The maximum proposed residence time in any study was 120 hours (Livingstone, 1989a).

Longer residence times should increase confidence in the likely pollutant removal, although the marginal additional benefits achieved from time periods of more than 24 hours need to be weighed against the increased size of pond required.

If a pond is sized to retain a one-year storm for 24 hours then smaller storms will pass through it more quickly (Hall *et al*, 1993). Pond design should consider several storage routeing calculations to determine the retention times of small frequent storms (which carry most pollution). The aim should be to achieve 15–24 h detention for the large majority of storms, but with at least 5–6 h for smaller storms. This is achieved by having multilevel outlets.

The length-to-width ratio determines the risk of short-circuiting. The criteria quoted generally vary from a minimum ratio of 1.5:1 (USEPA, 2000 and Maryland Department of the Environment, 2000) to 4:1 (Hall *et al*, 1993). The use of features such as islands and underwater berms can also lengthen the pond's flow path (these also provide valuable habitat). The establishment of perimeter wetland areas improves nutrient removal and biodegradation (Schueler and Helfrich, 1989).

A complex analytical method for assessing pollutant removal is given in CIRIA Book 14 (Hall *et al*, 1993). This considers an analysis of particle settling velocities, hydraulic retention time and the calculation of trap efficiency under steady flow conditions, for particles, metals and nutrients. The book also identified the need to assess pollutant-removal efficiency under the varied flow conditions that occur in practice as well as to assess time series flows. This too is reproduced in Appendix 6 and should be used for large and complex ponds or where the receiving waters are particularly sensitive. In other cases, ponds for pollutant removal may be designed using the rules of thumb that have been developed in the USA and the UK, as discussed above.

Erosion

Erosion protection to the sides and base of ponds should be provided at inlets and in watercourses below the outfall. Typically, a stilling basin and rip rap are provided below the outfall.

Extreme events

Ponds should be provided with overflows that allow the safe routeing of runoff from events that exceed the design criteria. The overflow may be a weir or high-level outlet pipe.

Overflows should normally be designed to carry flows in excess of the design water levels (from a 1 per cent probability or 1 in 100-year return period storm) to the downstream conveyance system, watercourse or sewer. The freeboard of the pond above the maximum design water level should be at least 0.3 m.

Design details

Ponds should be located well away from house foundations, septic tanks, slopes or any other sensitive structure that may be affected by the presence of water seeping into the ground. A minimum 8 m buffer zone should be provided around the pond to any developed part of a site.

Example design details are provided in Figure 9.11.6.

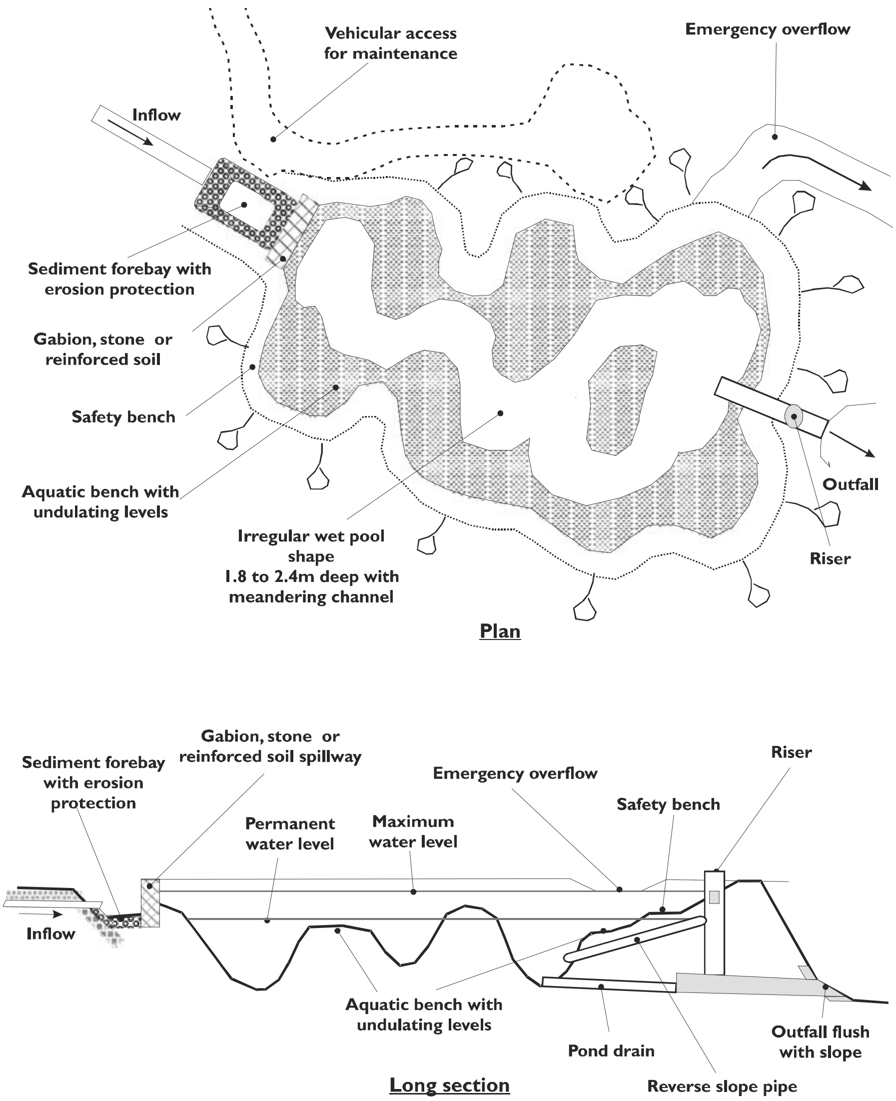

Figure 9.11.6 *Example details of a wet pond*

Construction of promontories and shallow berms is desirable from an aesthetic and wildlife perspective. Hard-covered all-year access for vehicles should be provided to maintenance areas for sediment removal.

The pond should be wedge-shaped (narrower at the inlet than the outlet) to improve the even flow of water through it (Schueler and Helfrich, 1989). Vehicular access should be provided to the pond and forebays so that maintenance can be undertaken easily.

The permanent pool depth should be a maximum of 1.2 m deep (City of Portland Environmental Services, 2002) to 1.8 m deep (Schueler and Helfrich, 1989). The ratio of emergent vegetation to open water should be around 50:50, and 25–40 per cent of the permanent pool area of the pond should have a water depth of less than 0.5 m (Ellis, 1989). The depth of 50–70 per cent of the pond areas should be greater than 1–1.5 m.

Ponds should be designed to eliminate the need for fencing. This can be achieved by providing an aquatic bench no greater than 450 mm deep and at least 3 m wide with 1:3 side slopes or less and barrier planting to discourage access (City of Portland Environmental Services, 2002). Slopes should be a maximum of 6 per cent (1:15) above the water line (in the area known as the safety bench).

An example detail is shown in Figure 9.11.7. Similar geometry requirements are quoted in other stormwater design manuals (for example, Maryland Department of the Environment, 2000 and Atlanta Regional Commission, 2001). Signs may be required stating that no swimming is allowed in the pond and a fixed sediment depth marker should be installed in the forebay.

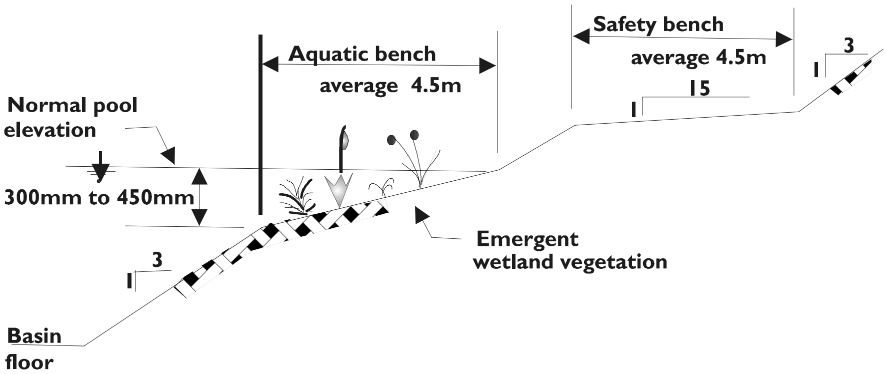

Figure 9.11.7 *Pond geometry (Atlanta Regional Commission, 2001)*

Inlets/outlets

Inlets should be located above the normal pool level and should enter the forebay to remove sediment. CIRIA Book 14 (Hall *et al*, 1993) states that the use of submerged weirs, bifurcating or gradually opening inlet expansion and cascades and stepped inlets will help maximise oxygenation, prevent silting, and provide good horizontal flow distribution in the pool. The inlet and forebay also need to be attractive, safe and easy to maintain.

The most effective method of discharge from a pond is a reverse-slope pipe with the opening located 0.3–0.9 m below the permanent pool water level (Schueler and Helfrich, 1989). This practically eliminates the risk of clogging because the inlet is below the level of surface debris and is not affected by silting.

The outlet to the pond should be provided with a secondary riser pipe (Figure 9.11.8) so that outflow can still occur even if the main outlet becomes blocked.

The inlets and outlets (including the overflow) should be designed to prevent erosion with rip rap, gabions or other reinforcement techniques. Anti-seepage collars (water bars) should be provided around all pipes through embankments.

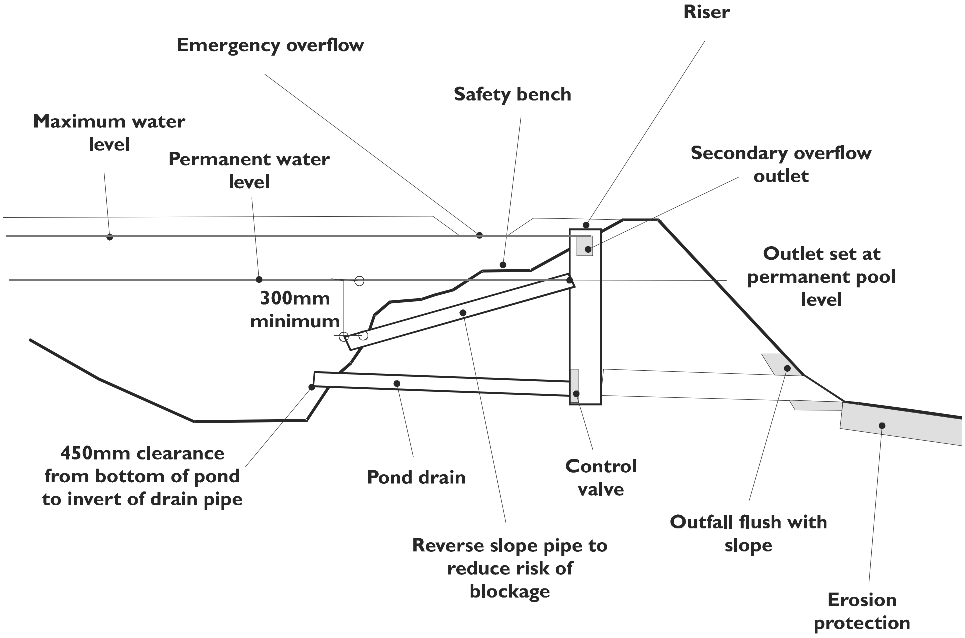

Figure 9.11.8 *Example outlet detail for ponds (Minnesota Metropolitan Council, 2001)*

Construction

Construction runoff should be prevented from entering ponds if possible. If it does, straw bales should be used to isolate the sediment forebay from the main pond, so as to ensure silt does not enter the main pool. All the construction silt should be removed from the forebay before hand-over to the owner. The sides of inlets and outlets and the pond sides should be protected against erosion until the vegetation is established.

Planting

The choice of plant species is important as it affects the pollutant removal, appearance and habitat value of a pond. It also contributes to safety. The different zones for plants that occur around a SUDS pond are shown in Figure 9.11.9.

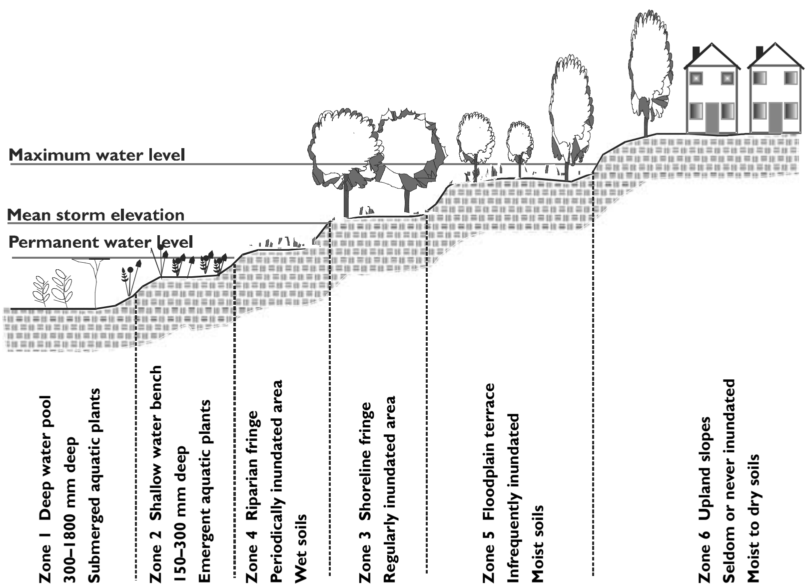

Figure 9.11.9 *Landscaping zones in a wet pond (Schueler and Helfrich, 1989)*

Aquatic species are provided in the permanent pool and species that can tolerate wet and dry periods are located in the area above the permanent pool that provides temporary storage. Using emergent species in the shallows around the edge of ponds improves pollutant removal, promotes settling and stabilises the base to reduce re-suspension.

Emergent species should also be located close to the inlets to enhance pollutant removal. *Phragmites australis* has proved to be especially resistant to severe oiling. *Phragmites* species also form dense strands that provide habitat for reed warblers, bearded tits and other wildlife. Other plants that are resistant to oil pollution include reedmace, fennel pondweed and water forget-me-not (Ellis, 1989).

Native species should be used to establish pond vegetation wherever possible to help establish a diverse ecology quickly. Further guidance on plant selection is provided in Appendix 5, in CIRIA Book 14 (Hall *et al*, 1993) and by SEPA (SEPA, 2000).

Operation and maintenance

The maintenance of wet ponds is crucial to their water quality performance. If correctly designed and maintained, ponds can last indefinitely. Access routes for vehicles should be provided to the pond and forebay to facilitate maintenance. The recommended maintenance schedule for ponds is provided in Table 9.11.6.

Table 9.11.6 *Maintenance requirements for wet ponds*

Operation	Frequency
Inspections to identify any areas not operating correctly, eroded areas, hydrocarbon pollution, blocked outlets, infiltration surfaces that have become compacted, and silt accumulation. Record any areas that are ponding and where water is lying for more than 48 hours. Report to client.	Monthly
Collect and remove from site rubbish that is detrimental to the operation of the SUDS and the appearance of the site, including paper, packaging, bottles and cans.	Monthly
Maintain grass height on side slopes within the specified range. Ensure that soil and grass does not become compacted. Do not cut during periods of drought or when ground conditions or grass are wet, without prior agreement.	Monthly or as required
Bank clearance to remove bank vegetation by cutting to ground level, using an approved technique and as directed on site, up to 25 per cent of all vegetation from the water's edge to a minimum of 1 m above water level, taking care not to damage banks and potential water vole habitat. The work should be undertaken between September and November in any one year. This is necessary to retain water storage, to stimulate vegetation growth at ground level, to protect banks from erosion, to control succession of vegetation to scrub and trees, and to provide cover for wildlife and maintain amenity.	Annually or every three years
Manage wetland plants. There will be a need to: • hand-cut submerged and emergent aquatic plants at least 100 mm above wetland base to include no more than 25 per cent of pond/wetland surface • determine whether a pond liner has been used to waterproof the pond/wetland and protect accordingly • remove all arisings, including floating weed, and spread on bank to dewater for 48 hours • remove arisings to wildlife piles, compost or from site to an approved tip (Sections 7.3 and 7.6).	Annually or every three years
Remove sediment from forebay when 50 per cent full.	3–7-year period
Reinstate design levels, repair eroded or damaged areas by returfing or reseeding, restore or improve infiltration and remove silt by removing existing or damaged vegetation and reinstating surface to design levels.	As required
Remove sediment when pool volume reduced by 25 per cent.	25 years or greater

9.11.2 Extended detention basins

Box 9.11.3 *Key considerations for extended detention basin design*

Description

Basins designed to detain runoff for a period of time to meet both volume objectives and water quality criteria. Normally dry.

Design criteria

- Pond shape irregular with islands and bars
- length:width 1.5:1 to 4:1
- inlet velocity 0.3–0.5 m/s.
- sediment forebay = 20% of permanent pool volume
- side slopes 1:3 maximum
- space above permanent pool for temporary storage
- pond area = 150–250 m^2/impermeable ha
- volume of permanent pool = V_t (exceptionally = $4V_t$).

Pollutant removal

Moderate.

Applications

Most suitable to large catchments with space to provide basin.

Limiting factors

Few limitations. Main one is space required.

Maintenance

- Monthly inspections
- monthly litter removal
- mowing of side slopes as required (typically monthly)
- bank clearance (annually or every three years)
- manage wetland plants (annually or every three years).
- remove sediment from forebay (three to seven years).
- repair damaged vegetation as required.
- remove sediment from main pool (typically every 25 years).

Description

Extended detention basins are depressions designed to detain runoff for a period of time to meet both attenuation objectives and water quality criteria. The detention time determines the amount of settling of particles and associated pollutants from the runoff that occurs. They differ from wet ponds in that there is no large permanent pool of water in the basin, although they can have small permanent pools at the inlets and outlets (Figure 9.11.10). These small pools prevent re-suspension of sediment particles in heavy storms.

Figure 9.11.10 *Extended detention basin*

They are also known as dry ponds, dry extended detention ponds, detention ponds, extended detention ponds and micropool extended detention ponds. Variations include dry detention ponds that have no micropools and are designed only to achieve attenuation criteria, with very limited pollutant removal.

Suitable applications

Extended detention basins have two main limitations.

1 Land take required.

2 They operate most effectively for larger catchments (a minimum of 4 ha is specified by the USEPA, 2002 and Atlanta Regional Commission, 2001) because of economies of scale and the limitations placed on the minimum size of outlet pipes to prevent blockage.

They can be used in most soil conditions, although they will require lining if underlain by permeable soils. Infiltration is not desirable, and they should be located above the groundwater table. Extended detention basins can accept runoff from hotspots provided they are lined with an impermeable liner.

Advantages and disadvantages

The advantages and disadvantages of extended detention basins are summarised in Table 9.11.7.

Table 9.11.7 *Advantages and disadvantages of extended detention basins*

Advantages	Disadvantages
Few limitations to use	Land take required
Can be retrofitted in detention ponds already present by constructing micropools and amending outlets to change the detention time	Only moderate pollutant removal when compared to other SUDS techniques
	Perceived safety implications can cause objections to their use

Performance

Pollutant removal

Considerable variation in the effectiveness of extended detention basins has been reported (USEPA, 2002) and correct design, construction and maintenance is vital to successful operation. They have moderate removal efficiency and limited removal of soluble pollutants because of the absence of a large permanent pool.

Monitoring of a demonstration extended detention basin in the USA found that removal efficiency was reduced significantly in an extremely large and long-duration storm (235 mm of rainfall occurred over five days). Removal efficiency reduced to 22–42 per cent of the median values recorded for all storms at the pond (Schueler, 2000e), but these values include the runoff that bypassed the system and was not treated. It was therefore concluded that even during extreme events the pond still cleaned up the first 12.5 mm of rainfall and performed well. The pond was designed to provide 72 hours of detention for the first 12.5 mm of runoff from the catchment. It was concluded that the poor performance reported for some extended detention basins was due to insufficient retention time.

