Project under EU RTD 5th Framework Programme

Contract No EVK1-CT-2002-00111

Adaptive Decision Support System (ADSS) for the Integration of Stormwater Source Control into Sustainable Urban Water Management Strategies

Report 5.1. Review of the Use of stormwater BMPs in Europe

prepared by Middlesex University

in collaboration with
Cereve at ENPC, Ingenieurgesellschaft Prof. Dr. Sieker GmbH, Water Pollution Unit at Laboratoire Central des Ponts et Chaussées, Division of Sanitary Engineering at Lulea University of Technology and Department of Water Resources Hydraulic and Maritime Works at National Technical University of Athens

18 August 2003 final version

WP / Task / Deliverable N°: WP5 / T5.1 / D5.1
Dissemination Level: PU

Document patterns
File name: *D5.1 version 2*

Sent : 2003-08-18 by M Revitt	Returned to author : J-C. Deutsch	Validated :	WP5 / T5.1 / D5.1 Diss. Level : PU
Received : 2003-08-18	Revised by authors : M Revitt, B Ellis and L Scholes	Validated by :	Version : Final

Keywords (for the Database):

Stormwater management, BMPs, design, performance

Acknowledgement
The results presented in this publication have been obtained within the framework of the EC funded research project DayWater "Adaptive Decision Support System for Stormwater Pollution Control", contract no EVK1-CT-2002-00111, co-ordinated by Cereve at ENPC (F) and including Tauw BV (Tauw) (NL), Department of Water Environment Transport at Chalmers University of Technology (Chalmers) (SE), Environment and Resources DTU at Technical University of Denmark (DTU) (DK), Urban Pollution Research Centre at Middlesex University (MU) (UK), Department of Water resources Hydraulic and Maritime Works at National Technical University of Athens (NTUA) (GR), DHI Hydroinform, a.s. (DHI HIF) (CZ), Ingenieurgesellschaft Prof. Dr. Sieker GmbH (IPS) (D), Water Pollution Unit at Laboratoire Central des Ponts et Chaussées (LCPC) (F) and Division of Sanitary Engineering at Luleaa University of Technology (LTU) (SE).
The programme is organised within the "Energy, Environment and Sustainable Development" Programme in the 5th Framework Programme for "Science Research and Technological Development" of the European Commission and is part of the CityNet Cluster, network of European research projects on integrated urban water management.

EXECUTIVE SUMMARY

This report represents a comprehensive review of the current state of knowledge on the use and performance of BMPs for stormwater treatment and control. It has been prepared as part of the EC funded DayWater project through contributions provided by several partners based on both their extensive knowledge and specific expertise of stormwater BMPs. An emphasis has been placed on the design, operation, maintenance and costing of stormwater BMPs, with particular regard to country specific factors. The accepted use of these systems varies with a wide range of structural and non- structural BMPs being employed in northern and temperate European countries for stormwater control, whereas their applicability is less well developed in southern European countries such as Spain, Italy, Greece and Portugal. An exception to this is street cleaning, which appears to be a common practice throughout Europe. There also appear to be patterns or trends in the types of BMPs preferred within various countries, with for example, rainwater harvesting being a popular stormwater BMP in France and Germany, but practised to a lesser extent in other European countries.

Different types of structural BMPs are evaluated against a range of factors which have been identified in terms of their influence on the selection and use of these systems. These comparisons indicate that:

? constructed wetlands, retention basins and extended detention basins appear to have the fewest physical constraints on their use,

? grass swales and filter strips perform best in terms of groundwater recharge potential and pollutant removal capabilities,

? infiltration systems, swales and retention basins may have some technological and sustainable advantages over other source control devices.

A variety of methods are available to assist the design of structural BMPs based on parameters or criteria which are relevant to the treatment process. Examples which have commonly been employed include particle settling characteristics, capture of the first 10-15mm of effective runoff, residence time, return period, infiltration capability and pollutant removal capability. These overall approaches are available through the publication of a range of design manuals, guidelines and recommendations, with a wide selection of computer models routinely being used to enable system performance to be evaluated under a variety of conditions.

Operation and maintenance (O&M) is a major concern when the use of stormwater BMPs is being considered. Although it is often stated that O&M requirements must be included in the initial design and costing process, this is not always the case in practice. The issue of O&M guidelines for the adoption of stormwater BMPs by an appropriate body is often problematic. However, this situation is now being addressed through, for example in the UK, the publication of a draft Framework Agreement by the Environment Agency for England and Wales.

The use of stormwater BMPs is generally accepted to result in reductions in treatment costs compared to conventional systems with savings ranging from 18-50% having been reported for a range of BMPs. However, the initial capital costs can be elevated such as in the case of road infrastructure BMPs where more expensive surfacing materials may be used. Costs can also vary considerably between sites depending upon local conditions, including engineering constraints (which will normally increase costs) and land constraints (which may lead to decreased costs but also a reduction in performance).

A considerable amount of data on the performance of a range of BMPs is presented and this demonstrates that BMPs can effectively manage both the quantity and quality of stormwater in northern and temperate European countries. There is currently little data available on the performance of BMPs in southern European countries. Where poor or variable removal performances have been reported, a range of reasons have been cited such as the re-entrainment of solids during high flows, short circuiting and low detention times. Key problems are identified in the way performance data are determined and calculated and represent an important area for consideration in future discussions of BMP performances.