The removal efficiencies for extended detention basins from the literature are summarised in Table 9.11.8.

Table 9.11.8 *Pollutant removal efficiencies for extended detention basins*

Pollutant	Removal efficiency (per cent)				
	USEPA, 2002	Atlanta Regional Commission, 2001[1]	Schueler 2000e	Winer, 2000	Design values from Section 3.4.2 of this book[2]
Method of estimation	Unknown	Unknown	EMC	Various	
Total suspended solids	61	80	71	60	65–90
Nitrate/nitrogen	31	30	26	31	20–30
Total phosphorous	19	50	14	20	20–50
Hydrocarbons	—	—	—	—	30–60
Cadmium	26–54	50	54	—	40–90
Copper			26	29	
Lead			55	—	
Zinc			26	29	

Notes

1 Assumes forebay and micropool provided.

2 Use lowest values for sites where maintenance may not occur or to give increased confidence that design parameters will be met.

Hydraulic performance

There is no published data on the hydraulic performance of extended detention basins.

Design criteria

Soil and groundwater requirements

The same requirements for wet ponds apply to extended detention basins (see Section 9.11.1).

Hydraulic design

The hydraulic design is on the same basis as wet ponds except there are only very small permanent pools of water at the outlet and inlet.

Pollutant removal

As with wet ponds, pre-treatment is vital and a sediment forebay is required to control silting and reduce the maintenance burden. A small pool with a volume equal to about 10 per cent of the water quality treatment volume should be provided (USEPA, 2002).

A micropool provided at the outlet prevents re-suspension of particulates during extreme rainfall events (Atlanta Regional Commission, 2001 and Maryland Department of the Environment, 2000), otherwise pollutant removal is poor. The micropool at the outlet should be sized to provide a permanent volume equal to 2.54 mm of rainfall per 4000 m^2 impervious area of catchment (Atlanta Regional Commission, 2001).

The area of the pond that is normally dry can be provided with a low-flow channel. This may be designed as an enhanced swale to help improve the pollutant removal (see Section 9.7).

The design of the extended detention basin should be based on sedimentation and residence times in the same way as described for wet ponds in Section 9.11.1. As discussed for wet ponds the optimum detention time is normally around 24 hours and short circuits should be prevented to improve water quality. A tear drop shape prevents short-circuiting (Millerick, 2003).

Erosion

The same criteria apply as for wet ponds (Design criteria, Section 9.11.1).

Extreme events

The same requirements apply as for wet ponds (Design criteria, Section 9.11.1).

Design details

Extended detention basins should have a high length-to-width ratio with recommended values varying between 1.5:1 and 5:1. They should be irregular in shape and have relatively flat side slopes that are less than 1:3 below the water line and less than 1:16 around the edge of the pond to ensure that the slopes do not pose a safety risk. The outfall should be designed to prevent scour and a pilot channel for low flows should be provided. An overflow is normally provided to convey extreme events.

Extended detention basins should be designed to ease maintenance. In this respect, a micropool at the outlet reduces the risk of re-suspension of sediment and of the outlet clogging. Vehicular access for maintenance of the micropools and area for stockpiling dredged sediment should be provided. The sediment stockpile area should not be greater than 10 m from the pond's edge (see Section 7.3). A non-clogging outlet should be provided, for example by using a reverse pipe taking water from below the surface of the micropool (Figure 9.11.7). Example design details for an extended detention basin are provided in Figure 9.11.11. A fixed vertical depth marker should be installed in the forebay to measure sediment deposition.

Inlets

Inlets should be provided to the same criteria as for wet ponds (Design criteria, Section 9.11.1).

Construction

Before construction of the extended detention basin begins, all trees, shrubs, logs, litter and debris should be removed from the basin area.

If an embankment is required to impound the water and provide the storage volume, then the embankment fill material should consist of inert natural soils that will not leach contaminants into the stored runoff.

Embankments should be constructed according to an engineering specification such as the *Specification for highway works* (Highways Agency *et al*, 1998a).

If construction runoff enters the pond the sediment forebay must be cleaned at completion of construction, before handover to client.

The banks of the basin should be stabilised within two growing seasons to minimise the risk of erosion. The area around the inlet and sediment forebay should be stabilised before a basin is commissioned into use.

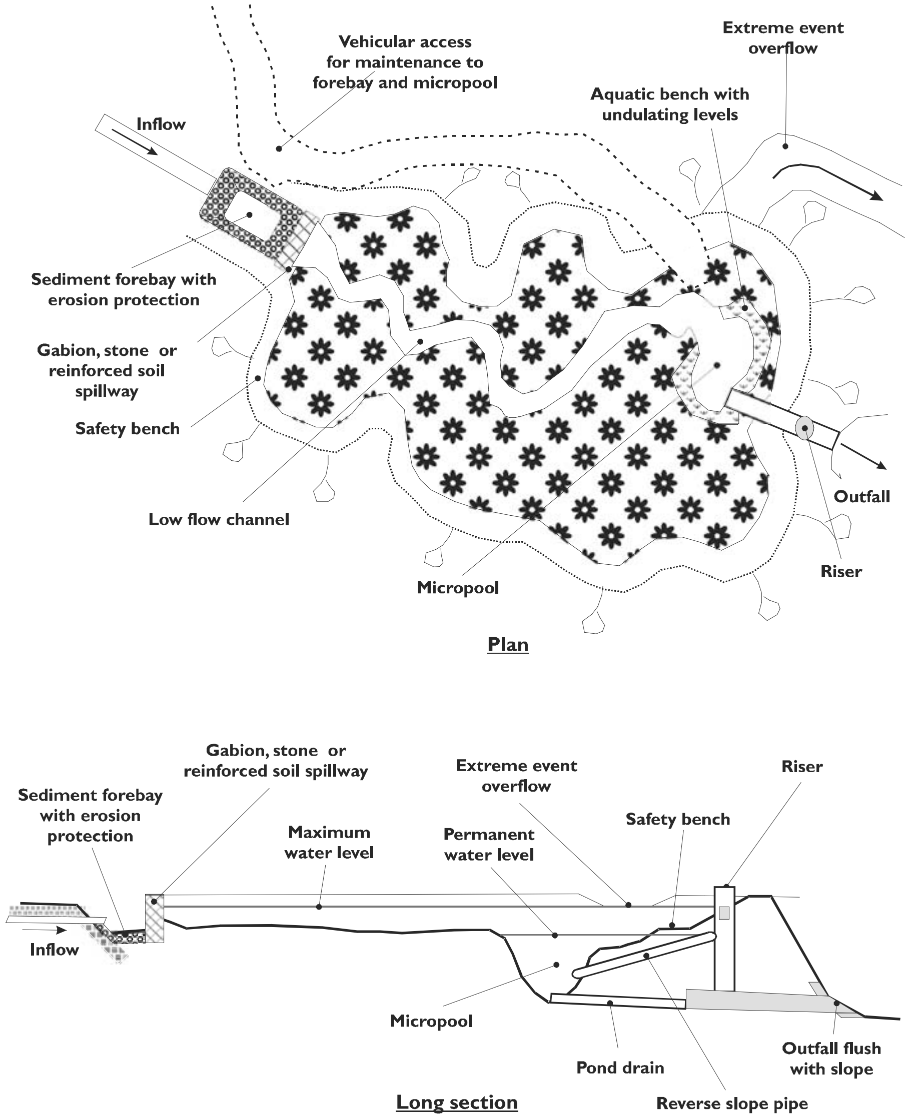

Figure 9.11.11 *Example details of an extended detention basin (Highways Agency* et al, *2001)*

Planting

A vegetated buffer zone should be maintained around extended detention basins. Plants within the detention zone need to be able to withstand wet and dry periods.

A novel method of planting dry extended detention basins with wildflower meadows was promoted by the Mercer County Soil Conservation District in the USA (Schueler, 2000a). The use of wildflower meadows gives a more attractive appearance without the need for frequent mowing. Annual mowing and overseeding is all the maintenance required. This approach can only be applied to the drier areas of the pond and the establishment of wildflower meadows was not successful in areas where inundation for periods greater than 48 hours occurred more than five times during the growing season.

Operation and maintenance

If extended detention basins are correctly designed, constructed, and maintained they can last indefinitely.

The recommended maintenance schedule for extended detention basins is provided in Table 9.11.9.

Table 9.11.9 *Maintenance requirements for extended detention basins*

Operation	Frequency
Inspections to identify any areas not operating correctly, eroded areas, hydrocarbon pollution, blocked outlets, infiltration surfaces that have become compacted, and silt accumulation. Record any areas that are ponding and where water is lying for more than 48 hours. Report to client.	Monthly
Collect and remove from site all extraneous rubbish that is detrimental to the operation of the SUDS and the appearance of the site, including paper, packaging materials, bottles, cans and similar debris.	Monthly
Maintain grass height on side slopes within the specified range. Ensure that soil and grass does not become compacted. Do not cut during periods of drought or when ground conditions or grasses are wet, without prior agreement.	Monthly or as required
Bank clearance to remove bank vegetation by cutting to ground level, using an approved technique and as directed on site, up to 25 per cent of all vegetation from waters edge to a minimum of 1 m above water level taking care not to damage banks and potential water vole habitat. The work should be be undertaken between September and November in any one year. This is necessary to retain water storage, to stimulate vegetation growth at ground level, to protect banks from erosion, to control succession of vegetation to scrub and trees, and to provide cover for wildlife and maintain amenity.	Annually or every three years
Manage wetland plants in micropool at outlet. Required actions are to: • hand-cut submerged and emergent aquatic plants a minimum of 100 mm above wetland base to include no more than 25 per cent of pond/wetland surface • determine whether a pond liner has been used to waterproof the pond/wetland and protect accordingly • remove all arisings, including floating weed, and spread on bank to dewater for 48 hours • remove arisings to wildlife piles, compost or from site to an approved tip (Sections 7.3 and 7.6).	Annually or every three years
Remove sediment from forebay when 50 per cent full.	3–7 year period
Reinstate design levels, repair eroded or damaged areas by returfing or reseeding, restore or improve infiltration, and remove silt by removing existing or damaged vegetation and reinstating surface to design levels.	As required
Remove sediment when pool volume was reduced by 25 per cent.	25 years or greater

9.12 CONSTRUCTED STORMWATER WETLANDS

Box 9.12.1 *Key considerations for constructed wetland design*

Description

A pond specifically designed with shallow areas and wetland vegetation to improve pollutant removal and enhance wildlife habitat.

Design criteria

- Forebay 10–12 per cent of wetland area
- length:width 1.5:1 to 4:1
- combination of deep and shallow areas
- retention time typically 16–24 hours
- water balance to ensure no drying out
- surface area = 1 per cent of catchment area.

Pollutant removal

Very good.

Applications

Usually restricted to use as a site or regional control because of need to maintain base flows.

Limiting factors

- Space
- need impervious soils or liner.

Maintenance

- Supplement plants if vegetation is not established (one-off event)
- monthly inspections
- monthly litter removal
- monthly mowing of side slopes
- bank clearance (annually or every three years)
- manage wetland plants (annually or every three years)
- remove sediment from forebay (typically 3–7 years)
- repair eroded areas as required
- remove sediment from main pond as required (typically 25 years).

9.12.1 Description

Stormwater wetlands are specifically constructed to treat pollutants in runoff and comprise a basin with shallow water and aquatic vegetation that provides biofiltration. They are one of the most effective SUDS techniques in terms of pollutant removal and offer valuable wildlife habitat. A constructed wetland provides varying degrees of deep and shallow water (Figure 9.12.1). They are not normally designed to provide significant attenuation but if required to act as a water detention device the temporary storage may be provided above the level of the permanent water level.

Figure 9.12.1 *Constructed wetland, Dumfries, Scotland*

A constructed wetland for treatment of runoff will have less biodiversity than a natural wetland. Existing natural wetlands should not be used to treat stormwater runoff, because the pollutants may cause a degradation in the water quality and lead to loss of habitat for some species.

Detailed guidance on the design, construction and management of constructed wetlands is provided in CIRIA Report 180 (Nuttall *et al*, 1997) and by the Environment Agency (Ellis *et al*, 2003). Although there is an abundance of information relating to the use of constructed wetlands to treat wastewater, the data may not be directly relevant to treatment of stormwater because of the differences in the water being treated. Wastewater produces fairly uniform inflows in terms of volume and pollutant loading whereas stormwater has highly variable volumes and loadings (Ellis *et al*, 2001).

The majority of constructed wetlands used to treat surface water runoff have been surface flow systems that resemble natural marshes. The inflow passes at low velocities as free surface flow and/or at shallow depths. There are other systems that make use of sub-surface flow, and smaller (pocket) systems that have been developed in the USA and are suitable for use on smaller sites (0.5–5 ha). Further information is provided in the Environment Agency report on constructed wetlands and links to sustainable drainage systems (Ellis *et al*, 2003).

9.12.2 Suitable applications

The main restriction on the use of constructed wetlands is the amount of space required, which limits their potential use in urban developments. They also require a large catchment (between 2 ha and > 8 ha) to maintain the permanent pool and reduce the risk of drying out (ASCE, 2001). If the wetland intersects the water table some research suggests that pollutant removal may be reduced. In permeable soils above the groundwater table a liner may be required to maintain water levels.

9.12.3 Advantages and disadvantages

The advantages and disadvantages of wetlands are summarised in Table 9.12.1.

Table 9.12.1 *Advantages and disadvantages of wetlands*

Advantages	Disadvantages
Very effective pollutant removal and remove nutrients	Require a large space to be implemented
Provide diverse wildlife habitat	May release nutrients in non-growing season
Can increase property prices around the wetland if well designed and maintained (Section 1.2)	
Provide amenity and aesthetic value	

9.12.4 Performance

Pollutant removal

Wide variations have been reported for the pollutant-removal efficiency of constructed wetlands (ASCE, 2001). They are efficient at removing total suspended solids and organic matter and can store phosphorous, although this is a short-term sink since it is released back into the water if the plants are not harvested. Nutrient removal is the most variable parameter and sometimes wetlands are net exporters of nutrients, although the reasons for this are not understood.

The highest removal efficiencies are associated with wetlands that have pre-treatment to remove sediment and also have a final settling pool (Ellis *et al*, 2001).

The performance of a wetland basin in Paris gave average removal efficiencies of 76 per cent for TSS. In another wetland it was found that the highest levels of heavy metals were present in the roots of plants within the system, suggesting that uptake by plants is a major removal pathway for these pollutants (Nuttall *et al*, 1997). Pollutant removal also depends on the time of year, with higher removal occurring in the growing season. Emergent vegetation is the main pollutant remover in spring and summer, whereas floating and submerged plants are more dominant in winter.

A review of the performance of a wetland in Minnesota, USA, found that over a period of 10 years the performance of the wetland declined significantly. Adsorption sites in the base of the wetland reduced over this time, as shown by the reduction in iron and aluminium in the sediment (Schueler, 2000l). The wetland provided treatment storage equivalent to 5 mm of rainfall over the catchment, which was predominantly housing and had an area of some 298 ha. The system experienced cold and snowy winters and the seasonal formation of ice.

In two wetlands in Maryland it was found that the removal of nutrients in a soluble form was greater than that for particulate forms, which was frequently negative (Schueler, 2000d). This was because soluble nutrients were taken up by algae and bacteria and incorporated into particulate forms.

Provision of an adequate treatment volume is critical to the satisfactory performance of a wetland system. Monitoring of a wetland in the USA with a treatment volume equal to 2.5 mm of rainfall on the catchment, demonstrated the poor performance this gave in large storms where the runoff exceeded the treatment volume provided in the wetland (Schueler, 2000n) The results are shown in Table 9.12.2 and show the significance of the adverse effects of large storms. The poor performance was also reported to be caused by the lack of sediment control as there was no inlet forebay or micropool provided at the outlet.

Table 9.12.2 *Pollutant removal of a wetland during large and small storms (Schueler, 2000n)*

Pollutant	**Removal efficiency (per cent) based on mass loading**	
	Small storms	**All storms**
Ortho-phosphorous	59	-5.5
Total soluble phosphorous	66	-8.2
Total phosphorous	76	8.3
Ammonia-nitrogen	68	-3.4
Total suspended solids	93	62
Total Kjeldahl N	81	15
Nitrate + nitrite	68	1.2
Total nitrogen	76	-2.1

Note Negative values indicate that concentrations in the outflow are higher than those in the inflow, so the wetland is adding pollution, probably caused by re-suspension of sediment.

The removal efficiencies quoted from various sources for stormwater wetlands are provided in Table 9.12.3.

Table 9.12.3 *Pollutant removal efficiencies for a constructed wetland*

Pollutant	**Removal efficiency (per cent)**								
Reference	**Godrej *et al*, 1999**		**ASCE, 2001**	**Winer, 2000**	**Ellis *et al*, 2001 (for treating urban runoff)**	**Schueler, 2000d**	**<www.bmpdatabase.org>**	**Atlanta Regional Commission, 2001**	**Design values from Section 3.4.2 of this book [1]**
Method of estimation	Median EMC	Median mass loading	Mass loading	Various	Unknown	Mass loading	Various	Unknown	
Total suspended solids	57.9	49.6	86	76	36–95	65	31–97	80	80–90
Nitrate/nitrogen	21.9	-24.9	46	30	—	22.8	-81–58	30	30–60
Total phosphorous	33.3	-0.3	70	49	—	39.1	-106–78	40	30–40
Hydrocarbons	0	-33.6	—	—	50–80	—	-17– -26	—	50–80
Cadmium	50	41.5	88	—	5–73	—	39	50	50–60
Copper	0	1.0	79	40	10–71	—	3–51		
Lead	0	10.6	83	—	6–70	—	12–95		
Zinc	23.4	-17.8	84	44	-36–70	—	9–95		

Note

1 Use lowest values for sites where maintenance may not occur or to give increased confidence that design parameters will be met.

Two constructed wetlands in Washington DC, USA, were monitored for pollutant removal (Godrej *et al*, 1999). They were provided with a micropool at the outlet but no sediment forebay, and the runoff received was from a housing development. The removal efficiencies were estimated using a variety of methods and are summarised in Table 9.12.3. Problems were reported in determining the inflow to the system, so the mass loading results should be treated with caution. The negative hydrocarbon removal rates are also surprising. The analysis was for total petroleum hydrocarbons, and any screening test used may have been affected by the presence of other organic material from the wetland in the sample.

The key findings of the study were:

- there was no significant variation in pollutant removal with season for most pollutants (TSS and nutrients)
- retention of metals was primarily by sedimentation
- generally pollutant removal was much better for small storms that did not exceed the capacity of the wetland
- pollutant removal improves with increasing volume-to-catchment ratio.

Hydraulic performance

Stormwater wetlands have typically been used for treatment of pollution and there is no readily available data on their hydraulic performance.

9.12.5 Design criteria

Successful design of stormwater wetlands requires early consultation with all stakeholders at the feasibility stage so that the constructed wetland is integrated into the development.

Soil and groundwater requirements

There are no particular soil or groundwater requirements for wetlands. If underlying soils are permeable and groundwater is present at depth, an impermeable liner may be required to maintain water levels. This can be compacted clay or a geomembrane.

Hydraulic design

Pre-treatment is vital to the successful operation of a stormwater wetland (USEPA, 2002 and Nuttall *et al*, 1997). A sediment forebay should be provided at the inlet to catch sediment and free hydrocarbons. The forebay is typically 10–12 per cent of the total volume of the wetland and around 1.2 m deep. If heavy winter salting occurs in the catchment, the volume of forebay should be increased so that the increased sediment in the runoff can be removed. The flow from the forebay in the wetland should be via a level spreader to promote even, well-distributed flow. The micropool at the outlet is typically 0.9–1.8 m deep.