The contribution that stormwater BMPs can make to sustainable urban development through their potential to address the needs and concerns of a diverse group of stakeholders is now being recognised. The environmental and urban community benefits offered by different BMPs can be compared through the development of a qualitative evaluation matrix. Both wetlands and retention basins score highly through such an approach although these evaluations are subjective, and there is a need to fully develop and apply robust and quantifiable sustainability criteria. As an initial step to addressing this requirement, a generic list of primary sustainability criteria is proposed as a starting point for the development of a multi-criteria methodology. The identified criteria could be quantified through benchmarks and hence compared with national sustainability targets.

This report provides a comprehensive review of the design, operation and performance of BMPs across Europe. It provides stakeholders and end-users with detailed information on the ability of BMPs to treat and control stormwater, whilst also discussing issues that have been a cause of concern (e.g. the adoption of O&M requirements) and highlighting areas for further research (e.g. development of quantifiable sustainability criteria). It can therefore be used as a balanced source of information on the current use of stormwater BMPs within Europe.

TABLE OF CONTENTS

SECTION TITLES

TABLE OF TABLES

TABLE OF FIGURES

1 BACKGROUND TO THE USE OF BEST MANAGEMENT PRACTICES (BMPS) AND OVERALL STRUCTURE OF THIS REVIEW

The continued and rapid growth of urban areas across Europe places increasing importance on the control of stormwater. However, the criteria defining what constitutes effective stormwater management are themselves undergoing change. Comprehensive stormwater management plans in both new and existing urban areas should not only address stormwater quantity and quality but also need to consider issues such as sustainable development. Furthermore, it is anticipated that the legal requirements for the control of stormwater, particularly with regard to the protection of receiving waters, are likely to become much more stringent through the implementation of the Water Framework Directive.

In order to meet these changing requirements a new approach to stormwater management is needed, which has led to increasing interest in the use of BMPs. BMPs encompass a wide range of solutions which enables the planning, design and management of stormwater to be tackled equally from hydrological, environmental and public amenity perspectives (CIRIA, 2001). BMPs can be used as an alternative to, or in combination with, conventional stormwater drainage systems.

This report is presented as Deliverable 5.1 of the DayWater project which is funded by the European Commission as part of the 5th Framework Programme for "Science Research and Technological Development" within the "Energy, Environment and Sustainable Development" Programme. The overall objective of the report is to outline the use of BMPs across Europe but with particular attention to the adaptability and relevance of these systems to the different European climatic regions. This review consists of six sections which are supported by a comprehensive literature review. Following this introduction (Section 1), Section 2 describes the different types of BMPs which have been applied within Europe with an emphasis on the non-structural versions. Comparisons of BMPs with conventional systems are made in Section 3 together with descriptions of the criteria on which the use of BMPs can be based. Section 4 provides detailed accounts of design and operation/maintenance requirements of specific structural BMPs as well as some comments on costing implications. Section 5 concentrates on performances of both structural and non-structural BMPs with regard to both water quantity and water quality aspects and the report concludes (Section 6) with some comments on the environmental and sustainability benefits of BMPs.

The Urban Pollution Research Centre, Middlesex University, as the leaders of Work Package 5, have coordinated the preparation of this review. The lead authors (Professor Bryan Ellis, Dr Lian Scholes, and Professor Mike Revitt) are grateful to their project partners from Cereve at ENPC, Ingenieurgesellschaft Prof. Dr. Sieker GmbH, Water Pollution Unit at Laboratoire Central des Ponts et Chaussées, Division of Sanitary Engineering at Lulea University of Technology and Department of Water Resources Hydraulic and Maritime Works at National Technical University of Athens for their valuable contributions which have made the depth and breadth of this review possible.

2 NATIONAL APPROACHES TO THE USE OF BMPS

2.1 Introduction

BMPs are divided into two main types as follows –

- structural BMPs (which involve the physical construction of a system for urban stormwater management)
- non-structural BMPs (which involve either the introduction of a new management practice or the modification of an existing management practice).

Examples of various structural and non-structural BMPs used in the UK are given in Table 2.1. There is no exact enumeration of differing types of BMPs and Table 2.1 therefore only gives a general indication of the relative popularity and usage of the various structural and non-structural approaches currently adopted in the UK. It should be noted that the prime objective of most structural BMPs (also know as Sustainable Urban Drainage Systems, SUDS, in the UK), is that of flow control and attenuation of peak stormwater discharges. Urban stormwater management is thus primarily focused upon flood rather than pollution control although the last 5-6 years has seen the adoption of more conjunctive design approaches combining the prime flow control function with those of secondary water quality and amenity objectives.

Table 2.1 BMP types found in the UK

	BMP TYPE																			
	Structural BMPs														**Non-Structural BMPs**					
			Infiltration Systems			Above ground storage Facilities					Road Surfacing									
	Filter strips/Grass Swales	Filter (french) drains	Soakaways	Infiltration Trenches	Infiltration Basins	Storage Tanks/Chambers	Lagoons	Detention & Extended Detention Basins	Retention (Balancing) Ponds	Constructed Wetlands	Porous Paving	Porous Asphalt	Rainwater Harvesting	Gully Pots (Oil Interceptors)	Street Cleaning	Reduction in Pollutant Usage	Snow Management Practices	Educational Practices	Routine Management Practices	Control of Impervious Area
VCF		X						X	X					X	X				X	
CF			X	X						X							X			X
OF	X					X	X				X	X				X		X		
RF					X								X							

KEY: VCF: Very Commonly Found (tending to standard or "normal" practice)
CF: Commonly Found (and quite frequently practiced)
OF: Occasionally Found (but of only local and limited interest)
RF: Rarely Found (only a few examples/sites)

The most common types of BMPs in Germany are swales and infiltration trenches. On-site retention systems, for example, swale-trench systems (see section 4.1.17), are also well known stormwater control measures. They are used in areas with difficult infiltration conditions and/or a high percentage of paved areas. In some cases soil filters are used for the treatment of stormwater. Green roofs, although well known as architectural elements, are not widely used as a part of stormwater management plans in Germany.

The increased occurrence of floods in France over the last 10 years has led to the widespread acceptance of the use of BMPs, such as retention basins, by developers for stormwater control. This has been partly due to an appreciation of the fact that flood control needed to take place upstream of the river basin, and also due to economic and aesthetic factors such as sewage cost reduction and landscaping. The use of porous paving with reservoir structures is also a popular BMP stormwater management measure in France. Initially, these systems were most widely used in regions where the authorities and developers were obliged to do so, such as in Bordeaux. However, the use of porous paving and reservoir structures is now increasing throughout the entire country.

In cold climate countries, such as Sweden and Denmark, retention ponds are frequently used to both reduce peak flows and retain pollutants from separate sewage systems. Swales and infiltration basins have also been used in cold climates to control both stormwater and meltwater, with the use of swales offering an additional advantage as a potential deposit area for snow.

The use of BMPs in Southern European countries, such as Greece, Italy, Spain and Portugal, is limited. However, interest in their use appears to be growing, with an increasing public awareness of environmental issues appearing to provide a strong incentive to planners to consider alternative treatment systems.

In Athens, Greece, the traditional approach to stormwater management is the use of separate, closed, drainage networks which convey runoff to the sea. The use of BMPs has been limited partly due to a lack of space for larger structures, such as detention and retention ponds, in densely populated urban areas and partly due to an unwillingness by developers to try alternative techniques. However, this situation is changing as a combination of covering rivers and rapid urbanisation has left the current system unable to cope and has increased the frequency of flooding in downstream areas. The use of BMPs are being reconsidered to address these issues, with various case studies currently underway. For example, the Olympic rowing basin is also being used as a detention basin (with pretreatment provided by a preliminary detention and settlement pond) and oil separation and detention ponds have been included as part of the stormwater control system at Athens airport. Municipalities in the Greater Athens area have also modernised their street cleaning equipment and undertake street cleaning on a regular basis.

BMPs have not been widely used in Spain, where differences in rainfall between Mediterranean countries and northern European countries (where BMPs are more common) have been cited as a potential concern. Most BMPs have been developed in regions where rain events are of a long duration and low intensity whereas rainfall in Mediterranean Spain is of short duration with high peak intensity and concerns have been expressed that BMPs may not be efficient under such conditions. However, despite these concerns interest in their use in Spain is increasing, with, for example, the use of BMPs being promoted in the Master Drainage plan of Barcelona (1997), and infiltration ponds and porous paving systems having been utilised in the Olympic village.

2.2 Structural BMPs

Table 2.2 briefly describes each of the structural BMPs referred to in this review.

Table 2.2 Description of types of BMPs

System type	Description
Filter drains	Gravelled areas where stormwater can drain through the gravel to be collected in a pipe.
Porous asphalt	Open graded powdered/crushed stone with binder: high void ratio.
Porous paving	Continuous surface with high void content, porous blocks or solid blocks with adjoining infiltration spaces; an associated reservoir stricture provides storage.
Sedimentation tank (also known as silt trap)	Symmetrical concrete structure containing appropriate depth of water to assist the settling of suspended solids under quiescent conditions.
Filter strip	Grassed or vegetated strip of ground that stormwater flows across.
Swales	Vegetated broad shallow channels for transporting stormwater.
Soakaways	Underground chamber or rock-filled volume: stormwater soaks into the ground via the base and sides.
Infiltration trench	A long thin soakaway.
Infiltration basin	Detains stormwater above ground which then soaks away into the ground through the base.
Retention ponds (balancing ponds)	Contain some water at all times and retains incoming stormwater.
Detention basins	Dry most of the time and able to store rainwater during wet conditions.
Extended detention basin	Dry most of the time and able to store rainwater during wet conditions for up to 24 hours.
Lagoons	Pond designed for the settlement of suspended solids
Constructed wetlands	Vegetated system with extended retention time.
Combined system	Combination of two or more of any of the above measures (but could also include a conventional drainage system as one of the elements).

Constructed wetlands are becoming increasingly popular in the UK and a 1997 survey undertaken in Scotland to quantify the various types of stormwater BMP in usage indicated that constructed wetlands comprise some 30% of all structural BMP types. If vegetated systems incorporated into conventional retention/detention basins and other treatment train devices (shown in brackets in Table 2.3) are included in the database, then 42% of Scottish structural systems possess wetland characteristics at some level of utilisation. A more recent 2001 survey (Wild *et al*., 2002) has shown that the growth in SUDS numbers has increased substantially since 1996/1997 such that some 767 SUDS sites in Scotland have now been identified, with some 25% of all SUDS sites comprising permeable paving options.

Table 2.3 Scottish BMPs Database

	Residential Housing	**Leisure & Amenity**	**Industrial**	**Highways And Roads**	**Commercial & Retail**
Flood Storage (Retention and/or Detention) Basins	5	4 (+1)	10 (+1)	-	2 (+2)
Wetlands	3 (+1)	1	4 (+1)	1	- (+1)
Infiltration Basins	1 (+1)	-	1	-	-
Grass Swales	9	-	3	2	2
Porous Paving	**-**	**-**	1	**-**	3
TOTALS	**18**	**5**	**19**	**3**	**7**

From: SEPA, 1997. *Urban Best Management Practice Database*. Tech. Report EQI, 17 December 1997, (G.McKissock), Scottish Environment Protection Agency, East Region, Edinburgh.