Most constructed wetlands for stormwater treatment are surface flow wetlands. These comprise shallow water areas that are generally 0.3–0.6 m deep in which the water flows above the support medium (the soil or aggregate in the base of the wetland). This type of wetland has a greater capacity to remove and store sediment.

Wetlands can also be designed as sub-surface flow systems where the water to be treated flows within the underlying support medium (typically gravel with a high permeability). The plants rooted in the support medium grow hydroponically in the water as it flows past the roots. More detail on sub-surface systems is provided in Nuttall *et al*, 1997).

Surface flow wetlands operate as an open channel. Pollutant removal is dependent on the retention time of runoff within the wetland. A time of 16–24 hours is suggested for high performance in secondary applications in waste water treatment (Nuttall *et al*, 1997) and similar values (24–36 hours) are quoted for stormwater wetlands by others (such as City of Portland Environmental Services, 2002 and the Highways Agency *et al*, 2001). The retention time is governed by the base slope, flow rate, water depth, type of vegetation, configuration and shape of the wetland. The required volume of wetland for any given retention time is estimated using the equation:

$$\text{Volume of wetland } (m^3) = \text{Retention time (days)} \times \text{inflow volume } (m^3/\text{day}). \qquad (9.12.1)$$

It is also important to prevent short-circuiting and surface skimming of water that significantly reduce residence times and thus pollutant removal. An alternative is to specify that the flow velocity through the wetland is maintained below 3×10^{-3} m/s to give adequate retention times (City of Portland Environmental Services, 2002). The flow velocity is obtained by dividing the inflow volume by the surface area of the wetland.

It is essential to carry out a water balance calculation for wetlands to ensure they will not dry out in a summer drought (they should be able to withstand a 30-day drought – Maryland Department of the Environment, 2000). Conversely the design should ensure that the temporary storage above the permanent water level is no greater than 0.65 m and empties in time so that wetland vegetation is not damaged by inundation. A maximum storage time above the permanent water level of 24 hours may be specified to prevent damage to vegetation, but this has to be weighed against the need to maximise retention time for pollutant removal (Urbonas, 1997).

More complex kinetic analysis to determine wetland volumes can also be carried out (Ellis *et al*, 2003).

Pollutant removal

Variations in water levels adversely affect pollutant removal (ASCE, 2001) and a consistent baseflow is required for a wetland if the pollutant-removal performance is to be maximised.

The root zone of the wetland vegetation is important for the removal of pollutants (Nuttall *et al*, 1997). Horizontal flow of water through it should be encouraged by using a gravel support medium in the base of the wetland. The gravel layer allows root growth but also has a high hydraulic conductivity to promote flow. It reduces re-suspension of sediment in heavy storm events and is a more suitable medium than soil for emergent macrophytes. The use of rock beds constructed in the base with 25–75 mm aggregate has also been proposed as a requirement to enhance nitrogen removal in wetlands (Maryland Department of the Environment, 2000).

Design for wildlife and amenity

The design requirements for the provision of wildlife habitat and amenity value are the same as for wet ponds as discussed in Section 9.11.1 and Box 9.11.2.

It is important to provide a random mixture of water depths, not concentric rings, and to ensure that deep water (> 1 m) comprises no more than 25 per cent of the pond surface area, because deep water supports fewer species than shallow water.

Erosion

Erosion protection should be provided at the inlets to the wetland and below the outlet.

Extreme events

An overflow weir should be provided to allow the safe passage of flows from extreme events that exceed the design storage capacity of the wetland.

Design details

The layout and shape of a wetland should be designed to suit each site, taking into account habitat and aesthetic issues. Maintenance access for vehicles to the outlet micropool and sediment forebay should be considered at the feasibility stage and designed into the wetland scheme. A typical detail is provided in Figure 9.12.2.

Various design criteria have been proposed for wetlands and these are summarised in Table 9.12.4.

At most, the side slopes should be 3:1, but preferably they should be less steep, to enhance the safety and ease of wetland maintenance.

Table 9.12.4 *Design criteria for wetlands*

Criteria	ASCE, 2001	USEPA, 2002	Nuttall *et al*, 1997	Maryland Dept of the Environment, 2000	City of Portland Environmental Services, 2002
Length-to-width ratio	2:1–4:1	Min 1.5:1	Min 4:1	Min 1.5:1	Min 3:1
Max depth fluctuation (temporary flood storage)	0.6 m	—	—		
Surface area of wetland	—	Min 1% of catchment area	—	Min 1% of catchment area	
Depth of support medium	—	—	0.2–0.3 m		

In addition to the above design criteria, various figures have been specified for the proportion of the wetland volume and surface area used for various habitats and sediment control features (Table 9.12.5).

Table 9.12.5 *Allocation of treatment volumes and surface area in a wetland (City of Portland Environmental Services, 2002; Urbonas, 1997 and Maryland Department of the Environment, 2000)*

Component	% of design volume	% of facility surface area
Sediment forebay	10–12.5	5–15
Micropool	10–12.5	5–15
Deep water (> 450 mm)	50	20–40
Deep wetland (150–450 mm)	20	25–30
Shallow wetland (< 150 mm)	10	25–35

Inlets

A sediment forebay and level spreader should be provided at the inlet to distribute flow evenly. Planting of vegetation around the inlet also helps in sediment removal and reduces the risk of erosion.

9.12.6 Construction

The construction requirements for ponds can also be applied to wetlands (Section 9.11.1).

9.12.7 Planting

Vegetation in constructed wetlands is important because it promotes the settlement of suspended matter and stabilises the sediments in the base of the wetland, thus preventing scour and resuspension during heavy storms (Nuttall *et al*, 1997). Plant die-off in winter also provides a dense litter layer that promotes pollutant removal.

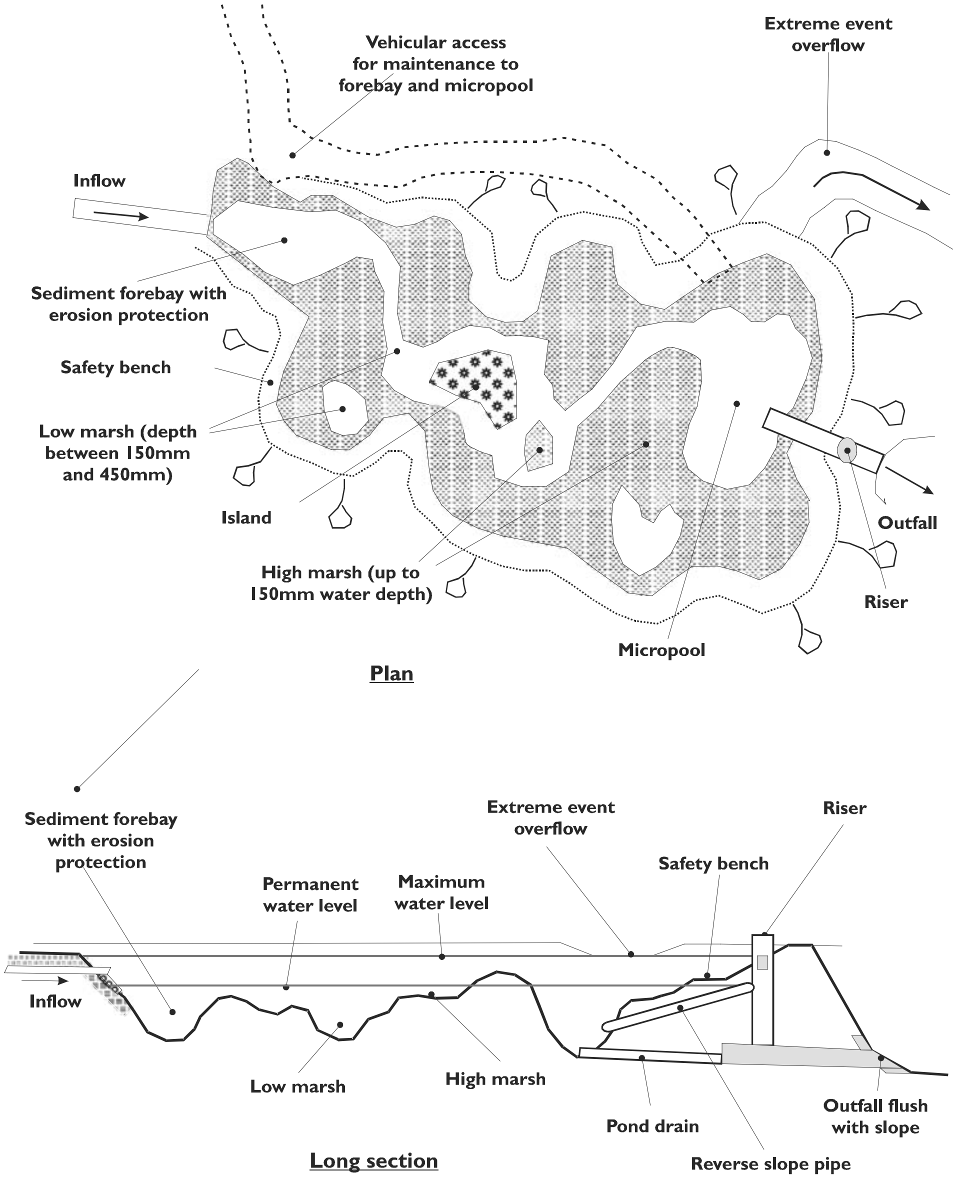

Figure 9.12.2 *Example details of a wetland for stormwater treatment (Maryland Department of the Environment, 2000)*

The least expensive and most effective way of planting a wetland is to allow natural colonisation (USEPA, 2002). The planting requirements for ponds also apply to those for wetlands (discussed in Section 9.11.1). Planting of wetlands should take place between early April and mid-June so that the plants have a full growing season to develop the root reserves they need to survive the winter.

Planting density varies but is usually between four to eight plants per square metre. Vegetation needs to be established quickly to promote pollutant removal and prevent erosion. Native species should be used.

If excavation for the wetland has extended into the subsoil below the site there will be limited nutrients available for the plants. A wetland mulch or topsoil should provide the nutrients and organic matter required by the plants to become established.

9.12.8 Operation and maintenance

If correctly designed and maintained wetland areas can last indefinitely.

The recommended maintenance schedule for wetland areas is provided below in Table 9.12.6.

Table 9.12.6 *Maintenance requirements for wetlands*

Operation	Frequency
Supplement plants if vegetation is not established after the second growing season.	One-off event
Inspections to identify any areas not operating correctly, eroded areas, hydrocarbon pollution, blocked outlets, infiltration surfaces that have become compacted and silt accumulation. Record any areas that are ponding and where water is lying for more than 48 hours. Report to client.	Monthly
Collect and remove from site all extraneous rubbish that is detrimental to the operation of the SUDS or that detract from the appearance of the site, including paper, packaging materials, bottles, cans and similar debris.	Monthly
Maintain grass height on side slopes within the specified range. Ensure that soil and grass does not become compacted. Do not cut during periods of drought or when ground conditions or grass are wet, without prior agreement.	Monthly or as required
Bank clearance to remove bank vegetation by cutting to ground level, using an approved technique and as directed on site, up to 25 per cent of all vegetation from the water's edge to a minimum of 1 m above water level, taking care not to damage banks and potential water vole habitat. The work should be undertaken between September and November in any one year. This is necessary to retain water storage, to stimulate vegetation growth at ground level to protect banks from erosion, to control succession of vegetation to scrub and trees and to provide cover for wildlife and maintain amenity.	Annually or every three years
Manage wetland plants. This will include the need to: • hand-cut submerged and emergent aquatic plants a minimum of 100 mm above wetland base to include no more than 25 per cent of pond/wetland surface • determine whether a pond liner has been used to waterproof the pond/wetland and protect accordingly • remove all arisings including floating weed and spread on bank to dewater for 48 hours • remove arisings to wildlife piles, compost or from site to an approved tip (Sections 7.3 and 7.6).	Annually or every three years
Remove sediment from forebay when 50 per cent full.	Three to seven year period
Reinstate design levels, repair eroded or damaged areas by returfing or reseeding, restore or improve infiltration and remove silt by removing existing or damaged vegetation and reinstating the surface to design levels.	As required
Remove sediment when pool volume reduced by 25 per cent	25 years or greater

9.13 ON-/OFF-LINE STORAGE

Box 9.13.1 *Key considerations for on-/off-line storage*

Description

Storage of runoff in underground tanks or other structures such as oversized pipes.

Design criteria

- Standard surface water drainage design using limiting outflow rates to determine storage volumes
- *Sewers for adoption*, 5th edition (WRc, 2001a)
- structural design to relevant standards.

Pollutant removal

Very poor.

Applications

Suitable where there is limited space and treatment is not a priority.

Limiting factors

- Does not provide any treatment and so needs to be used in conjunction with other treatment techniques
- may require deep excavations for large storage volumes.

Maintenance

- Inspection for silting and blockages every six months
- removal of silt and blockages as required.

9.13.1 Description

This section refers to on-line or off-line storage in tanks or other underground structures. On- and off-line storage is also provided by other SUDS techniques (for example, ponds and wetlands), but these provide some degree of treatment to the runoff. Tanked storage does not provide any significant treatment of pollution in runoff.

Tanked storage is provided to detain runoff on site and release it at the required rate into the receiving watercourse or sewer, thus reducing peak storm flows from a site. The tanks can take the form of oversized pipes, concrete tanks, corrugated steel pipes and plastic cellular tank systems, among others.

The design of on or off-line storage is well understood and only those aspects not covered in existing design standards and guidance are discussed here.

9.13.2 Suitable applications

Underground on- or off-line storage may be provided where there is little room for other above-ground techniques such as ponds, which require large areas to implement. On- or off-line storage does not provide any significant treatment to runoff and should be used in conjunction with other techniques.

9.13.3 Advantages and disadvantages

The advantages and disadvantages of on- or off-line storage in underground tanks are summarised in Table 9.13.1.

Table 9.13.1 *Advantages and disadvantages of on- or off-line storage systems*

Advantages	Disadvantages
Well understood both in design and construction terms	Does not provide any treatment of runoff
Does not take up large amounts of site area and can be located under most areas of a site	Can require deep excavations if a large storage volume is necessary

9.13.4 Performance

Pollutant removal

On- or off-line storage is used only to attenuate peak flows from a site. It does not provide any reduction in volume or significant pollutant removal and must be combined with another SUDS technique to achieve the water quality criteria (Section 4.3).

Hydraulic performance

On- or off-line storage is a conventional drainage technique whose performance is well understood.

9.13.5 Design criteria

Pipes or tanks

The hydraulic and structural design of on- or off-line storage using pipes or tanks should be in accordance with *Sewers for adoption*, 5th edition (WRc, 2001a). The structural design of pipes should also be in accordance with BS EN 1295:1998 *Structural design of buried pipelines under various conditions of loading*.

9.13.6 Structural design of geocellular plastic structures

Modular plastic geocellular units are increasingly being used as a cost-effective method of providing stormwater infiltration and attenuation tanks below new developments (Figure 9.13.1). It is emphasised that these tanks are structures and should be designed as such using structural theory, in a similar way to tanks constructed in other materials such as concrete. They are often used below areas that are trafficked by heavy goods vehicles that can impose significant loads on them.

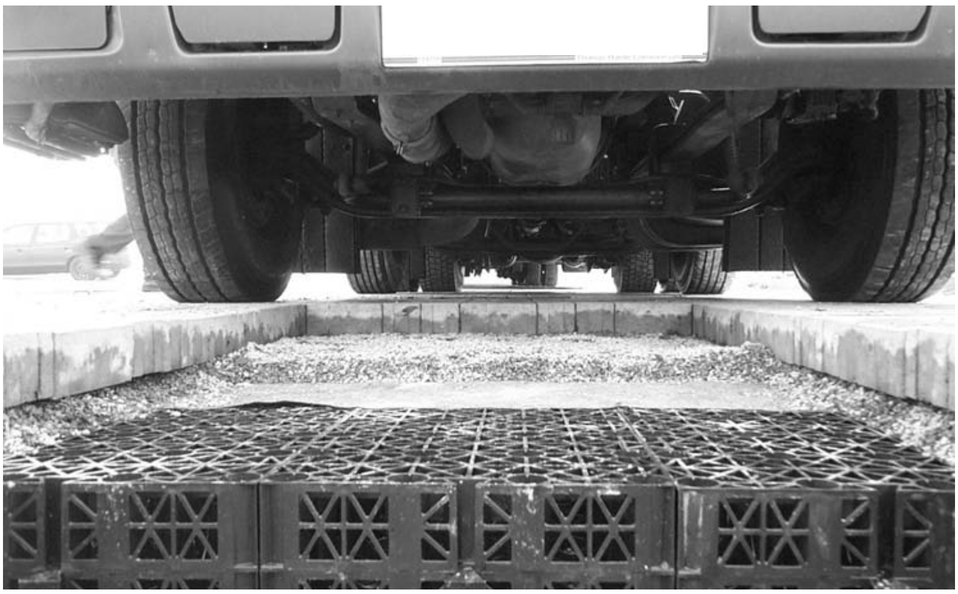

Figure 9.13.1 *Plastic modular storage tank below a trial car park at Coventry University. View taken during deconstruction at the end of a one-year trial (SEL Environmental Limited)*

In particular the effects of creep and deflections on overlying paved surfaces should be carefully considered. On occasions the individual units are also subject to bending, which will require analysis. Limit state design methods can be used to design these tanks (Box 9.13.2).

Box 9.13.2 *Limit state design of geocellular structures*

The philosophy of limit state design can be used so that the structures remain safe and suitable for use throughout their design life. A limit state is defined as "a limiting condition beyond which the structure stops fulfilling its intended function" (Day, 1997). The concept of limit state design is to consider the probability distributions of all parameters (applied loads and material strength and stiffness) to provide better level of control over risk and improved consistency than can traditional designs based on permissible stress or lumped factors of safety.

The load and material factors used for the structural design of concrete or steel are derived to achieve a target probability of failure and are specific to particular load and material types. With careful consideration, however, the guidance on appropriate load and material factors used for other structures can be applied to the design of plastic tanks.

The two most common limit states to be considered are:

- **ultimate limit state** – the structure should not collapse under foreseeable overload. The main consideration is strength
- **serviceability limit state of deflection** – in this case, deflections should be at acceptable levels (to prevent cracking in the overlying surfacing, for example).

Loads

Characteristic loads are a best estimate of the load likely to be placed on a structure during its design life. The characteristic load is multiplied by a partial factor of safety to produce a design load. This allows for:

- statistical variations in load
- increased loads due to tolerances in construction
- unforeseen load conditions.

The partial factors depend on the consequences of the limit state and the probability of particular combinations of load occurring at the same time. The loads that are applied to plastic tank structures are the same as those applied to other structures (such as traffic loads applied to bridges) and the probability of occurrence will be the same. Therefore, the guidance from structural design codes for other materials (eg BS 8110:1997) can be used to determine the partial load factors for plastic tank design (Table 9.13.2). The most common combination of loads will be dead plus live load.

Table 9.13.2 *Partial load factors from BS 8110, Part 1:1997 (dead and live load combination)*

Load type	Ultimate limit state	Serviceability limit state
Dead load	1.4	1.0
Live load	1.6	1.0

The consequences of collapse are more serious than for cracks occurring in the surface. A higher factor is used for the ultimate limit state, therefore, so that the risk of the limit state being achieved is lower. Lorries can also impose very high dynamic loads on the boxes, depending on their speed, and factors should be applied to allow for this in design.