A recent 2000 survey of wetland systems in England and Wales has identified over 100 such structural BMP systems. Table 2.4 shows the distribution of these wetlands in terms of predominant BMP category, urban land use type and flow system. The numbers would be considerably larger if all combined retention/detention basins carrying self-seeded aquatic vegetation were to be included in the inventory. Another popular BMP in the UK is the use of filter drains, which have been estimated to be utilised to collect surface runoff from 25% of all roads.

Table 2.4 Constructed Wetlands in UK Urban Surface Drainage Systems within England and Wales

Land Use Type	Total Wetland Numbers	Wetland Type				Wetland Flow Type		
		Constructed Wetlands	Wet Retention Basins	Combined Retention Detention	Extended Detention Basins	Surface Flow	Sub Surface Flow	Vertical Flow
Residential Housing	14	6	2	1	5	11	2	1
Commercial & Retail	17	2	10	1	1	13	1	
Industrial	12	6	1		5	11	1	
Highways & Roads	32	12	10	2	8	28	4	
Mixed Land Use	14	8	9			16	1	
Leisure & Amenity	7	2	4		1	7		
Airport	7	3	4			4	2	1
TOTALS	**103**	**39**	**40**	**4**	**20**	**90**	**11**	**2**

From: Ellis, J B., Shutes, R B and Revitt, D M. 2000. *Best Practice in the Use of Constructed Wetlands for Pollution Control*. R&D Project Report P-2-159, Environment Agency, Reading, Berks.

Direct discharge to ground is prohibited within designated groundwater source protection zones under the 1998 Groundwater Protection Policy (GPP) which effectively prevents BMP infiltration practices in many parts of SE England which is underlain by fissured chalk strata. Soakaways are BMPs mainly associated with major (trunk, A Class) highways and motorways and most residential and commercial properties also have small soakaways to direct roof drainage to ground. Building Regulations (Part H3, Schedule 1) are being currently revised to recommend the full use of BMPs to receive such discharges. The use of infiltration basins in the UK has been limited to date mainly due to high construction and operation and maintenance (O&M) costs in relation to their perceived flow and quality control performance capabilities. However, there is a growing interest in and market for the use of modular plastic geo-cellular units to provide a cost-effective basis for stormwater infiltration systems and attenuation tanks. The use of gullypots are common practice with an estimated 17 million gullypots in service within England & Wales. Roadside filter (and fin) drains, soakaways, detention and retention basins, constructed wetlands and gullypots (with or without oil/grit interceptors), are the most commonly installed structural stormwater management devices, probably comprising up to at least 80%-85% of all the stormwater BMPs in the UK. There is an increasing tendency to consider retention storage ponds and constructed wetlands (and/or vegetated wet retention basins) as comprising a “best” pollution control BMP device.

2.3 Non-Structural BMPs

Table 2.5 gives several non-structural BMPs and sets-out various aspects of these management practices which may be introduced or modified to enhance stormwater management.

Table 2.5 Non-structural BMPs

Management practice	Examples of aspects which may be introduced/modified
Street Cleaning	Cleaning frequency, type of cleaning equipment
Reduction in Pollutant Usage	Type and frequency of use of e.g. herbicides
Snow Management Practices	Zoning of snow according to pollutant load
Educational Aspects	Increase public awareness of e.g. litter control
Routine Management Practices	Frequency of e.g. grass cutting and sediment removal
Control of Impervious Area Development	Consideration of the balance between impermeable and permeable areas during planning and development
Flood Prevention Techniques	Prioritisation of USWM in the early stages of the planning and development

2.3.1 Street cleaning and gullypot emptying

Street cleaning is undertaken on a regular basis within the UK, with local authorities statutorily required (under Section 86 (9) of the 1974 Control of Pollution Act), to "*keep roads and highways clean, as far as is practicable*" although responsibility for motorways lies with the national Highways Agency. The work is usually undertaken under contracted arrangements using direct labour or independent agencies. Four standards of street cleanliness are described in the "*Code of Practice for Litter and Refuse*" (DoE, 1991) ranging from Grade A (litter free) to Grade D (heavily littered), together with 11 urban land use zones divided according to intensity of use and traffic volumes. The non-statutory parts of the Code contain advice on "best practice" indicating the times (hours/days) within which an area should be restored to its grade allocation if the cleanliness falls below the standard. However in practice, many authorities still refer to and use an earlier 1989 Code which sets out cleaning baselines for road/highway cleaning (Table 2.6).

Table 2.6 Recommended highway cleaning frequencies

Highways Type	Cleaning Frequency
Rural Areas	
Un-kerbed roads	Cleaned/swept as the need arises
Kerbed Roads	
Category 2	Twice per year
Category 3 and 4	Once per year
Urban Areas	
Town centres and principal shopping centres/areas	Weekly
Category 2 and 3 roads	Monthly
Category 4 roads	Quarterly

From: Local Authorities Associations. 1989. *Highway Maintenance: A Code of Good Practice*. Association of County Councils, London.

Most urban drainage studies have indicated that conventional street cleaning is only of limited effect as a BMP management strategy in terms of stormwater pollution control, and that it largely serves a "cosmetic" function. Despite this, street cleaning is carried out on a regular basis in many European counties including Sweden, France and Greece. Studies in the first two of these countries have investigated several aspects of street cleaning, including its performance as a stormwater control measure and the impact of increasing the frequency of street cleaning operations, and data from these studies are presented in this review (see Section 5.2.5).

Roadside gullypot emptying is undertaken by vacuum tankers on at least an annual (or twice annual) cleaning frequency with removed material disposed to landfill. Cleaning efficiency can range from 20% to 85% depending on local car parking conditions (CIRIA, 1995). During the emptying process, some 10% of the sediment originally present in the gullypot can be washed into the sewer line. Average unit costs range from €2 to €4 per gully.