Surfacing and allowable deflections

The type of surface overlying the storage tanks determines the levels of deflection acceptable under loading. A reinforced aggregate surfacing, for example, is able to tolerate greater deflections than an asphalt surfacing. The nature of the deflections also needs to be considered, as they are elastic and will be repeated during the lifetime of the structure. Block paving is a relatively flexible material that can tolerate elastic deflections up to about 1.5 mm without adverse effects.

To account for factors such as variations during manufacture, variability and uncertainties in material strength (for example, due to extrapolation of data), damage during installation, and environmental effects, the design strength must be obtained by applying a material partial factor of safety γ_m , appropriate to the material and limit state. This also allows for the effects of fatigue (reduced strength as a result of repeated application of load).

The only readily available guidance on choice of material factors for thermoplastic materials in load-bearing applications is for geogrids used in earth reinforcement applications (BS 8006:1995 and Ingold, 1994).

The partial factor for materials, γ_m , is made up of the components listed below.

- γ_{m11} – applied to reduce the characteristic strength to give a minimum likely value. It covers possible reductions from the control test specimens and allows for inaccuracies in the assessment of the resistance of a structural element resulting from modelling errors. For tightly controlled geogrid production, γ_{m11} is normally between 1.05 and 1.1. Depending on the level of testing undertaken on stormwater storage units and the extent of quality control testing, a conservative value is usually adopted. Also the systems are often complex three-dimensional structures, which should be taken into account.

- γ_{m12} – applied to take account of the extrapolation of creep test data. It is also used to allow for the absence of fatigue testing. A suggested value of γ_{m12} is (Ingold, 1994):

$$\gamma_{m12} = \text{Log}\,(t_d/t_t) \qquad (9.13.1)$$

where:

t_d = design life

t_t = duration of creep test

- γ_{m21} – applied to take damage during construction into account.
- γ_{m22} – applied to take environmental conditions into account. Polyolefins used in the manufacture of most stormwater units are resistant to most contaminants they are likely to come into contact with (although a site-specific assessment should be undertaken). A minimum value of 1.1 should be adopted, which is the minimum value recommended for reinforced earth applications (Ingold, 1994).

The factors should also allow for synergistic effects, that is, the combined effects of construction damage, environmental conditions and lower-than-expected strength may combine to give a greater effect than the three acting individually. Lower material factors may be used depending on the consequences of failure (for example, lower values may be used where a thin 150 mm plastic tank is placed below a paved area, since collapse is unlikely to cause overturning of vehicles). Again greater factors are applied to the ultimate limit state analysis so that the risk of collapse is at an acceptable level.

Materials and laboratory testing

Most cellular stormwater tanks are manufactured using plastic (usually polypropylene or polyethylene) and are complex structures in their own right. Many manufacturers quote a single value of compressive strength for the units or simply express strength as a load the units can carry. Product literature often does not make clear how the strength or load has been derived.

On cellular structures where the load capacity is provided by a series of vertical columns or plates, compression testing should be undertaken at different points to find the worst-case load capacity. Bending tests may be required to allow the design of some configurations. Care should be taken to ensure that the strength derived from testing is representative of the system's performance in service, and more than one test configuration may be required (Figure 9.13.2). Where columns are an important load-bearing component, the structure may need to be tested with more than one size of platen to determine how load is distributed through the structure.

A complete set of independent test results for any proposed units should be requested from the manufacturer including, as a minimum, stress and strain curves for vertical and lateral compression and creep tests under sustained long-term loads. This allows the ultimate compressive strength and deflection performance of the units to be determined. In the absence of a specific test method for these types of materials, the method described in BS EN 124:1994 for determining the strength of manhole covers can be used, as it applies the load via a 300 mm plate, which is similar in dimensions to a vehicle tyre footprint. Testing with the load applied in several positions may be required to determine the worst credible parameters for a unit.

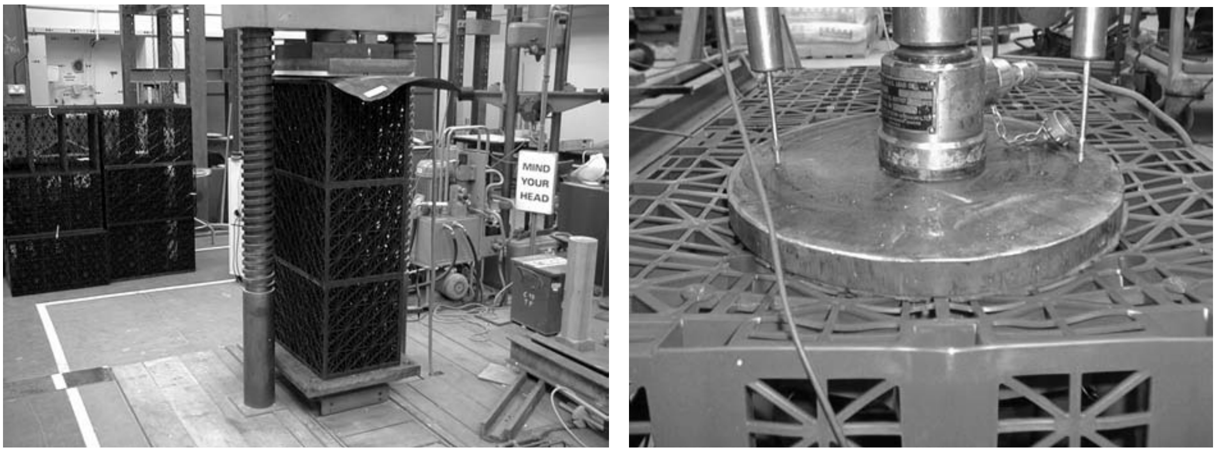

Figure 9.13.2 *Compression test configurations on plastic cellular structures*

In the tests shown in Figure 9.13.2, the units were placed on a concrete floor and the load applied using a plate that covered the whole unit (a) and also a 300 mm-diameter circular plate (b). Several sets of tests should be undertaken on the top and sides of the units, with the load applied at different locations to determine the worse-case strength and stiffness parameters.

Typical results from laboratory tests to determine short-term compressive strength and deflection rates for a plastic cellular unit are shown on Figure 9.13.3. The design lines can be determined following the advice provided by the American Society for Testing and Materials in ASTM D-1621-00 (ASTM, 2000). The initial load-deflection relationship shows a lag similar to the effects of seating error in soils. As specified in ASTM D-1621-00, this part of the graph is ignored and the straight part is extended backwards to establish the correction for the zero offset. The ultimate compressive strength is determined at the yield point.

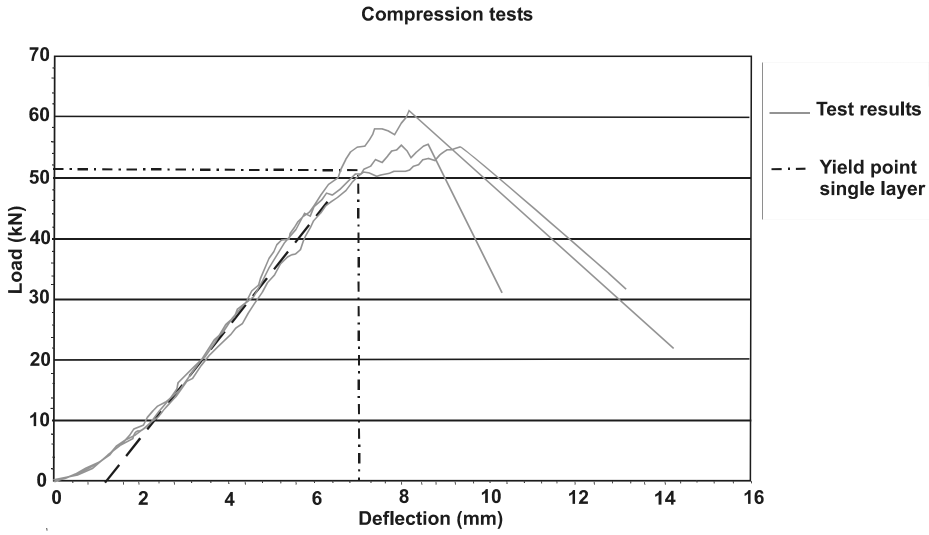

Figure 9.13.3 *Example stress-strain curve for compression tests (illustration only)*

Bending

Some systems use the individual units or columns to form tanks with an open internal void. This means the units are subject to bending stresses, and analysis using simple compression tests can underestimate the ultimate strength and possible deflections (Figure 9.13.4).

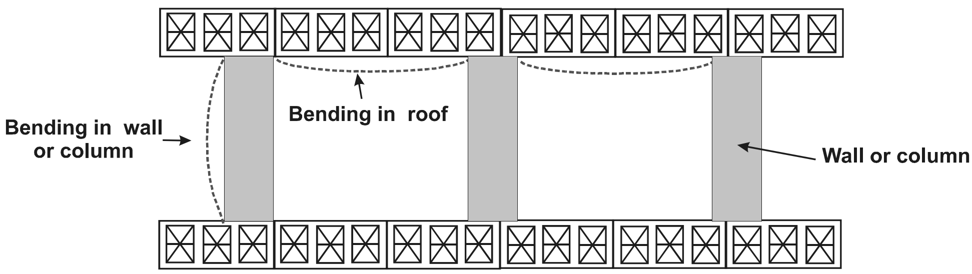

Figure 9.13.4 *Bending in box structure with an internal void*

Bending tests are required to allow a more rigorous structural analysis of these structures.

Creep

Creep and fatigue can significantly affect the long-term performance of plastic structures and need careful consideration in design. Creep occurs because the long polymer chains which form the polyolefin tend to slide over each other so that there is a time-dependency to the stress-strain diagram. A load placed on a polymer material will result in an initial deformation, but with the load remaining over time, further deformation will occur.

The rate of creep becomes greater as the applied load increases. Plastics also behave in a viscoelastic manner, so that if loads are removed some of the creep is recovered. Fatigue is loss of strength that occurs due to repeated application of traffic or other loads, which may reduce the strength of the units in the long term. The results from an example creep test are shown in Figure 9.13.5.

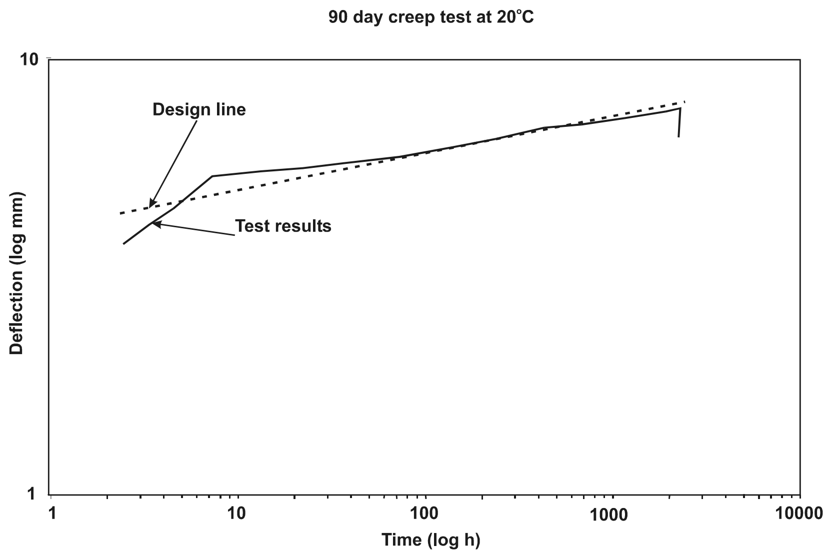

Figure 9.13.5 *Example creep test results*

The results of creep tests are normally plotted as deflection versus time on a log-log graph so that the relationship between deflection and time can be more clearly identified. The intercept on the y axis is the extent of the seating error and initial elastic deflection that occurs on loading. Thus a long-term rate of deflection can be determined. The only advice available on creep test data in a similar situation relates to geogrids used in reinforced earth structures (Jewell, 1996). This suggests that creep test data should not be extrapolated in time to more than two orders of magnitude. For example, using the results of a 90-day test means that a design life of up to 20 years can be allowed for.

9.13.6 Structural design considerations

Designers of plastic cellular water storage systems should consider the following:

- service dead and live loads should be identified
- dead loads will include fill material placed over the units and any other permanent or long-term loads such as storage tanks, for example
- live loads include distributed loads and point loads from wheels. Wheel loads from vehicles can impose very high concentrated loads on the units. Analysis is needed to determine the thickness of overlying material required to distribute the loads evenly and prevent overloading or excessive deflection of the units (Figure 9.13.6).

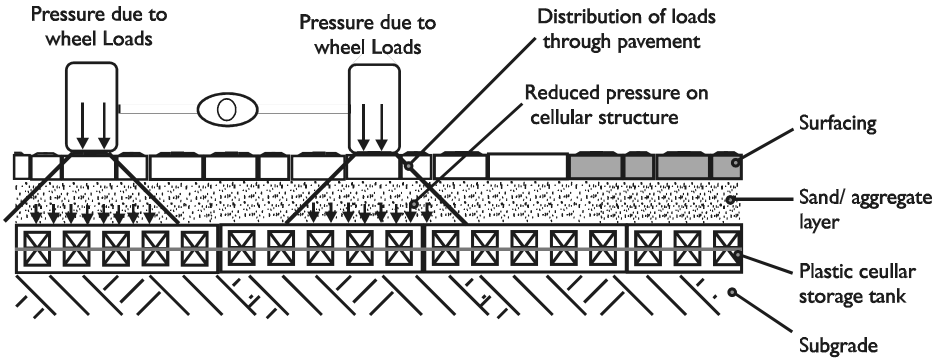

Figure 9.13.6 *Spread of load below a wheel*

- construction plant such as excavators, cranes and compaction plant can impose significant loads on the systems before they are provided with final cover. The deformations that occur during construction should also be considered
- earth and water pressures impose lateral loads. These should be assessed and allowed for by designers
- flotation can occur if tanked systems are located below the water table
- the bearing capacity and settlement characteristics of the underlying soil
- risk of chemical or biological attack
- the effects of temperature variations on the plastic materials (especially with respect to creep).

Full-scale testing

Where very shallow cover depths or unusual configurations are proposed, or where heavy loads are to be applied, the design may be confirmed by testing of full-scale sections of pavement (Figure 9.13.7). This gives increased confidence in the predicted performance of a system.

Figure 9.13.7 *Testing of a full-scale pavement incorporating a plastic cellular sub-base replacement system*

Monitoring of installed systems under actual full-scale loading can also be undertaken to validate design theories, as shown in Figure 9.13.1.

9.13.7 Operation and maintenance

Conventional storage is often perceived to be maintenance-free. This is incorrect, although the methods are different and the frequency of maintenance may be less than that required for other SUDS techniques.

The recommended maintenance schedule for storage tanks is provided in Table 9.13.3.

Table 9.13.3 *Maintenance requirements for storage tanks*

Operation	Frequency
Inspection for silting and blockage of outlets	Six-monthly
Removal of silt and blockages	As necessary

9.14 OIL SEPARATORS

Oil separators may be included in SUDS schemes to provide pre-treatment to runoff where necessary, (for example, surface water runoff from stormwater hotpsots where the potential for spillages of hydrocarbons is high).

In comparison with other SUDS systems, oil separators are heavily reliant on frequent routine maintenance to prevent pollution. As they are hidden, any pollution that is trapped in the system is not obvious; if not removed, such pollution can easily become re-suspended in heavy rainfall events. This may be mitigated to some extent by incorporating automatic monitors, as required by British Standard BS EN 858-1:2002. The advantage of oil separators is that they do not take up surface space and can be used in urban situations.

Oil separators should be designed in accordance with BS EN 858-1:2002, *Separator systems for light liquids (eg oil and petrol). Part 1: Principles of product design, performance and testing, marking and quality control*. Guidance is also provided in Pollution Prevention Guideline no 3 (PPG 3), *Use and design of oil separators in surface water drainage systems*, published by the Environment Agency/Scottish Environmental Protection Agency.

9.15 INNOVATIVE TECHNIQUES

There is continuous innovation in the area of SUDS techniques and particularly in the development of modular systems that can be used in dense urban areas, where the scope for using other techniques may be limited. The suitability of these techniques for use on any site should be assessed on their own merits.

In the USA, a system has been developed that incorporates filtration, sedimentation and a submerged gravel wetland system into a tank just 3 m in diameter. The use of internal baffles and compartments creates a tortuous route for the runoff's flowpath through the system (Winkler, 1997). The system can be used in urban situations and is capable of removing up to 98 per cent TSS.

The use of pervious surfaces is limited in stormwater hotspot locations, for example where there is a high risk of spillages of hydrocarbons. One method of overcoming this is to incorporate an oil interceptor into a pervious pavement (Wilson *et al*, 2003). The system is constructed using a plastic sub-base replacement to provide the storage. Its pollutant retention capabilities for a range of scenarios have been assessed including a catastrophic oil leak from a car engine, followed by car washing and then a fuel spillage. The results indicated that the performance of the system was much better than required for a conventional oil interceptor (BS EN 858-1:2002) by a factor of between 10 and 50.

There are various hydrodynamic devices (known as swirl separators in the USA) that have become more widely used in recent years. The concept is that sediment is removed as the runoff flows in a swirling path (USEPA, 2002). There are several types available, each of which incorporates a different detail, such as additional oil and silt traps. They do require continuous maintenance to ensure continuing operation, however. Another drawback is the lack of independent data on the systems' effectiveness in removing pollutants (USEPA, 2002).

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BS 6229:1982 *Code of practice for flat roofs with continuously supported coverings*

BS 7370:Part 3:1991 *Grounds maintenance. Recommendations for maintenance of amenity and functional turf (other than sports turf)*

BS 7533-1:2001 *Pavements constructed with clay, natural aggregate or concrete pavers. Guide for the structural design of heavy duty pavements constructed of clay pavers or concrete paving blocks*

BS 8006:1995 *Code of practice for strengthened/reinforced soils and other fills*

BS 8110:Part 1:1997 *Structural use of concrete: Code of practice for design and construction*

BS EN 124:1994 *Gulley tops and manhole tops for vehicular and pedestrian area. Design requirements, type testing, marking, quality control*

BS EN 752-4:1998 *Drain and sewer systems outside buildings. Hydraulic design and environmental considerations*

BS EN 858-1:2002 *Separator systems for light liquids (eg oil and petrol). Principles of product design, performance and testing, marking and quality control*

BS EN 1295:1998 *Structural design of buried pipelines under various conditions of loading*

BS EN 12056-3:2000 *Gravity drainage systems inside buildings. Roof drainage, layout and calculation*

BS EN ISO 14001:1996 *Environmental management systems – specification with guidance for use*

USEFUL WEBLINKS

Health and Safety Executive	<www.hse.gov.uk>
National stormwater best management practices (BMP) database.	<www.bmpdatabase.org>
Information on SUDS and current research in the UK	<www.ciria.org>
Information on green roofs	<www.greenroof.com>
Information on green roofs and biodiversity	<www.blackredstarts.org.uk>
Information on rainfall data and climate change	<www.met-office.gov.uk>
Information on water industry specifications	<www.wapug.org.uk>
Office of the Deputy Prime Minister, planning guidance	<www.planning.odpm.gov.uk>
Environment Agency	<www.environment-agency.gov.uk>
SEPA	<www.sepa.org.uk>
Department of the Environment (Northern Ireland)	<www.doeni.gov.uk>
Community environmental charity	<www.stroudvalleysproject.org>
Forest education initiative	<foresteducation.org.uk>

A1 Decision-making for SUDS techniques

The following process is a coarse aid to decision-making that should allow the most appropriate techniques to be identified for any site. Once these have been identified they should be combined to provide the most effective surface water management train.

A screening process is used to determine the most appropriate techniques, or combination of techniques for a site. Each technique is given a score from 1 to 5 to indicate its performance against a variety of criteria in Tables A1.2a, A1.2b and A1.2c.

The scores indicate:

1 Very poor/very low/very high cost.

2 Poor/low/high cost.

3 Moderate.

4 Good/high/low cost.

5 Very good/very high/very low cost.

This process should be carried out at the feasibility stage for a project to ensure that the SUDS strategy is clearly identified and is integrated into the development design.

Other innovative and proprietary techniques are continuously being developed for SUDS. Each technique should be assessed on its own merits and a product or technique specific rating developed where necessary.

The decision-making process is shown graphically on the following page, together with a description of each of the six steps.

SUDS Decision making process

Step 1
Review masterplan and incorporate prevention

Step 2
Divide site into subcatchments

Step 3
Score techniques on site specific constraints

Step 4
Score techniques on community and environmental factors

Step 5
Score techniques on cost and maintenance factors

Step 6
Assess combinations of suitable techniques in management train to provide optimum pollutant removal and robustness

Step 1 – Review site master plan and identify areas where SUDS can be incorporated and any changes to the plan needed to enhance SUDS on the site. Identify where prevention techniques can be applied.

Step 2 – Divide the site into sub-catchments (based on location, land use, site layout or topography) to promote source control and keep areas where heavily polluted runoff may occur separate from other catchments (for example, lorry parking separate from roof drainage).

Step 3 – Score each technique on the basis of its pollution reduction performance, hydrological control effectiveness, land use and physical site features (use Tables 3.7, A1.2a and A1.2b). The scores for each parameter should be inserted in the columns on the SUDS decision sheet. Take into account the weightings (for various criteria – 1 if desired, 2 if essential). The overall scores may be compared to identify those techniques more suited to the site. This will screen out some techniques as unsuitable and reduce the number of techniques that need to be considered in Step 4.

Step 4 – From the techniques remaining after Step 3, identify the techniques that achieve the best balance between community acceptance and benefits, environmental benefits, cost and maintenance burden, and compliance with any regulatory requirements (Table A1.2c).

Step 5 – From the techniques remaining after Step 4, identify those techniques that can be used within the constraints posed by the economic and maintenance criteria (Table A1.2c). Again, this will reduce the list of techniques that are suitable.

Step 6 – Check the pollutant removal efficiency and design robustness of combinations of techniques (Section 3.4) to determine the optimum combination of techniques that are to be placed in series to give the required design confidence and provide a management train.

Table A1.1 *Decision criteria for selecting SUDS techniques (after Ellis et al, 2003)*

	Criteria	Assessment	Weighting	Pervious pavements	Green roofs	Bioretention	Filtration techniques	Grassed filter strips	Swales	Infiltration devices	Filter drains	Infiltration basin	Extended detention ponds	Wet ponds	Stormwater wetlands	On-/off-line storage
Hydrological	Is pollutant removal a priority?	*Eg pollutant removal from roof runoff may not require treatment*														
Hydrological	Is water quantity control a priority?	*Eg in places attenuation can have negative impacts on downstream flows*														
Hydrological	Is flow rate control a priority?	*Eg does the rate of flow require reduction*														
Hydrological	Is groundwater recharge required?															
Land use	Suitability to type of development	*Dense urban, car park, road, housing, stormwater hotspot*														
Physical site features	Catchment area	*State sub-catchment area and choose appropriate score*														
Physical site features	Site slope	*State site slope and choose appropriate score*														
Physical site features	Space required	*Place score in this row if there is limited space for SUDS on site*														
Physical site features	Soil infiltration rate	*State infiltration rate and apply appropriate score*														
Physical site features	Water table depth	*State if greater than 1 m depth to water table and appropriate score*														
	Total score															
Community and environment	Safety															
Community and environment	Pond premium															
Community and environment	Aesthetics															
Community and environment	Wildlife habitat															
Community and environment	Community acceptance															
	Total score															
Economic and maintenance	Life-span															
Economic and maintenance	Initial cost															
Economic and maintenance	Maintenance burden															
	Total score															

Other criteria that should be considered but not scored

Criteria	Assessment
Is there a suitable drainage outfall (surface water or sewer)?	If no outfall infiltration techniques must be used at the end of the management train
Sediment load	If large sediment load then pervious surfaces and infiltration techniques (without substantial pre-treatment) should not be used

Table A1.2a *Selection matrix for SUDS techniques – hydrological and land use*

	Treatment suitability		Hydrological						Land use									
Technique	**Pollutant removal** (see Table 3.6 for details)		**Water quantity control**		**Groundwater recharge**		**Flow rate control**		**Dense urban developments**		**Car parks**		**Roads**		**Housing**		**Stormwater hotspots** (see Section 3.2)	
Pervious pavements	Yes	5	Yes 0.5% or greater	5	Possibly	1 or 5	Yes	4	Yes	5	Yes	5	Yes [c]	3	Yes	3	Possibly, with additional treatment and storage techniques	3
Green roofs	Yes	5	Yes 3.3% or greater	4	No	1	Yes	4	Yes	5	No	1	No	1	Yes	3	No	1
Bioretention	Yes	5	Limited 10% or greater	2	Yes	1 or 5	No	2	Possibly	3	Yes	4	Yes	4	Yes	4	Yes, if lined to prevent infiltration	3
Filtration technique	Yes	4	No	2	No	1	No	2	Yes	4	Yes	4	Yes	4	Yes	2	Yes	5
Grassed filter strips	Yes	2	No	2	Very limited	3	No	2	No	1	Yes	4	Yes	5	Possibly	2	Yes	4
Swales	Yes	4	Yes 10% or greater [a]	3	Limited	3	Yes	4	Difficult	2	Yes	4	Yes	5	Yes, if located outside gardens	3	Yes, if lined to prevent infiltration	3
Infiltration devices	Yes	3	Yes 0.5% or greater	5	Yes	5	No	4	Possibly [b]	4	Yes	4	Yes	4	Yes	5	Not usually (unless additional treatment provided)	1
Filter drains	Yes	3	Yes 10% or greater	3	Not usually	1	Yes	4	Possibly	3	Yes	4	Yes	5	Yes	2	Yes	4
Infiltration basin	Yes	3	Yes 0.5% or greater	5	Yes	5	No	4	No	1	Yes	4	Yes	4	Yes	4	Not usually (unless additional treatment provided)	1
Extended detention basin	Yes	3	Yes 0.5% or greater	4	Possibly	2	Yes	3	No	1	Yes	4	Yes	5	Yes	4	Yes	4
Wet ponds	Yes	4	Yes 0.5% or greater	5	No	2	Yes	3	No	1	Yes	4	Yes	5	Yes	4	Yes	4
Stormwater wetlands	Yes	5	Yes 1% or greater	3	No	2	Yes	3	No	1	Yes	4	Yes	5	Yes	4	Yes	4
On-/off-line storage	No	1	Yes 0.5% or greater	5	No	1	Yes	3	Yes	5	Yes	5	Yes	5	Yes	4	Yes	5

Notes

a Lower for very small catchments

b If it can be located more than 5 m from buildings

c Subject to limitations. See CIRIA C582 (Pratt et *al*, 2002)

Table A1.2b *Selection matrix for SUDS techniques – physical site features*

Technique	Suggested drainage sub-catchment area	< 2 ha	2–8 ha	> 8 ha	Site slope	0–10%	10–15%	> 15%	Space required		Soil considerations	Infiltration rate < 10^{-6} m/s	> 10^{-6} m/s, < 10^{-3} m/s	> 10^{-3} m/s	Water table < 1 m	> 1 m	Roof slope
Pervious pavements	Can be used for drainage of any size area provided it is split into sub-catchments	5	5	5	Ideally, level site. If sloping terracing or check dams within pavement required and care to prevent surcharging at low points	5	2	1	No additional space beyond car parking requirements	5	May need membrane to prevent infiltration or protect weak subgrades [a]. For infiltration should have infiltration coefficient > 1×10^{-6} m/s [b]	5	5	5	4	5	n/a
Green roofs	Can be used on roofs of any size	5	5	5	No restriction	5	5	5	No additional space	5	None	5	5	5	5	5	Low: no restriction Mean: may need baffles High: may be difficult
Bioretention	0.1–0.8 ha max sub-catchment size	5	1	1	Ideally no more than 6–10%, but with careful design can be used on steeply sloping sites	5	3	2	Minimal to large, depending on existing landscaping	3	May need membrane to prevent infiltration	5	5	5	3	5	n/a
Filtration techniques	4 ha max 0.8 ha max for perimeter filter	5	3	1	Ideally no more than 6–10%	5	5	2	Minimal to moderate	5	None	5	5	5	5	5	n/a
Grassed filter strips	2 ha max	5	1	1	Ideally no more than 6–10%	5	2	1	Moderate to high	2	May need membrane to prevent infiltration	5	4	3	5	5	n/a
Swales	2 ha max	5	1	1	Ideally no more than 4–10%	5	3	2	Moderate	2	If infiltration required, soils should have infiltration coefficient > 1×10^{-6} m/s [b]	5	4	3	3	5	n/a
Infiltration devices	2–4 ha max	5	3	1	Ideally no more than 6–10%	5	1	1	Minimal	5	Requires soils with infiltration coefficient > 1×10^{-6} m/s [b]	1	5	2	1	5	n/a
Filter drains	2–4 ha max	5	3	1	Ideally no more than 6–10%	5	3	2	Minimal	3	May need membrane to prevent infiltration	5	3	2	3	5	n/a
Infiltration basin	4 ha max	5	2	1	Ideally no more than 15%	5	3	3	Substantial	1	Requires soils with infiltration coefficient > 1×10^{-6} m/s [b]	1	5	2	1	5	n/a
Extended detention basin	8–10 ha min	1	2	5	Ideally no more than 15%	5	3	3	Substantial	1	Requires impermeable soils, otherwise liners needed	5	4	3	3	5	n/a
Wet ponds	8–10 ha min	1	2	5	Ideally no more than 15%	5	2	1	Substantial	1	Require impermeable soils, otherwise liners needed	5	4	3	3	5	n/a
Stormwater wetlands	8–10 ha min (except for pocket wetlands, 2 ha min)	1	2	5	Ideally no more than 8–15%	5	3	1	Substantial	1	Require impermeable soils if above water table, otherwise liners needed	5	4	3	4	4	n/a
On-/off-line storage	Drainage areas of any size if good-sized flow control devices provided	5	5	5	Place storage parallel to site contours. Care to prevent surcharging in system	5	4	3	Minimal (can be put below most site areas, including buildings)	5	None	5	5	5	5	5	n/a

Notes

a See CIRIA C532 (Masters-Williams *et al*, 2001)

b See CIRIA Report 156 (CIRIA, 1996)

Table A1.2c *Selection matrix for SUDS techniques – economics, maintenace, community and environment*

	Economics and maintenance			Community and environment				
Technique	**Life-span**	**Initial cost**	**Maintenance burden**	**Safety**	**Pond premium** (see Section 1.2)	**Aesthetics**	**Wildlife habitat**	**Community acceptance**
Pervious pavements	Very high 5	Moderate 3	Moderate 3	Very good 5	No 1	Low 2	None 1	Moderate 3
Green roofs	Very high 5	Moderate to high 3	Low to moderate 4	Very good (safety of maintenace workers to be considered) 5	No 1	Moderate 3	Moderate 3	Low (at present) 2
Bioretention	Moderate 3	Low 4	Moderate to high 2	Very good 5	No 1	High 4	Moderate 3	High 4
Filtration techniques	Moderate 3	Moderate to high 2	Moderate to high 2	Very good 5	No 1	Low 2	Very low 1	Moderate 3
Grassed filter strips	High 4	Low (cost of land take can be high) 4	Low 4	Very good 5	No 1	Low to moderate 3	Moderate 3	High 4
Grassed swales	Very high 5	Moderate 3	Moderate 3	Good 4	No 1	Moderate 3	Low 2	High 4
Infiltration trench/ soakaway	Moderate to high 4	Moderate 3	Moderate 3	Very good 5	No 1	Very low 1	Very low 1	Moderate to high 3
Filter drains	Moderate 3	Moderate 3	Moderate 3	Very good 5	No 1	Very low 1	Very low 1	Moderate to high 3
Infiltration basin	Moderate to high 4	Moderate 3	Moderate 3	Moderate – design to prevent fast inundation 3	No 1	Low 2	Low 2	Moderate 3
Dry detention ponds	High 4	Low (cost of land can be high) 4	Low 4	Moderate – risk assessment required 3	No 1	Moderate 3	Moderate 3	Moderate 3
Wet ponds	Very high 5	Low (cost of land can be high) 4	Low 4	Moderate – risk assessment required 3	Yes 5	High 4	High 4	High 4
Stormwater wetlands	High 4	Moderate (cost of land can be high) 3	Low 4	Varies – risk assessment required 3	Yes 5	Very high 5	Very high 5	High 4
On-/off-line storage	Moderate to high 4	Moderate to high 2	Low 4	Very good 5	No 1	None 1	None 1	Very high 5

A2 Worked examples

The site is a park-and-ride car park with extensive areas of landscaping proposed.

Constraints are:

- site gradient is 2 per cent
- water quality is an essential consideration, as is a reduction in flood risk
- there is no requirement to recharge groundwater and the soils below the site are clays with an infiltration rate of 1×10^{-8} m/s
- the overall site area is 55 000 m^2, but it is possible to split this into sub-catchments of approximately 5000 m^2
- the water table is at a depth greater than 1 m below final ground levels.

Using the approach set out in Appendix 1 the following tables may be completed.

Decision criteria for selecting SUDS techniques

Step 1 – Assume site master plan has been reviewed and all prevention techniques have been considered.

Step 2 – Site is split into sub-catchments of 5000 m^2.

Step 3

	Criteria	Assessment	Weighting	Pervious pavements	Green roofs	Bioretention	Filtration techniques	Grassed filter strips	Swales	Infiltration devices	Filter drains	Infiltration basin	Extended detention ponds	Wet ponds	Stormwater wetlands	On-/off-line storage
Hydrological	Is pollutant removal a priority?	*Yes – essential. Scores from Table A1.1 × weighting*	*2*	*10*	–	*10*	*8*	*4*	*8*	*6*	*6*	*6*	*6*	*10*	*10*	*2*
	Is water quantity control a priority?	*Yes – essential. Scores from Table A1.1 × weighting*	*2*	*10*	–	*4*	*4*	*4*	*6*	*10*	*6*	*10*	*8*	*10*	*6*	*10*
	Is flow rate control a priority?	*Yes – essential. Scores from Table A1.1 × weighting*	*2*	*8*	–	*4*	*4*	*4*	*8*	*8*	*8*	*8*	*6*	*6*	*6*	*6*
	Is groundwater recharge required?	*No*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Land use	Suitability to type of development	*Car park. Scores from Table A1.1 × weighting*	*1*	*5*	–	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*5*
Physical site features	Catchment area	*0.5 ha. Scores from Table A1.2 × weighting*	*1*	*5*	–	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*1*	*1*	*1*	*5*
	Site slope	*Generally around 2 per cent. Scores from Table A1.2 × weighting*	*1*	*5*	–	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*
	Space required	*There are no space limitations, so do not score. Scores from Table A1.2 × weighting*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Soil infiltration rate	*Infiltration rate is 1×10^{-8} m/s. Scores from Table A1.2 × weighting*	*1*	*5*	–	*5*	*5*	*5*	*5*	*1*	*5*	*1*	*5*	*5*	*5*	*5*
	Water table depth	*Greater than 1 m depth to water table. Scores from Table A1.2 × weighting*	*1*	*5*	–	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*4*	*5*
	Total score			***53***	**–**	***42***	***40***	***36***	***46***	***44***	***44***	***44***	***40***	***42***	***41***	***43***

Step 4

From Step 3 the techniques with the highest scores are pervious surfaces, bioretention, swales, infiltration, filter trenches, wet ponds and in/offline storage. Take these techniques to the next stage.

	Criteria	Assessment	Weighting	Pervious pavements	Green roofs	Bioretention	Filtration techniques	Grassed filter strips	Swales	Infiltration devices	Filter drains	Infiltration basin	Extended detention	Wet ponds	Stormwater wetlands	On-/off-line storage
Community and environment	Safety	*Concerns not excessive as it is a car park*	*1*	*5*	–	*5*	–	–	*4*	*5*	*5*	*3*	–	*3*	–	*5*
	Pond premium	*Not of concern*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Aesthetics	*Desirable, but not essential*	*1*	*2*	–	*4*	–	–	*3*	*2*	*2*	*2*	–	*4*	–	*1*
	Wildlife habitat	*Desirable, but not essential*	*1*	*1*	–	*3*	–	–	*2*	*1*	*1*	*2*	–	*4*	–	*1*
	Community acceptance	*Not of concern in remote location*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Total score			***8***	**–**	***12***	**–**	**–**	***9***	***8***	***8***	***7***	**–**	***11***	**–**	***7***

Step 5

From Step 5 we can now discount infiltration basins and on-/off-line storage. The remaining techniques can be assessed on economic and maintenance factors.

	Criteria	Assessment	Weighting	Pervious pavements	Green roofs	Bioretention	Filtration techniques	Grassed filter strips	Swales	Infiltration devices	Filter drains	Infiltration basin	Extended detention	Wet ponds	Stormwater wetlands	On-/off-line storage
Economic and maintenance	Life-span	*Long life-span essential*	*2*	*10*	–	*6*	–	–	*10*	*8*	*6*	–	–	*10*	–	–
	Initial cost	*Not of concern*	*1*	*3*	–	*4*	–	–	*3*	*3*	*3*	–	–	*4*	–	–
	Maintenance burden	*Low-maintenance preferred*	*1*	*3*	–	*2*	–	–	*3*	*3*	*3*	–	–	*4*	–	–
	Total score			***16***	**–**	***12***	**–**	**–**	***16***	***14***	***12***	**–**	**–**	***18***	**–**	**–**

So the optimum combination on this site could be a combination of pervious pavements, swales and a wet pond.

Other criteria that should be considered but not scored

Criteria	Assessment
Is there a suitable drainage outfall (surface water or sewer)?	If no outfall infiltration techniques must be used at the end of the management train
Sediment load	If large sediment load then pervious surfaces and infiltration techniques (without substantial pre-treatment) should not be used

Step 6

Check pollutant removal efficiency of combination of techniques in a management train.

A2.1 EXAMPLE RISK ASSESSMENT OF POLLUTANT REMOVAL PERFORMANCE

Consider the conceptual SUDS scheme that has been developed for part of the car park shown in the plan below (Figure A2.1).

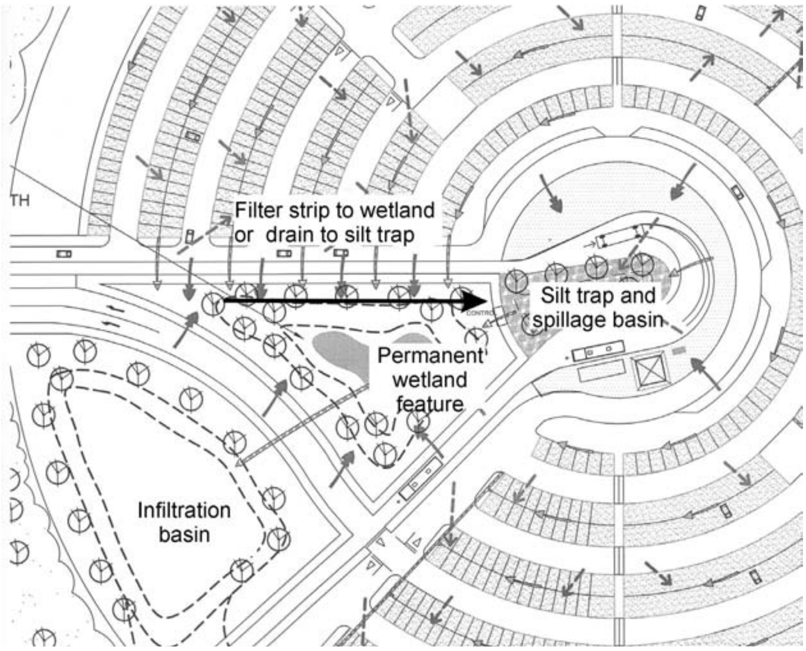

Figure A2.1 *Site plan*

The car park is part of a park-and-ride scheme on the outskirts of a major city in the Midlands of the UK. The conceptual design of the SUDS proposals include two options for part of the management train.