2.3.2 Pollutant usage

The control of weeds on paved and highway surfaces within urban areas is necessary to prevent structural damage, to maintain safety and provide aesthetic improvements. A typical annual load of herbicides applied by local authorities in the UK is 186 tonnes of which 94% are used in the weed control programmes of roads and highways, parks, amenity grass and municipal paved areas. The key factors that affect the runoff removal of herbicides applied to hard surfaces are persistence, adsorption, rainfall intensity and the time period between application and rainfall. EC directives incorporated into the UK Water Supply regulations specify a maximum admissible limit of 0.1 ?g/l for individual pesticides and 0.5 ?g/l for total pesticides. Research in an urban catchment in Essex, SE England, has consistently shown diuron concentrations in excess of these levels in surface waters receiving runoff from highway and other urban hard surfaces (Revitt *et al,* 2002).

2.3.3 Snow management and de-icing measures

In cold regions, snow handling procedures place great demands on municipalities and their engineers. Snow handling measures, such as ploughing and transport, are necessary in order to achieve safe road conditions, but are expensive and can have a detrimental effect on the environment. The environmental impact of these measures will vary depending on the snow-handling strategy employed and whether the snow, and its associated pollutants, are transported to a local or central deposit and dumped either on land or in a water body.

The benefits to be derived from the use of salt in winter road maintenance need to be weighed against the associated environmental costs. In Sweden, significant environmental effects are associated with the high concentrations of chloride found in receiving waters during periods of snowmelt. The environmental risk due to chlorides is increased in stormwater management facilities, which may discharge chloride-laden runoff to groundwater aquifers. Potential impacts also include toxic conditions in ponds and constructed wetlands, pollutant release from bottom sediment by ionic exchange, the leaching of metals and dissolved oxygen deficiency as a result of chemical stratification due to impeded vertical mixing. However, it has also been reported that many of these issues can be addressed through the careful use of de-icers, adapting the design of BMPs to allow chloride dilution and by reducing or preventing chloride discharge to sensitive surface receiving waters (Marsalek, 2003).

The reported impact of the use of chlorides in Sweden contrasts with the situation in the UK where, despite event mean concentration (EMC) chloride levels averaging 380 mg/l (and ranging between 160 mg/l to 2174 mg/l) for motorways and trunk roads, there are no reports of increased chloride concentrations in British groundwaters. However, de-icing activities are reported to influence suspended solids (SS) concentrations in sewer dry weather flow during winter periods when road salt can represent up to 33% of accumulating solids on the road surface. Current UK recommended precautionary application rates for de-icing salt are 10g/m^2 (increased to 15g/m^2 if the salt is wet due to open storage) and 25g/m^2 to 40g/m^2 if freezing conditions are expected following rain or snow events.

The selection of BMP type to manage snowmelt events can be largely dependent on the phase of snowmelt being targeted and the location of the event. Treatment of chemically-induced snowmelts on heavily travelled urban roadways should focus on the collection and detention or filtration of particulates, whereas BMPs used to treat runoff from early in the snowmelt in a suburban area should focus on infiltration and dilution. Diversion of flow to different BMPs can be designed according to the nature of the pollutants being carried and the sensitivity of the receiving water. For example, a chloride-laden early first-flush from a heavily-travelled roadway could be diverted to a holding area for later release when higher, less concentrated flows will occur, thus diluting the effects of the chloride. Similarly, a metals-rich melt could be diverted around a sensitive receiving water and directed downstream where a reduced sensitivity exists, or diverted to an infiltration area where soil filtration processes could provide treatment.

Understanding the movement of soluble pollutants from the snowpack is one of the biggest challenges in managing the water quality of snowmelt, as determination of how and when these pollutants move from the snowpack is the key to identifying the most appropriate treatment type (see Section 5.2.6). Research has suggested that in densely developed urban centres, the soluble content of the melt is likely be low due to adsorption of dissolved species to particulates (Sansalone and Buchberger, 1996; Viklander, 1999). However, in less densely developed residential areas, the proportion of solubles could be higher, thus promoting *in situ* infiltration or diversion of melt to infiltration basins as effective BMPs.

2.3.4 Educational and training aspects

Improved water quality and landscaping of urban BMP structures enhance aesthetic values for ecological, amenity and recreational use. Surveys carried out in Scotland have shown that public attitudes towards wetlands and retention basins is much more positive than for other BMP types, particularly valuing their wildlife and amenity benefits. The incorporation of nature conservation into urban flood storage facilities has stimulated many local authorities and local nature trusts to develop them as outdoor classrooms and nature trails for environmental studies. The establishment of field and information centres together with interpretation boards/leaflets, boardwalks, bird hides, pond dipping platforms etc., have collectively helped to raise both local public awareness of BMPs and their potential educational use.

In the UK, the success of the 1.3ha, 10,000m^3 Anton Crescent stormwater wetland in the London Borough of Sutton and the Kings Cross Camley Street Local Nature Reserve wetland are just two notable examples of the intrinsic value of this educational function. These wetlands fully involve the local community, schools and colleges as integral elements in the operation of the nature reserves, fulfilling the objectives of Local Agenda 21. Over 350,000 people a year visit the Sandwell Valley stormwater wetlands near Birmingham where the Royal Society for the Protection of Birds (RSPB) operate an educational centre. A number of retention and wetland basins in the Milton Keynes area have active conservation groups and field centres offering visits, courses and environmental education training. Bray (2003) has described the adoption of SUDS options on school sites by Worcestershire County Council which in addition to cost-effective drainage solutions, can also offer sports and play areas as well as wildlife habitat for education purposes.

There is an increasing requirement for developers in the UK to participate in consultation and discussions with landowners and the local community as well as regulatory bodies such as the Environment Agency and vested interest groups in respect of house design, road and drainage layout, landscaping both during the planning approval process and following site completion. This is particularly the case where use of BMPs is being considered and where there may be community amenity and/or recreation interests associated with the drainage facility. Countryside Properties Ltd for example have been closely involved in the Great Notley Garden Community Liason Group throughout the planning and post-development phases at this 188 ha greenfield site in Essex. This Community Liason Group is about to disband after 13 years post-project formation although the Residents Association will take over much of the Group remit and concerns. The development company has worked up an Ecological Handbook as part of their post- project awareness and community educational programme.

SUDS training courses, mainly aimed at developers and planners, have been convened in Scotland by a number of organizations including SEPA, the Scottish Institute for Sustainable Technology, the Construction Industry Environment Forum and the Urban Wastewater Technology Centre at the University of Abertay, Dundee. Within the UK generally, CIRIA, Hydro International Ltd., HR Wallingford, CIWEM and the University of Coventry have organized a variety of seminars and conferences focused on SUDS design, operation and implementation issues. The CIRIA Sustainable Drainage website receives about 5000 hits per month reflecting considerable stakeholder interest and concern.

2.3.5 Rainwater harvesting

The cost of water from rainwater harvesting has been found to be expensive in comparison to conventional water supplies and the resource savings may only be marginal (Mikkelsen *et al.*, 1999). However, the general public increasingly sees stormwater harvesting for sub-potable water supply in households and industry as a sustainable solution (Mikkelsen *et al*., 2002).

The potential to reuse stormwater has gained interest in those regions where surface water or groundwater resources are scarce. This is generally not the case in Scandanavian countries where rainwater harvesting also becomes difficult when precipitation falls as snow, which occurs approximately 50% of the time. The re-use of stormwater is a well-known technique in Germany (see section 4.1.15). It has also been widely practised in France over the last 80 years, with many suburban houses having a specific tank to collect and store rainwater from roofs for garden watering. Two major research programmes launched by the French Ministry of Equipment and Housing have investigated the use of innovative and sustainable building technologies for rainwater harvesting. One of the main interests in harvesting rainwater is the opportunity it gives to reduce the amount of drinking water used for non-drinking purposes when the distributed water is of poor quality. This is the situation in the Lens area of northern France where more than 500,000 inhabitants receive poor quality water from the public supply network due to a nitrate concentration in excess of 100 mg/l.

Rainwater can be re-used for a range of applications such as garden watering, surface cleaning, car washing and toilet flushing. The amount of water used for these purposes ranges from 30% to 60% of the total annual domestic consumption, and it has been estimated that, depending on the annual rainfall of the location, rainwater could cover 50% to 80% of the total water consumption of a single device. France has an annual rainwater depth of 700 mm and, allowing for water losses on the roof and in gutters, this figure has been used to calculate a mean rainwater recovery value of 600 L/year/m^2 of roof surface area, in comparison to the mean domestic water consumption of 150m^3/year for four people. A range of other uses, such as in air-conditioning, heating, fire-fighting, swimming-pools, skating rinks, washing machines and bathing and showering, have also been put forward, and some of these are currently being investigated.

Rainwater harvesting to supply drinking and service water needs was once a traditional practice in Greece, particularly in the arid areas of the Aegean islands, Crete and the southeastern Peloponnese. However, this practice has been almost entirely abandoned as water supply networks have been developed throughout the country and technologies such as seawater desalination introduced.

A major issue associated with the reuse of rainwater is water quality, which varies with both geographical area and the level of local industrial activity (although there is no strict correlation). Tables 2.7 and 2.8 provide the mean values for a range of pollutants monitored in rainwater in France. A further concern is the presence of pesticides with a recent study having found pesticides present in 52-67% of rainwater samples collected at 5 locations in Northern France. Between 8 and 14% of these rainwater samples contained pesticide concentrations in the range of 1-5 µg/L.

Table 2.7 Mean annual pollutant concentrations and loading rates in rainwater in France

Parameters	**Mean concentration (mg/l)**	**Maximum concentration for potable water (mg/l)**	**Range of loading rates (mg/m^2/year)**
Sulphates	0.5	150 - 250	100 - 1000
Nitrates	0.3	25 - 50	10 - 400
Ammonium	0.3 – 0.6	0.1	100 - 1400
Potassium	0.05 – 0.25		30 - 250
Calcium	0.2 – 0.8		100 - 800
Magnesium	0.05 – 0.9		30 - 700
Chloride	0.2 – 10	250	200 - 10000
Sodium	0.2 - 6	200	100 - 6000
pH	5	6.5 – 8.5	4.8 – 5.6

Table 2.8 Inter-regional variations of rainwater characteristics

	Minimum value		Maximum value	
pH (annual concentration)	4.7	Bas-Rhin (1991)	5.5	Alpes-Maritimes (1993)
pH (monthly concentration)	3.8	Ardèche (1996)	7.8	Alpes-maritimes (2000)
Sulphate (mg/m^2/year)	70	Haute-Vienne (1991)	1050	Pyrénées-atlantiques (1993)
Nitrates (mg/m^2/year)	33	Haute-Vienne (1991)	640	Bas-Rhin (1995)
Ammonium (mg/m^2/year)	94	Haute-Vienne (1991)	1362	Nièvre (1994)

2.3.6 Flat roof storage

Flat roofs have been used as rainwater storage devices in France since the beginning of the 1980s. For example, this technology was employed in a 25.6 ha urban catchment basin in the South of France, which mainly consisted of small buildings. The total flat roof surface area was 7 ha, and had an impervious coefficient of 0.78. A comparison between monitored values and modelling predictions have shown that, depending on the storm event, storage on flat roofs can reduce peak flows at the basin outlet by 30%. In spite of this performance, there has been a considerable delay in architects recommending flat roofs for rainwater storage due to concerns over the potential for water to leak into buildings.