1 Runoff from impermeable areas to a filter strip connected to a wetland (missing the silt trap or forebay) to an infiltration basin.

2 Runoff from impermeable areas to a filter drain connected to a wetland (via silt trap or forebay to an infiltration basin.

A limitation of the system is that the space available to install the filter strip is restricted and the minimum width recommended cannot be achieved. The most effective combination in terms of pollutant removal is required.

It has been agreed with the regulators that there are two types of pollutants of concern.

1 Total suspended solids.

2 Hydrocarbons.

Considering Tables 3.3 and 3.6, the EMCs for the pollutants that are to be used in the risk assessment are based on use of the site as a park-and-ride car park. The section under consideration is the bus route into the site, which will be in regular use by buses and cars throughout the day. We will use the values of pollutant load for "other main roads" in Table 3.3. The values for hydrocarbons are taken from Table 3.6 for highways.

Pollutant	EMC
TSS	156.9 mg/l
Hydrocarbons	29 mg/l

List the techniques in the order that they occur in the system and determine pollutant removal for each one from Table 3.7.

Table A2.1 *Filter strip connected to a wetland (missing the silt trap or forebay) to an infiltration basin*

TSS

1	2	3	4	5	6	7	8
Technique	**Inflow EMC**	**Pollutant removal efficiency (Table 3.7)**	**Apply 50 per cent reduction?**	**Outflow concentration**	**Mean pollutant concentration for technique (Table 3.8)**	**Higher of 5 and 6**	**Comments**
Filter strip	From impermeable surface 156.9 mg/l	50%	No	78.5 mg/l	n/a	78.5 mg/l	Use low values since width of filter strip is below recommended minimum
Wetland (without forebay)	From filter strip 78.5 mg/l	60%	Yes 30%	54.9 mg/l	29 mg/l	54.9 mg/l	60 per cent used because runoff from filter strip misses silt trap
Infiltration basin	From wetland 54.9 mg/l	75%	Yes 37.5%	34.3 mg/l	n/a	34.3 mg/l	

Hydrocarbons

1	2	3	4	5	6	7	8
Technique	**Inflow EMC**	**Pollutant removal efficiency (Table 3.7)**	**Apply 50 per cent reduction?**	**Outflow concentration**	**Mean pollutant concentration for technique (Table 3.8)**	**Higher of 5 and 6**	**Comments**
Filter strip	From impermeable surface 29 mg/l	70%	No	8.7 mg/l	n/a	8.7 mg/l	Use low values since width of filter strip is below recommended minimum
Wetland (without forebay)	From filter strip 8.7 mg/l	40%	Yes 20%	7.0 mg/l	n/a	7.0 mg/l	40 per cent used because runoff from filter strip misses silt trap
Infiltration basin	From wetland 7.0 mg/l	Insufficient information; assume 10%	Yes 5%	6.6 mg/l	n/a	6.6 mg/l	

Table A2.2 *Filter drain connected to a wetland (via silt trap or forebay) to an infiltration basin*

TSS

1	2	3	4	5	6	7	8
Technique	**Inflow EMC**	**Pollutant removal efficiency (Table 3.7)**	**Apply 50 per cent reduction?**	**Outflow concentration**	**Mean pollutant concentration for technique (Table 3.8)**	**Higher of 5 and 6**	**Comments**
Filter strip	From impermeable surface 156.9 mg/l	85%	No	23.5 mg/l	n/a	23.5 mg/l	
Wetland	From filter strip 23.5 mg/l	90%	Yes 45%	12.9 mg/l	23 mg/l	23 mg/l	
Infiltration basin	From wetland 23 mg/l	75%	Yes 37.5%	14.3 mg/l	n/a	14.3 mg/l	

Hydrocarbons

1	2	3	4	5	6	7	8
Technique	**Inflow EMC**	**Pollutant removal efficiency (Table 3.7)**	**Apply 50 per cent reduction?**	**Outflow concentration**	**Mean pollutant concentration for technique (Table 3.8)**	**Higher of 5 and 6**	**Comments**
Filter strip	From impermeable surface 29 mg/l	70%	No	8.7 mg/l	n/a	8.7 mg/l	
Wetland	From filter strip 8.7 mg/l	80%	Yes 40%	5.2 mg/l	n/a	5.2 mg/l	
Infiltration basin	From wetland 5.2 mg/l	Insufficient information; assume 10%	Yes 5%	4.9 mg/l	n/a	4.9 mg/l	

The management trains give the following comparative pollution outflow based on EMCs.

Table A2.3 *Estimation of pollutant removal*

Techniques	TSS at inflow	TSS at outflow	Hydrocarbon at inflow	Hydrocarbon at outflow
Filter strip, wetland, infiltration basin	156.9 mg/l	34.3 mg/l	29 mg/l	6.6 mg/l
Filter drain, wetland, infiltration basin	156.9 mg/l	14.3 mg/l	29 mg/l	4.9 mg/l

The outflow hydrocarbon concentrations are at a similar level and there is little to choose between the techniques. TSS removal is significantly improved by the use of the filter drain and therefore in this case will be incorporated into the design. Not only will the pollutant removal be enhanced but also the life-span of the infiltration basin before clogging will be improved.

Consider the design robustness for pollutant removal of TSS (Table 3.9) and it is seen that the robustness for the filter strips is low to moderate while that for the filter drain is high. Thus the risk of the filter drain not performing as required and higher pollutant levels occurring at the outlet is lower than the filter strip. Again, this suggests that the use of the filter drain would be the preferred option in this case, to provide increased confidence that risk of pollution of the minor aquifer is low.

Design examples

Design of SUDS components for a car park to a small commercial or office development (Figure A2.2). We will design the treatment techniques to deal with water quality volume. (Assume treatment of 90 per cent of the average annual rainfall is required. Use a fixed rainfall depth to estimate the treatment volume that will achieve this – taken to be 15 mm rainfall.)

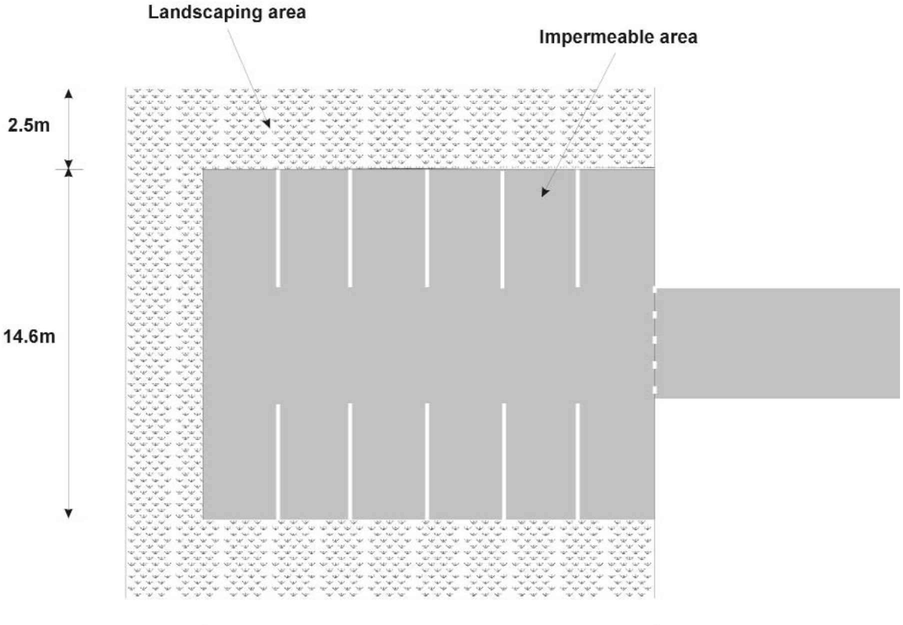

Figure A2.2 *Site layout*

Bioretention design

The bioretention is required to treat the water quality volume. An overflow will allow flows in excess of the design capacity to flow directly to the piped outfall system.

The landscaping areas along each edge of the car park are available for bioretention.

Total W_{Qv} = area of car park × rainfall = 219 × 15/1000 = 3.3 m^3 assuming 100 per cent runoff (which is conservative).

Preliminary section of bioretention area to provide 150 mm maximum depth of surface storage will be as shown below to fit into the 2.5 m-wide landscaping area (Figure A2.3).

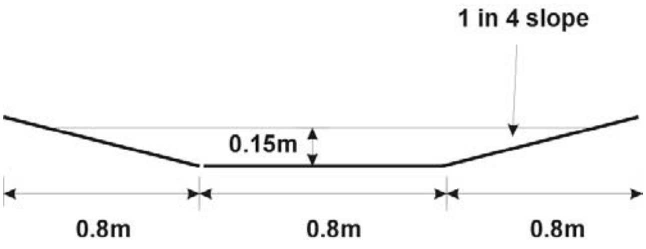

Figure A2.3 *Section of bioretention area*

Volume of storage = $[(0.8 \times 0.15) + 2(0.6 \times 0.15)/2] \times 15$ m = 3.15 m^3 along each side of the car park.

Runoff to each side will be 3.3/2 = 1.65 m^3, so there is sufficient storage capacity in the surface. Indeed, there is excess capacity that will be able to deal with more runoff than required in the design.

From Section 9.4.

The surface area of the bioretention area required is given by:

$A_f = Q_{wq} \times d_f/[(k \times (h + d_f)(t_f)]$

Where:

A_f = surface area of bioretention planting bed (m^2)

Q_{wq} = water quality treatment volume (m^3) = 1.65 m^3 in this example

d_f = planting soil bed depth (m) assume 0.5 m in this example

k = coefficient of permeability of water (m/s) for filter material – assume $k = 1 \times 10^{-4}$ m/s, but apply a factor of safety of 10 to allow for blockages and silting, so $k = 1 \times 10^{-5}$ m/s

h = average height of water above bioretention bed (half maximum height) (m) = 0.075 m

t_f = time required for water quality treatment volume to percolate through treatment bed (s); we require a 48-hour treatment time in accordance with Section 9.4 = 172 800 s.

So $A_f = 1.65 \times 0.5/[(1 \times 10^{-5} \times (0.075 + 0.5)(172\,800)]$

$A_f = 0.83\ m^2$

The actual area is 2.5 m by 15 m, which gives a much greater area. Therefore the area for the bioretention could be reduced or the extra capacity used to treat a wider range of storm events.

Perimeter sand filter

The sand filter will be provided along one edge of the car park and will treat the W_{Qv} of 15 mm, so the total volume will be the same as before, ie 3.3 m^3.

From Section 9.5.5.

The area of the sedimentation chamber is given by:

$A_s = -(Q_o/W)\ln(1-E)$

Where:

A_s = surface area (m^2)

Q_o = discharge rate from basin (water quality volume/detention time) (m^3/s) = $3.3/(24 \times 60 \times 60) = 3.8 \times 10^{-5}$ m^3/s

W = particle settling velocity (m/s) = 1.8×10^{-4} for fine silt particles (from CIRIA Book 14)

E = removal efficiency – typically assumed to be 90 per cent (0.9)

The minimum detention time in the filter system should be 24 hours.

A_s $= -(3.8 \times 10^{-5}\ m^3/s/1.8 \times 10^{-4})\ln(1^{-0.9})$

Surface area of sedimentation chamber, $\mathbf{A_s = 0.49\ m^2}$

So a 15 m-long filter with a width of at least 0.49/15 = 0.03 m^2 is required.

The volume of the sedimentation chamber will be at least 25 per cent of the W_{Qv}, so = 0.825 m^3.

The surface area of the filter bed can be determined using the following equation from Section 9.5.5:

A_f $= Q_{wq} \times d_f/[(k \times (h + d_f)(t_f)]$

Where:

A_f = surface area of filter bed (m^2)

Q_{wq} = water quality treatment volume (m^3) = 3.3 m^3

d_f = filter soil bed depth (m) = 0.4 m chosen

k = coefficient of permeability of filter medium for water (m/s) = 1×10^{-5} m/s including factor of safety (see bioretention example) based on particle size distribution for a typical filter sand

h = average height of water above filter bed (half maximum height) (m) = 0.075 m

t_f = time required for water quality treatment volume to percolate through treatment bed (s) = 48 h × 60 × 60 = 172 800 s.

So minimum area of filter:

A_f $= 3.3\ m^3 \times 0.4\ m/[(1 \times 10^{-5}\ m/s \times (0.075\ m + 0.4\ m)(172\ 800\ s)]$

A_f $= 1.6\ m^2$

So for 15 m-long filter A_f = 1.6/15 = 0.1 m minimum width of filter bed. In practice, the filter bed would be wider and thus would deal with events of a lower probability and give increased design robustness.

Swale

Swale is required to treat the water quality volume and convey runoff from all events up to 1 per cent annual probability without erosion. The runoff from the 1 per cent annual probability event should also be limited to a flow of 3 l/s/ha to provide the river flood protection.

The length of swale is 30 m. The gradient is 3 per cent. A preliminary layout is shown in Figure A2.4.

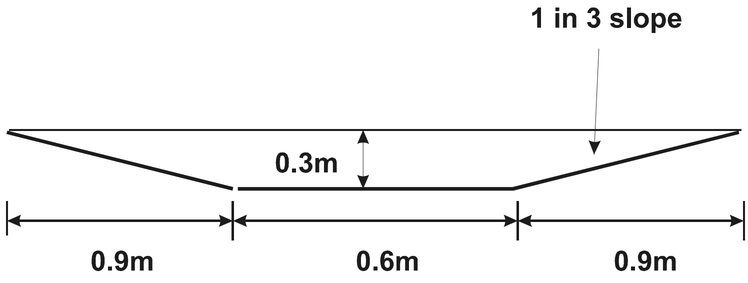

Figure A2.4 *Preliminary layout*

Treatment volume

Treatment volume = 3.3 m^3; assume this is over 1 hour, so intensity is 15 mm/h and maximum flow from car park is 3.3 m^3/h (ignoring time of concentration and losses).

Assume flow depth is 100 mm.

$$V = \frac{1}{n} R^{\frac{2}{3}} S_o^{\frac{1}{2}}$$

Where:

V = mean cross-sectional flow velocity (m/s)

n = Manning's roughness coefficient (note this coefficient is often given as dimensionless but it is not; here it is $m^{-1/3}$ s) = use 0.3 for preliminary design

R = hydraulic radius of channel = A/P_w

A = cross-sectional area through which water is running (m^2) = (0.6 m × 0.1 m) + (2 × 0.1 m × 0.3 m/2) = 0.09 m^2

P_w = wetted perimeter of channel (the cross-sectional length of channel in contact with the water) = 0.32 + 0.32 + 0.6 = 1.24 m

S_o = channel slope = 3% = 0.03

So V = $(1/0.3) \times (0.09/1.24)^{0.667} \times 0.03^{0.5}$

V = 0.096 m/s

Volume of flow Q = 0.09 m^2 × 0.096 m/s × 60 × 60 = 31.1 m^3/h.

Now adjust flow depth and or channel width until the calculated Q equals the required Q (3.3 m^3/h in this case)

If calculated Q is higher then decrease the slope, channel width or flow depth.

If calculated Q is lower then increase the slope, channel width or flow depth.

So reduce the flow depth to 30 mm.

Then Q calculated = 3.8 m^3/h, which is sufficiently close to the required Q of 3.3 m^3/h.

V = 0.05 m/s, which is less than 0.3 m/s and acceptable.

So the actual flow depth will be 30 mm, which is acceptable. If space had been tight then the width of the swale could have been reduced.

Check for residence time in the swale.

If flow is 3.8 m^3/h then the residence time of the water quality volume in the swale is:

Velocity = distance/time

So time = distance/velocity = 30 m/0.05 m/s for 30 mm water depth

Residence time = 600 s = 10 minutes. This is acceptable, as residence time should be at least 10 minutes. If this was not acceptable the gradient could have been reduced by using check dams.

River flood protection and erosion of swale

Check to ensure that the flow from the swale during the 1 per cent annual probability event does not exceed 3 l/s/ha and that the velocities will not cause erosion.

Assume 54 mm of rainfall occurs over 2 hours so intensity is 27 mm/h and maximum flow from car park is 5.9 m^3/h (ignoring time of concentration and losses).

Assume flow depth is 40 mm.

$$V = \frac{1}{n} R^{\frac{2}{3}} S_o^{\frac{1}{2}}$$

Where:

V = mean cross-sectional flow velocity (m/s)

n = Manning's roughness coefficient (note this coefficient is often given as dimensionless but it is not; here it is $m^{-1/3}$ s) = use 0.3 for preliminary design

R = hydraulic radius of channel = A/P_w

A = cross-sectional area through which water is running (m^2) = (0.6 m × 0.04 m) + (2 × 0.04 m × 0.12 m/2) = 0.029 m^2

P_w = wetted perimeter of channel (the cross-sectional length of channel in contact with the water) = 0.13 + 0.13 + 0.6 = 0.86 m

S_o = channel slope = 3% = 0.03

So V = $(1/0.3) \times (0.029/0.86)^{0.667} \times 0.03^{0.5}$

V = 0.059 m/s

Volume of flow Q = 0.029 m^2 × 0.059 m/s × 60 × 60 = 6.2 m^3/h.

This is sufficiently close to the required Q of 5.9 m^3/h.

V = 0.059 m/s, which is less than 1 m/s and acceptable.

So the actual flow depth will be 40 mm, which is acceptable. If space had been tight then the width of the swale could have been reduced.

Check the outlet flow.

Q = 5.9 m^3/h = 1.63 l/s.

Allowable = 3 l/s/ha = 3 × 219/10 000 = 0.066 l/s.

So additional storage and flow control are required to limit flows into the receiving stream.

Grassed filter strip

A filter strip is required to carry flow to an infiltration trench.

The slope is 2 per cent and the width of the strip is 4 m. Filter strips will be provided on two sides of the car park.

So water quality volume is 3.3 $m^3/h/2 = 1.65\ m^3/h$

The flow across the filter strip can be determined using Friend's equation for overland sheet flow (Section 9.6.5):

$$t_0 = (107nL^{0.333})/S^{0.2}$$

Where:

t_0 = overland sheet flow travel time (minutes)

L = overland sheet flow path length (m) = 4 m

n = Horton's roughness value for the surface (can be taken as Manning's roughness coefficient). The roughness coefficients for swales (Table 5.9.4 and Section 5.9.5) may be used for filter strips. Use 0.3 for this example

S = slope of surface (%) = 0.02

Travel time $t_0 = (107 \times 0.3 \times 4^{0.333})/0.02^{0.2}$

t_0 = 2.5 minutes

This is less than the minimum of 5 minutes that is recommended, so increase the width or provide additional techniques in the management train.

A3 Design information checklist

Description	Details for the particular project	Consultees and sources of information
Existing site parameters ***Physical***		
Topography		Site survey or inspection
Area of catchment		Site survey
Soil type		Site investigation
Infiltration potential of soil		Site investigation
Structural properties of soil – CBR, stiffness		Site investigation and laboratory testing
Former land use		Local authority, Ordnance Survey maps, local library
Hydraulic		
Hydrology of catchment		Site inspection and observations
Flood risk		Environment Agency/SEPA/DoE Northern Ireland/local authority
Rainfall data		Meteorological Office or Wallingford Procedure
Discharge design criteria – quality		Environment Agency/SEPA/DoE Northern Ireland or water service company
Frequency of ponding on surface that is acceptable		Environment Agency/SEPA/DoE Northern Ireland or water service company
Storage capacity and permeability of materials		Laboratory testing and test sections or manufacturer's specifications
Environmental		
Contamination of ground below site		Local authority, Ordnance Survey maps, local library and site investigation
Details of receiving water/ watercourse/aquifer		Environment Agency/SEPA/DoE Northern Ireland or water service company
Environmental sensitivity of site		EA/SEPA/DoE(NI)/local authority, English Nature (Countryside Council in Wales)
Groundwater vulnerability and source protection status		Environment Agency/SEPA/DoE Northern Ireland
Design-specific parameters		
Site		
Developmental type and land use		Proposed development plans
Potential areas for SUDS		Proposed development layout plan
Riparian rights for overflow routes		
Structural		
Structural properties of materials		Laboratory testing and test sections or manufacturer's specifications
Construction and design loads		Proposed development plans
Health and safety		All affected parties

A4 Case studies

CASE STUDY 1 AZTEC WEST

Location Aztec West Commercial Development, Bristol.

Techniques used Retention ponds and detention basins.

Management train Three ponds in series.

Lessons to be learnt SUDS can operate successfully with minimal maintenance for at least 20 years if correctly designed.

Education of site owners and tenants is essential to avoid future works compromising the SUDS.

SUDS can be integrated into the landscaping of a site to provide additional amenity and aesthetic value that owners value.

Innovative design can remove the need for costly structures such as oil interceptors and replace them with more visually attractive features that satisfy the same criteria.

Date of construction Between 1978 and 1982.

Design philosophy The discharge from the site was limited and the site was provided with a conventional drainage system leading to four main ponds. Three of the ponds are arranged in series (cascaded) and are retention ponds. The fourth "pond" is a detention basin that is dry for most of the time Figure A4.1)

Design at the time followed the guidance in Road Note 35 (TRRL, 1976) and used a 30-year return period Bilham event calibrated to local rainfall data obtained from the Meteorological Office. 100 per cent runoff was assumed from paved areas.

The quality of the pond water and the impact on the aesthetics was of concern (the impact of pollution from runoff on watercourses was not a major concern at the time). The pond was designed as a tear-drop shape with the inlet and outlet at opposite ends to prevent short-circuiting.

In 1980 the cost of oil separators to minimise the volume of hydrocarbons entering the ponds was estimated at between £60 000 and £250 000. An alternative to the separators was to use large ornamental fountains to improve the inherent pollutant removal capability of the ponds by aerating the water and promote the aerobic degradation of hydrocarbons. They also disturb the surface and prevent the formation of thin oil films and iridescence.

Paths and furniture were provided around the ponds to allow the users of the site access to this valuable amenity.

The ponds have proved so successful that others have been constructed elsewhere on the site.

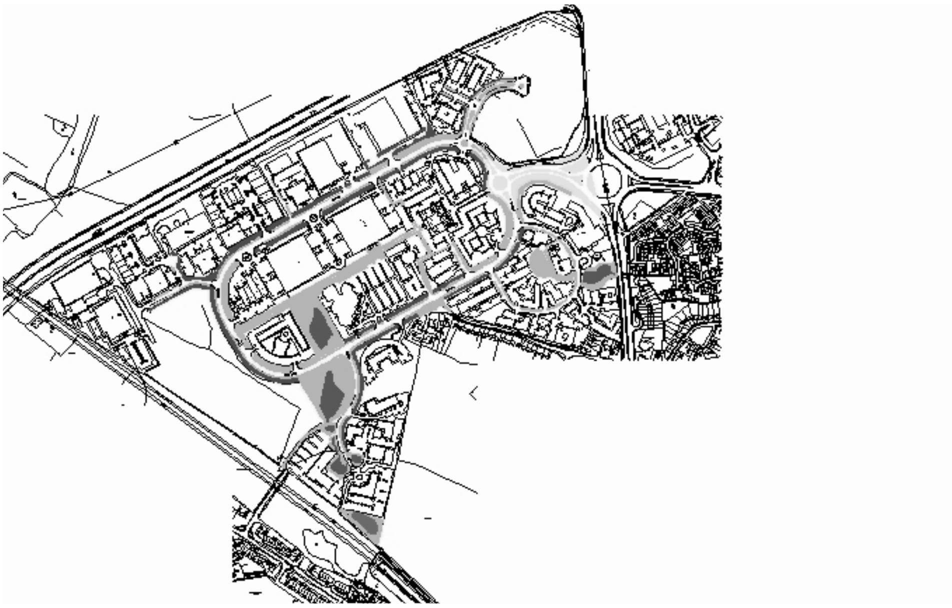

Figure A4.1 *Plan of drainage system (Millerick, 2003)*

Figure A4.2 *View of the ponds at Aztec West (Millerick, 2003)*

Maintenance

The fountains are inspected and maintained quarterly by divers. A little silt build-up around the base of the fountains has been noted but none elsewhere. Silt has never been removed from the ponds.

Maintenance requirements have proved to be minimal.

General comments

The information in this case study was obtained from Millerick, 2003 and from information provided by Aidan Millerick at Micro Drainage Limited.

Hydraulic performance

No site flooding has been reported. Calibration of the design model with a storm event was carried out in 1982. The water level in the ponds was 100 mm lower than predicted.

Water quality performance

In 20 years no problems with visible signs of oil pollution have been reported. In 2002 the Environment Agency checked the health of the fish population and found that the population was thriving and was becoming overpopulated, which indicates a healthy ecosystem within the ponds.

CASE STUDY 2 LINBURN POND, DUNFERMLINE EASTERN EXTENSION, SCOTLAND

Location Duloch Park, Dunfermline, Scotland.

Techniques used Wet pond (retention pond).

Management train Detention basins followed by wet pond.

Lessons to be learnt The majority of silting appears to occur from construction runoff.

Pollutant removal for well-designed ponds is good.

Silt removal may be required after about eight years (25 per cent of pond volume).

The concentration of pollutants in sediment may not be hazardous.

Public perception of well-designed and maintained ponds is generally good.

Well-designed ponds give good attenuation of flows.

Date of construction Constructed in spring/summer 1998 as part of the advance infrastructure for the development.

Design philosophy The pond receives drainage from a multi-purpose catchment of 67.5 ha that is drained by conventional drainage, swales and pervious surfaces. It is known as the Lower Linburn catchment.

The catchment includes homes, a leisure park and roads. The built-up area is 24 per cent of catchment, and the remainder is agricultural land. The maximum slope on the catchment is 10 per cent.

The pond was required to reduce the impact of drainage on flooding and water quality downstream, in the Lyne Burn.

Data collection began in May 1999, when the catchment was undeveloped. Construction of a major housing development within the catchment began in September 1999 and the main distributor road infrastructure for the whole catchment was in place at this time.

The pond has five inlets. Four are at the north-eastern end of the pond, at the opposite end to the outlet. The fifth one is situated relatively close to the outlet. The catchment and inlets/outlets are shown on Figure A4.4. It has one outlet at the opposite end to the four main inlets.

The surface area of pond is 10 200 m^2 and the permanent water volume is 15 500 m^3.

The pond was not designed in accordance with this book, as there is no sediment forebay and no vehicular access for maintenance or sediment removal. One inlet appears to be close to the outlet.

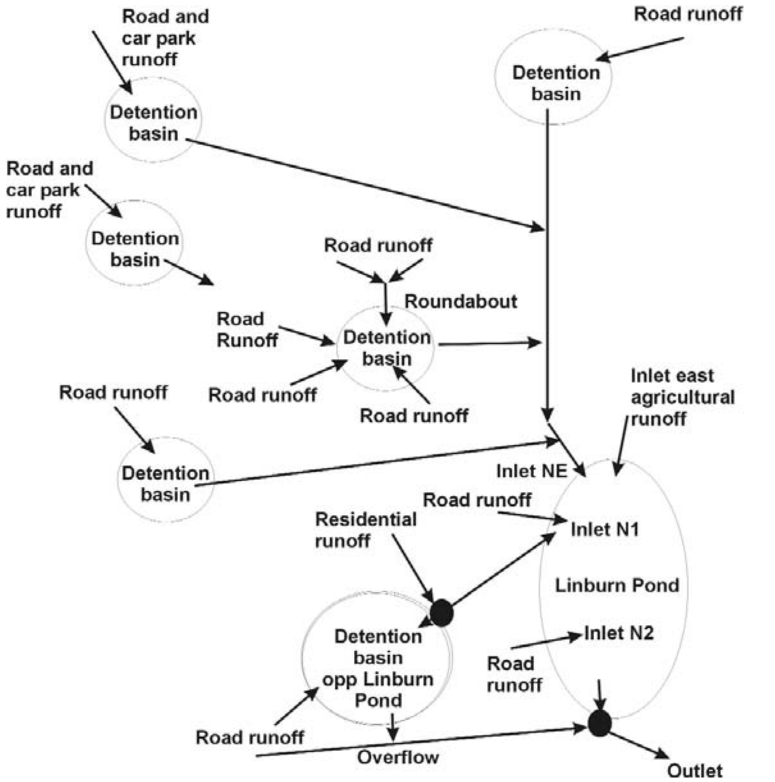

Figure A4.3 *Schematic of Linburn Pond catchment (Jefferies, Spitzer and Duffy, 2002)*

Figure A4.4 *Linburn Pond*

Maintenance

There is no information on the maintenance regime.

General comments

The information in this case study was obtained from Heal, 2000; Jefferies, Heal and D'Arcy, 2001; Schluter, Spitzer and Jefferies, 2000; Jefferies, Spitzer and Duffy, 2002; Johnstone, 2000; and Spitzer, 2000b.

Hydraulic performance

Measured runoff into the pond rarely exceeded 2.4 l/s/ha. In one event for a rainfall depth of 37.7 mm the outflow from the pond was 63 m^3/ha (some 16.8 per cent of the rain that had fallen). A typical hydrograph is shown in Figure A4.5.

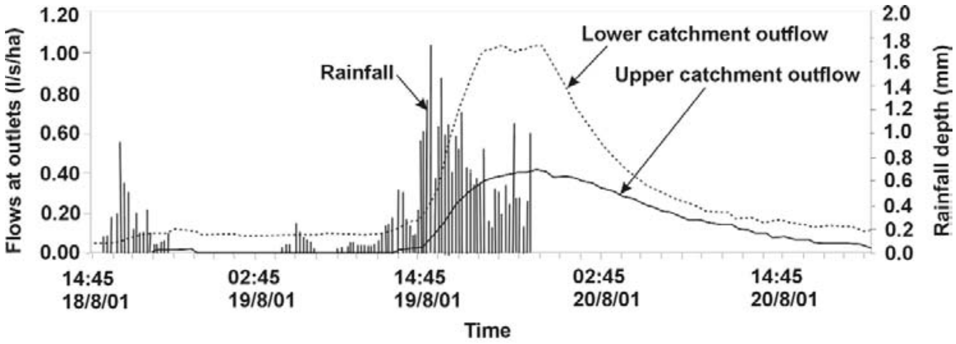

Figure A4.5 *Outflow hydrograph for a typical rainfall event (Schluter, Spitzer and Jefferies, 2000)*

The catchment response time has decreased significantly as development has proceeded, from 4 hours 15 minutes in the pre-development state to 2 hours on completion of the first housing development and roads. It is reported that the attenuation provided by the pond is satisfactory.

Water quality performance

The performance of the pond in removing pollutants is reported to be satisfactory. The ponds remove orthophosphate and total oxidised nitrogen, and the best removal rates are in the summer months. Removal of ammoniacal nitrogen is very low. TSS removal is very good and outlet water is usually clear, despite the fact that the design does not meet all the design requirements of this report. The maximum recorded concentration of TSS at outlet is 46 mg/l and turbidity is usually below 100 NTU.

In June 2000 there was a prolonged dry spell and the water at the outlet was almost a standing pool. This is thought to have caused increased dissolved oxygen concentrations that were generally between 40 per cent and 60 per cent.

Continuous monitoring data for water quality parameters up to 2000 are summarised on Table A4.1.

Table A4.1 *Pollutant levels continuously monitored at outlet to Linburn Pond (Spitzer, 2000b)*

Parameter	Minimum	*Maximum*
Dissolved oxygen (%)	7	120
Temperature (deg C)	2	15
pH	7.6	9.4
Turbidity (NTU)	2	270
Conductivity (µs/cm)	620	800

The water quality data for samples taken at the inlet to the pond show that to date it has been relatively clean. A summary of the quality data at the inlet and outlet is provided in Table A4.2. Despite the clean inflow there does appear to be a general trend of improvement in the quality. For example, the range of BOD for the inlet is classified as excellent to poor, but at the outlet is always excellent and similarly for ammoniacal nitrogen.

Table A4.2 *Pollutant levels at inlet and outlet to Linburn Pond (Spitzer, 2000)*

Parameter	Inlet		Outlet	
	Minimum	*Maximum*	Minimum	*Maximum*
PH	7.3	7.8	7.6	7.8
TSS (mg/l)	1.3	211	3.3	5.2
BOD (mg/l)	1.5	10	1.4	2
Ammoniacal nitrogen (mg/l)	< 0.02	17.5	0.26	0.69
Total oxidised nitrogen (mg/l)	0.37	9.17	< 0.1	1.04
Orthophosphate (mg/l)	0.01	11	< 0.01	0.052
Chloride (mg/l	19.8	159	36.6	38.0
Conductivity (μs/cm)	458	1510	654	681

Generally the outlet flow was classified as excellent in accordance with the Scottish River Classification System.

Silting

Sediment build-up has been monitored every year. Greatest sedimentation occurs in the sediment forebay close to the four main inlets. There is less sedimentation in the secondary basin, where slightly elevated levels are close to another inlet (Figure A4.6).

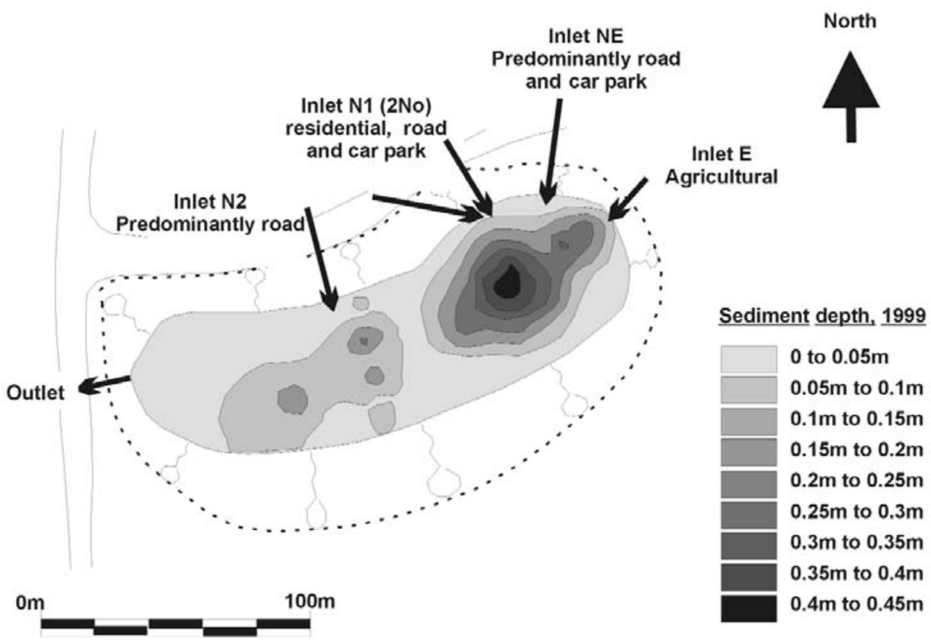

Figure A4.6 *Sediment depth in pond in July 1999 (Heal, 2000)*

The change in mean sediment depth is shown in Figure A4.7 and indicates that the majority of sediment to date was present at the end of construction. The time to fill the entire pond volume based on the increase in sediment during 2001 is estimated to be 31 years based on 501 m^3 entering the pond in 2001. It is interesting to note that in 2000 very little sediment entered the pond and the elevated level in 2001 may been caused by construction activities. The recommendations are to remove silt when it fills 25 per cent of the pond volume. In the worst case, this will require silt removal after about eight years. The most optimistic view using the data from 2000 is that silt removal is likely to be required after a much greater length of time.

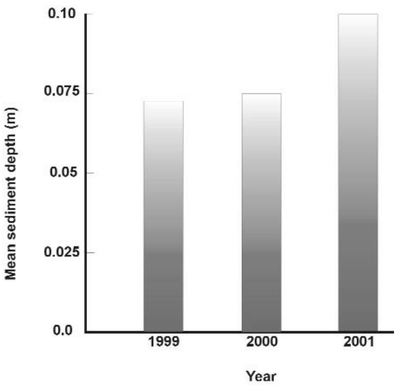

Figure A4.7 *Change in mean sediment depth (Heal, 2000)*

The pollutant concentrations in the sediment have been recorded on several occasions (Table A4.3).

The highest levels of pollutants were mostly associated with the deepest areas of sediment.

The heavy metal concentrations in the sediment were compared to the Swedish Environmental Protection Agency's classification for aquatic sediment quality. Zinc was found to be very low and at background concentrations. Cadmium, lead and copper were at low levels and chromium and nickel were moderate to high. Hydrocarbon concentrations were also low.

Table A4.3 *Sediment quality in 1999*

Parameter	Minimum (mg/kg)	Maximum (mg/kg)	Mean (mg/kg)
Cadmium	0	1.62	0.15
Chromium	14.2	109	53.6
Copper	13.8	25.1	20.7
Iron (%)	2.3	8.78	4.07
Nickel	11.8	71.1	43.4
Lead	9.9	30.2	20.8
Total nitrogen	1092	4484	2518
Total phosphorous	424	3713	1113
Zinc	50.2	85.9	68.1
Hydrocarbons	38.1	610	246

Other

The pond was inspected over a two-year period (50 visits) to determine if litter, blockages or other factors were affecting the performance of the pond. The pond was scored on a scale of 1 (no evidence) to 5 (severe problem). The average scores are summarised below and shoe that there were no severe issues that affected performance.

Algae	Litter	Vandalism	Inlet clogging
2.1	2.4	2	1.2

At the same time a survey to determine the public attitude to the pond was undertaken. The response was generally positive.

Algae diversity and population have been monitored as indicators of the health of the pond. *Cladophera* species is the dominant species in the pond.

CASE STUDY 3 MATCHBOROUGH FIRST SCHOOL, REDDITCH

Location	Matchborough First School, Redditch.
Techniques used	Swales, detention basins, constructed wetland.
Management train	Swales and/or detention basins followed by a wetland. Roof runoff direct to wetland.
Lessons to be learnt	Incorporating and allowing for SUDS early in the development design will reduce costs. SUDS can effectively control overland flows and land drainage flows from adjacent sites. SUDS are cost-effective compared to conventional drainage. Well-considered design provides valuable amenity and habitat for marginal cost. Water safety issues need not prevent the use of SUDS. Retrofitting SUDS to existing sites is feasible.
Date of construction	Completed 2003.

Design philosophy

The site is a school development that was originally designed with conventional drainage that flowed to a pumping station from where it was pumped against the site gradient to a sewer. During construction it became apparent that one playground area could not be drained by gravity to the pumping station. At this stage the school building was constructed.