2.3.7 Control of impervious area development

In the UK, local authorities are the planning authorities for new developments with allowable surface water discharges and consents negotiated with the regulatory Environment Agency and/or the appropriate water company (sewerage undertaker). Although the final decisions on land use planning lie with the local authority (subject to any legal appeal process), responsibility for surface water drainage is shared between the local and highway authorities, the Environment Agency, sewerage undertakers and private landowners. Current drainage law was drawn up long before the introduction and the widespread use of BMPs, and this together with the shared responsibilities, can cause some difficulty in respect of provision, operation and maintenance. In Scotland, a recent framework agreement stipulates shared drainage responsibilities such that above-ground BMPs (swales, dry/wet basins, wetlands etc.) were the responsibility of local authorities, with the water company maintaining below-ground BMPs (infiltration trenches, filter drains etc.). Although this framework agreement ran into difficulties and was not always implemented or followed, the use of SUDS in now standard practice within Scotland and the 2003 Water Environment & Water Services Act now provides for Scottish Water to be given statutory powers to adopt and maintain all public SUDS. A complementary Framework Agreement is being developed for England & Wales (see Section 4.2).

The planning departments of local authorities in the UK draw up Local and Structure Plans which identify areas deemed appropriate for development and also recommend standards for that development in terms of land use type and building density. Problems with surface water drainage arise given that development density requirements in UK National Policy & Planning Guidance (PPG) Notes PPG3 ("*Housing*") tend to be incompatible with drainage requirements as set out in PPG 25 ("*Development and Flood Risk*"). The former PPG3 advises 30 – 50 dwellings per hectare as a minimum density which forces a relatively high impermeability index, and also reduces the land area available for source control drainage. However, PPG25 advocates that all development plans should promote the use of BMP drainage and that developers should be required to implement appropriate drainage systems to prevent an increase in flood risk. PPG25 indicates that local authorities should work closely with the Environment Agency, sewerage undertakers, navigation authorities and developers to co-ordinate surface water runoff control "*as near to the source as possible through the use of sustainable drainage systems*". This new guidance should greatly assist the wider adoption of BMP structures and provide the associated environmental benefits. However, drainage design must still conform to statutory regulations including the 1991 Building Regulations, the 1998 Groundwater Regulations (which restricts direct discharge to ground in certain areas; see Section 2.2 above) and the 1991 Water Resources Act (in respect of discharge to controlled waters). Local authorities can set planning conditions which could restrict discharge of surface water to sewers but this power is rarely invoked.

In a recent development in the UK, a proposal to change the size of development surface area above which the Environment Agency for England and Wales (EA) must be notified has been put forward. It has been proposed that this value should be increased from 1 hectare to 10 hectares, which would greatly reduce the number of planning applications requiring approval from the EA prior to development.

Developers in the UK are now being encouraged through national and local planning policy advice (rather than required by statutory legislation) to utilise *in-situ*, source control BMP approaches for the drainage of both greenfield and brownfield sites. A number of Local

Authorities, County and District Councils are now adopting detailed policies for promoting BMPs in their Local and Structure Plans, Development Plans and Agenda 21 policy documents.

The national SUDS Working Group (NSWG) within England & Wales and the Sustainable Urban Drainage Scotland Working Party (SUDSWP), together with the various CIRIA reports have collectively raised knowledge and awareness regarding the opportunities offered by SUDS/BMP solutions for stormwater drainage such that many outstanding institutional, legal, regulatory and methodological issues are being addressed in one form or another.

In Germany, each state has its own water resources laws. In some states, for example, in North Rhine-Westphalia, new buildings and other paved areas must have their own on-site stormwater treatment facilities (North Rhine-Westphalia SS51a). In addition, the German Water Association (ATV) sets out in its technical standard ATV2002 the most appropriate type of control measure for runoff from a variety of surfaces (Figure 2.1).

				Surface infiltration			Underground infiltration	
	Fläche	Contant of pollutants	Quality assessment	A_S:A_i?5 infiltration wide	5<As:Ai?15 swales, swale-trench-systems	5<As:Ai?15 central infiltration ponds	trenches	infiltration drains (shafts?)
	1	2	3	4	5	6	7	8
1	Green roofs, meadows, unpaved areas		harmless	+	+	+	+	+
2	Roofs without metall; Terraces in housing areas			+	+	+	+	(+)
3	Roofs with common shares of metal (uncoated, <10%)		tolerable	+	+	+	(+)	(+)
4	Footpathes in housing areas			+	+	(+)	(-)	(-)
5	Yards, parking lots and streets with less than 300 cars/day			+	+	(+)	(-)	-
6	Streets with 300 - 5.000 cars/day			+	+	(+)	(-)	-
7	Runways on airports			+	+	(+)	(-)	-
8	Roofs in industrial areas			+	+	(+)	(-)	-
9	Streets with 5.000 - 15.000 cars/day			+	+	(+)	-	-
10	Parking lots with heaxy traffic (e.g. shopping malls)			+	(+)	(+)	-	-
11	Metal roofs; heavy polluted streets and yards (e.g. farms, markets)			+	(+)	(+)	-	-
12	Streets with more than 15.000 cars/day; autobahns			+	(+)	(+)	-	-
13	Streets and yards in industrial areas		not tolerable	(-)	(-)	(-)	-	-
14	special areas, e.g. parking lots for trucks, de-icing areas on airports			-	-	-	-	-

+	usually allowed	A_s	sealed area
(+)	usually allowed with pre-treatment	A_i	infiltration area
(-)	usually not allowed		
-	not allowed		

Figure 2.1 Infiltration facilities and their recommended use for runoff from different contributing surfaces in Germany.