The use of SUDS was proposed to overcome this and also to remove the need for the pumping station and the ongoing maintenance costs. The SUDS scheme drains the site following the site gradient downhill to the Ipsley Stream (removing the annual charge for the sewer connection).

Swales are used to collect the overland flows from an adjacent site and the car park and playground runoff to provide source control to a large part of the site. The main driveway is drained to an extended detention basin. All these systems then connect to the constructed wetland, which also takes roof runoff directly (the roof runoff has a lower risk of pollution).

The system is designed to cope with events with an annual probability of 1 per cent (1 in 100 return). Overland flow routes are provided for events that exceed these design criteria.

The SUDS system has also been designed to provide a valuable amenity and teaching resource for the school.

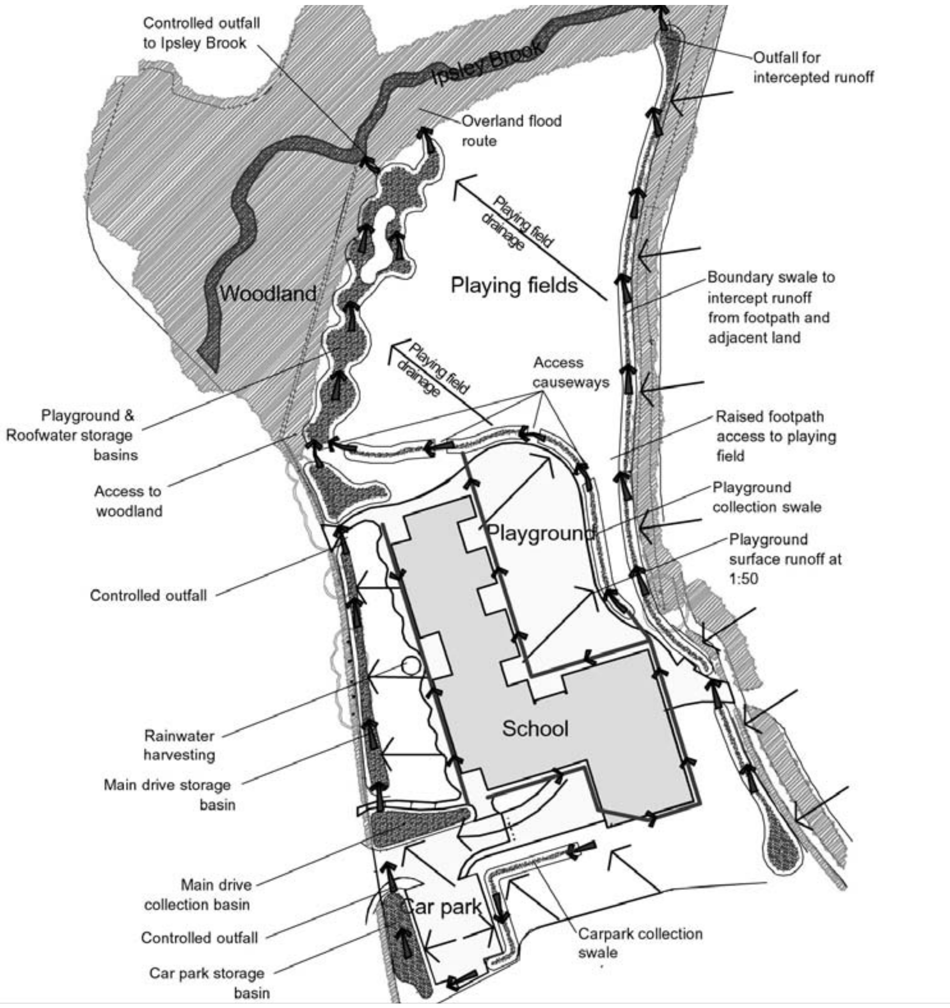

Figure A4.8 *Plan of drainage system*

Maintenance

The site has recently been completed and has not required maintenance yet. Costs are expected to be lower than for the conventional drainage system since most of the work will be a marginal extension to the landscape contract required for the school grounds. Regular inspections will be undertaken by the school caretaker.

General comments

Further information on the site is provided in Bray, 2003.

Hydraulic performance

The site has been recently completed and no data is available.

Water quality performance

The site has been recently completed and no data is available.

Costs

A comparison of the costs between the conventional drainage and the SUDS scheme is provided in Table A4.4.

Table A4.4 *Cost comparison*

Item	Cost (£)	
	SUDS	**Traditional**
Trenches, pipework and associated fittings	16 825	53 170
Drainage accessories	400	2380
Drainage channels	9630	4010
Manholes	3300	10 400
Pumping station	0	10 880
Connection to sewer	0	750
Headwall to stream	750	3000
Land drainage to playing field	32 110	32 110
Constructing swales, basins and wetlands	25 000	0
Reducing levels of site to accommodate SUDS because it was not incorporated earlier in development of project	5000	0
Total cost	**93 015**	**116 700**

The annual cost for the sewer connection would have been £3180 per year and the annual maintenance cost for the pumping station would have been £800 a year (2003 prices). Maintenance costs for the SUDS will be marginal since landscaping maintenance for the school grounds is already required.

CASE STUDY 4 BRISTOL BUSINESS PARK

Location

Bristol Business Park is north of Bristol approximately 1 km west of the M4/M32 junction. It is accessed from Coldharbour Lane using a roundabout that also gives access to the University of the West of England.

Techniques used

Permeable paving, swales, wet detention pond.

Management train

Pervious pavements to swales followed by a wet detention pond.

Lessons to be learnt

Permeable paving minimised loss of land to detention ponds.

Permeable paving and short swales satisfied the SUDS planning policy of the local authority.

The permeable paving required careful programming on site and early installation of services and drainage.

Care was needed to avoid contamination of the system at all stages, especially from sand, topsoil etc.

Well-designed ponds may be considered by clients to be an asset that improves the site.

Date of construction

First phase completed 1994, Phase 4 completed 2003, final phase to be completed.

Design philosophy

Permeable paving has been used in the Phase 3 parking areas with a total site area of approximately 1.2 ha. Discharges from this paving connect to swales, which in turn are conveyed by a conventional gravity drainage system carrying earlier conventionally paved phases through a wet detention pond, through a control feature (hydrobrake), which discharges into an off-site watercourse. Runoff from the roofs of the Phase 3 development also discharge into the permeable paving.

The car parking areas are surfaced with a mixture of permeable and impermeable paving supplied by Formpave Limited, with a porous sub-base running throughout. Rainwater falling on the permeable paving flows through the gaps into the underlying porous sub-base. The impermeable aisles are laid to falls so that the runoff is shed to the permeable paving, where it discharges through the joints into the underlying gravel. Rainwater downpipes from the roofs discharge into shallow pipes via small accessible silt traps, distributing water into the porous gravel through a simple tree branch pipe arrangement to aid dispersal. Concern over the possibility of clay heave and shrinkage led to the inclusion of an impermeable liner below the sub-base, tucked up the sides. Discharge pipes of 100 m diameter convey flows to the swales.

As the site has been developed in phases, the drainage designs have been dictated by the capacity of the four catchments. The last phase to be completed (Phase 3) was within a catchment drained by a small watercourse that begins near the boundary of the site. Downstream this watercourse has a very shallow bed adjacent to a road, which frequently floods. It was therefore important to minimise any increase in the risk of flooding. It is also planning policy of the local authority, South Gloucestershire Council, that all new developments should incorporate sustainable drainage features (SUDS).

The original plan was to form a large wet detention pond with a controlled outlet restricting flows to the agricultural runoff intensity. However, the developer was keen to maximise the development area, and also have high-quality landscaped ponds in prominent areas within the development, rather than at the "back" of the development where the large detention pond would need to be.

The Phase 3 permeable system connects into an existing system that already incorporated a small wet detention pond.

The Formpave System comprises paving blocks with notches formed in the ends to allow water to flow through to the bedding material while maintaining the normal interlocking to form the pavement. Fine gravel bedding was used, placed on a porous geofabric separation membrane. Below this is punctured macadam, over approximately 350 mm of porous gravel. The bedding layer performs the water quality improvement function, and the porous gravel performs the storage function.

Figure A4.9 *Swale and pervious pavement*

Construction

The construction was procured using a design-and-construct contract, but the permeable paving was a condition of the employer's requirements, and installed largely in accordance with the original scheme. The contractor decided to place the permeable gravel early in the contract and protect it with a layer of macadam, which was later punctured before installation of the bedding layer and paving blocks.

Consequently, the services, drainage and ducts needed to be installed at a very early stage in the contract, to avoid subsequent contamination of the permeable gravel or damage to the impermeable membrane.

The final block paving layer was laid towards the end of the contract, and care had to be taken with topsoil and sand deliveries to avoid blocking the gaps between the blocks.

Maintenance

No information available

General comments

This case study was provided by Clive Onions of ARUP.

Hydraulic performance

The pavement has been observed during and after a range of heavy and prolonged storms, and only negligible flows have been observed discharging into the swales, demonstrating the attenuating attribute of the paving system.

Water quality performance

No information available.

A5 Planting for SUDS

From *Ponds, pools and lochans* (SEPA, 2000).

Appropriate plants for adding to new ponds

This appendix lists plants that are common and widespread throughout the British Isles (including Scotland) and that can be transplanted to new ponds.

Submerged and floating-leaved plants of base-rich ponds

Submerged plants do not always survive transplantation to a new pond, particularly where the water quality differs from that of the original site, and it is often best just to let them colonise naturally. The following submerged plants are fairly tolerant of conditions in at least moderately unpolluted base-rich ponds:

Curled pondweed (*Potamogeton crispus*)	Various water-crowfoots (*Ranunculus species*)
Various water-starworts (*Callitriche species*)	Spiked water-milfoil (*Myriophyllum spicatum*)
Rigid hornort (*Ceratophyllum demerum*)	Marestail (*Hippuris vulgaris*)

Three common floating-leaved plants are tolerant of a wide range of conditions:

Broad-leaved pondweed (*Potamogeton natans*)	Yellow water-lily (*Nuphar lutea*)
White water-lily (*Nymphaea alba*)	

Plants for the drawdown zone and shallow water

Most marginal water plants are tolerant of natural water level fluctuations and will grow both in shallow water and on damp marshy ground. When planting up the pond edge, encourage a mix of tall emergents and, just as important, low grasses and herbs. Plant in small mixed clumps – they will soon spread. Perennial species planted into damp ground at the water's edge generally take well regardless of the time of year in which they are planted.

Taller marginal plants

Note that the last five of these species are usually very vigorous. It is inadvisable to plant them at the edge of small shallow ponds, unless a marshland pond dominated by tall emergents is required, or continuous plant management is to be undertaken.

Yellow iris (*Iris pseudacorus*)	Great pond-sedge (*Carex riparia*)
Marsh woundwort (*Stachys palustris*)	Reed canary-grass (*Phalaris arundinacea*)
Gipsywort (*Lycopus europaeus*)	Reed sweet-grass (*Glyceria maxima*)
Purple loosestrife (*Lythrum salicaria*)	Branched bur-reed (*Sparganium erectum*)
Various species of rush (*Juncus species*)	Bulrush (*Typha latifolia*)
Great water-dock (*Rumex hydrolapathum*)	

Lower-growing herbs and grasses that can be added to ponds on base-rich soils

Amphibious bistort (*Persicaria amphibia*)
The floating sweet-grasses (*Glyceria species*)
Creeping bent (*Agrostis stolonifera*)
Common water-plantain (*Alisma plantago-aquatica*)
Watercress (*Nasturtium officinale*)
Marsh-marigold (*Caltha palustris*)
Marsh pennywort (*Hydrocotyle vulgaris*)
Water forget-me-not (*Myosotis scorpioides*)
Water mint (*Mentha* aquatica)
Marsh foxtail (*Alopecurus genicultatus*)
Fool's water-cress (*Apium nodiflorum*)
Common spike-rush (*Eleocharis palustris*)

Plants to avoid

Avoid introducing non-native plants, especially into ponds in the wider countryside. It is particularly important not to introduce some of the very vigorous alien plants that can take over ponds and exclude native species. These include:

Canadian pondweed (*Elodea canadensis*)
Nuttall's pondweed (*Elodea nuttallii*)
Curly waterweed (*Lagarosiphon major*)
Parrot's-feather (*Myriophyllum aquaticum*)
Water fern (*Azolla filiculoides*)
New Zealand swamp-stonecrop (*Crassula helmsii*)
Floating pennywort (*Hydrocotyle ranunculoides*)

Additional native wetland plants suitable for planting in SUDS wetlands

Sweet flag (*Acorus calamus*)
Fools watercress (*Apium nodiflorum*)
Lesser water parsnip (*Berula erecta*)
Nodding burmarigold (*Nidens cerrua*)
Flowering rush (*Butomus umbellatus*)
Bog arum (*Calla palustris*)
Lesser pond sedge (*Carex acutiforis*)
Glaucus sedge (*Carex Flacca*)
Great tussock sedge (*Carex paniculata*)
Pendulus sedge (*Carex pendula*)
Cyperus sedge (*Carex pseudocyperus*)
Greater pond sedge (*Carex riparia*)
Galingale (*Cyperus longus*)
Meadowsweet (*Filipendula ulmaria)*
Floating sweet grass (*Glyceria fluitans*)
Reed sweet grass (*Glyceria maxima*)
Marestail (*Hippurus vulgaris*)
Yellow flag (*Iris pseudacorus*)
Sharp flowered rush (*Juncus acutiflrus*)
Sharp rush (*Juncus acutus*)
Soft rush (*Juncus effuses*)
Hard rush (*Juncus inflexus*)
Yellow loosestrife (*Lysimachia vulgaris*)
Purple loosestrife (*Lythrum solicaria*)
Water mint (*Mentha aquatica*)
Water forget-me-not (*Myosodis scorpioides*)
Water cress (*Nasturdium officinale*)
Fine leaved water dropwort (*Oenanthe aquatica*)
Henluck water dropworth (*Oenanthe Crocata*)
Common reed (*Phragmites ommunis*)
Amphibious bistort (*Polygonum amphibium*)
Lesser spearwort (*Ranunculus flammula*)
Greater spearwort (*Ranunculus lingua*)
Arrowhead (*Sequittaria* sagith*f*olia)
Common club rush (*Scirpus lacustris*)
Branched bur reed (*Sparganum* erectum)
Lesser reedmace (*Typha angustifolia*)
Brooklime (*Veronica beccabunga*)

Marginal plants appropriate for acid conditions

Star sedge (*Carex echinata*)
Common sedge (*Carex nigra*)
Bottle sedge (*Carex rostrata*)
Marsh thistle (*Cirsium palustre*)
Tufted hair-grass (*Deschampsia caespitosa*)
Common spike-rush (*Eleocharis palustris*)
Marsh willowherb (*Epilobium palustre*)
Floating sweet-grass (*Glyceria fluitans*)
Yellow iris (*Iris pseudacorus*)
Articulated rush (*Juncus articulatus*)
Sharp-flowered rush (*Juncus acutiflorus*)
Bulbous rush (*Juncus bulbosus*)
Soft rush (*Juncus effusus*)
Hard rush (*Juncus inflexus*)
Ragged-robin (*Lychnis flos-cuculi*)
Creeping forget-me-not (*Myosotis secunda*)
Bog-myrtle (*Myrica gale*)
Tormentil (*Potentilla erecta*)
Lesser spearwort (*Ranunculus flammula*)
Marsh violet (*Viola palustris*)
Marsh speedwell (*Veronica scutellata*)
Deergrass (*Trichophorum caespitosum*)
Bog stitchwort (*Stellaria uliginosa*)

Aquatic plants appropriate for acid conditions

White water-lily (*Nymphaea alba*)
Intermediate water-starwort (*Callitriche hamulata*)
Bog pondweed (*Potamogeton polygonifolius*)
Alternate water-milfoil (*Myriophyllum alterniflorum*)

A6 Design accreditation checklist

SITE .... DEVELOPER ....

LOCATION .... GRID REFERENCE ....

This accreditation checklist is a means of evaluating sustainable drainage proposals for development sites.

Using the checklist – against each subject, confirm the check requirement with a tick or cross in the response box.

			Response
1	**UNDERSTANDING SUDS**		
	1.1	Provide a clear explanation of the SUDS proposal and demonstrate it meets the philosophy of the SUDS approach to drainage	☐
2	**PLANNING SUDS**		
	2.1	Design criteria – planning requirements including design return period(s) and permitted rates and volumes of runoff	☐
	2.2	Initial data review – existing conditions / natural drainage / location of discharges / infiltration potential (Appendix 3 – Design information checklist)	☐
3	**OUTLINE PROPOSALS – STAGE 1 CONSULTATION**		
	3.1	Prevention – minimise runoff, prevent pollution, contain spillages and manage silt	☐
	3.2	Source control – show attenuation and pollution control sequence on site	☐
	3.3	Conveyance – describe flow routes, low flow recurrence intervals, extreme flood route	☐
	3.4	Site or regional control – on catchment scale rather than at source	☐
4	**DETAILED DRAINAGE DESIGN – FINAL CONSULTATION**		
	4.1	Process – check that quality, quantity and amenity design criteria have been considered equally	☐
	4.2	Detail – check that drainage pathways reflect natural drainage patterns	☐
	4.3	Maintenance – check that maintenance can be carried out easily	☐
	CRITICAL ELEMENTS		
	4.4	Prevention – minimise runoff, prevent pollution, contain spillages and manage silt	☐
	4.5	Design rainfall criteria review – relevant criteria from Section 4 met, flood frequency, recurrence intervals, low and high flow routes, runoff storage hierarchy and infiltration potential	☐
	4.6	Quality – pre-treatment features to control silt and pollution, "treatment stages" required, the management train principle, "first flush" containment and treatment, groundwater protection	☐
	4.7	Amenity – evaluate community value, resource management (eg rainwater use), multi-use of space, education, water features, habitat creation, biodiversity action plans	☐
5	**HEALTH and SAFETY STATEMENT**		
	5.1	Confirm risk assessment – collection devices, inlets and outlets, storage features, wetlands and ponds and Construction (Design and Management) Regulations 1994 (CDM)	☐
6	**CONSTRUCTION – SITE CONTROL MEASURES THROUGH CONSTRUCTION**		
	6.1	Contractor method statement – control of silt and other contamination during construction – health and safety audit – CIRIA C532 (Masters-Williams, 2001)	☐
7	**MANAGEMENT**		
	7.1	Confirm management plan, landscape maintenance schedule to include all SUDS features, review details, eg inlets and outlets, provide site information sheet	☐
8	**SUSTAINABILITY AUDIT**		
	8.1	Review design components, scheme design life, resilience in use, future management	☐

Checked by .... Date checked ....

A7 Construction inspection checklist

Phase and inspection item	Inspection date	Condition*	Date phase completed	Remarks/remedial works
Pre-excavation				
Runoff from areas of bare soil diverted to site control				
Runoff from contaminated areas diverted to site control				
Excavation				
Soil is not smeared or compacted so that permeability is reduced				
Excavation is to required size and gradient and is located in correct position				
Side slopes are correct				
All debris (eg loose roots) removed from base feature				
There is no groundwater seepage in the base of the feature				
Depth of excavation is correct				
Construction				
Earthworks materials to specification with test results				
Filter materials in accordance with specification with test results				
Compaction acceptable				
Inlets and outlets constructed in accordance with drawings and specification and drawings				
Construction to required line and levels				
Planting				
Planting in accordance with specification				
Planting established				
Handover inspection				
No silting from construction				
No erosion or bare areas of plant-ing				
All litter removed and inlets and outlets operating correctly				

* Acceptable or unacceptable