In France, the Water Quality Law (January 3, 1992) strengthened the role of local authorities, assigning them new responsibilities in the area of drainage and sewerage. Article 35 of this law stipulates that municipalities are to demarcate, subsequent to a public hearing, two types of zones:

? the first pertains exclusively to either wastewater or a wastewater-stormwater mix, i.e. zones drained by means of collective and non-collective systems. As regards the latter, municipalities are compelled to perform the demarcation step;
? the second type pertains to stormwater and runoff; for this category, municipalities are to specify not only the zones where measures must be adopted to limit soil impermeability and ensure control over stormwater/runoff flow rate and volume, but also zones where it is necessary to identify and lay out installations to collect, ultimately store and, if need be, treat both stormwater and runoff whenever inflowing pollution has the potential to seriously disrupt drainage system efficiency.

Since specific measures or installations to be introduced have not been set forth in the pertinent legislative or regulatory texts, the choice of control measure to attain the required output thresholds is left up to each municipality. The facilities to be built will necessitate either conventional solutions (collection pipe networks, water treatment) or novel alternative solutions that depend on technical, economic and environmental considerations.

The 1992 Water Quality Law also requires that all French projects that use water resources, modify river flow or discharge into a river make a declaration to, or receive authorisation from, the State Administration, in accordance with a range of threshold values. The types of urban and sanitation projects covered and threshold values involved are identified in Tables 2.9 and 2.10.

Table 2.9 Main urban and sanitation projects with legal French threshold values

Heading	N°	Threshold	Declaration	Authorisation
Sewage plant	5.1.0	Pollution expressed in BOD_5	12kg < Fp < 120 kg	Fp ? 120 kg
Storm overflow on a sewer	5.2.0	Pollution expressed in BOD_5	12kg < Fp < 120 kg	Fp ? 120 kg
Storm overflow in a river	5.3.0	Total area (in hectares)	1 < St < 20 ha	St ? 20 ha
Sludges land disposal	5.4.0	Annual quantity of sludges	Qb > 50 000 m³ or > 500 kg of BOD_5 or > 1 tonne of nitrogen	Qb > 500 000 m³ or > 5 tonnes of BOD_5 or > 10 tonnes N
Control of stormwater	6.1.0	cost in millions of euros	1 < Ct < 1.8 M€	Ct ? 1.8 M€
Creation of impervious zones	6.4.0	Surface (in hectares)	none	Se ? 5 ha

Key: Fp = permitted inlet pollution load/hour; St = total area
Qb = annual sludge load; Ct = cost
Se = surface area

Table 2.10 Threshold values for authorisation/declaration in high density and low density urban areas

In high density urban context:	
? Creation of impervious zones over 5 ha	✍ authorisation
? Stormwater discharge in the river,	
the total area being over 20 ha,	✍ authorisation
or between 1 and 20 ha	✍ declaration
In low density urban context:	
? creation of ponds,	
with a surface between 0.2 and 3 hectares,	✍ declaration
	✍ authorisation

with a surface over 3 hectares	✍ authorisation
? drainage of wet lands	

As well as the above declaration/authorisation requirement, the developer must also submit an environmental assessment to the State Administration which sets out measures to correct or reduce the impact on aquatic ecosystems and must also demonstrate its compatibility with SAGE and relevant water quality objectives.

In addition, in order to comply with the European Wastewater Treatment Directives, local authorities in France must achieve strict effluent standards, including during rainfall events, when efficient treatment of wastewater/stormwater mixes is required. The considerable financial implications associated with this legal requirement have resulted in considerable interest in the adoption of innovative drainage solutions.

With regard to future legislation, a significant new piece of European law, which aims to protect all waters across the European Union, is currently being developed. The Water Framework Directive will establish a framework for the protection of all surface waters, ground waters, coastal and estuarine waters. Its implementation will require the establishment of river basin management plans (RBMPs) that will set out how a series of ecological objectives for each type of water body will be met. The RBMPs will require a scientific, technological, environmental and economic assessment of all the options available to enable the most appropriate solutions to be selected. It is considered that BMPs will contribute an important role towards the achievement of these objectives.

3 APPLICATION CHARACTERISTICS OF BMPS

3.1 General comparison of conventional systems with BMPs

Conventional systems and BMPs approach the issue of stormwater control from different perspectives. The conventional approach to stormwater control is to directly drain stormwater flows as quickly as possible to the nearest receiving watercourse or sewer system to avoid the risk of flooding and to protect human health. BMPs aim to treat stormwater as close as possible to its source, reducing runoff volumes, pollutant loads and flow rates by collecting, temporarily storing and subsequently discharging at a controlled rate to the soil or the downstream receiving watercourse or sewer. As well as ensuring individual safety and flood protection, BMPs also aim to improve the urban environment through their potential for multifunctional use. For example, as well as providing stormwater control, retention basins can also act as recreational areas and provide habitat for wildlife. Table 3.1 sets out a general comparison of the different approaches to stormwater control based on their underlying principles.

Table 3.1 General comparison of conventional systems with BMPs

	Piped systems	BMPs
Cost to construct	May be equivalent but potential of multifunctional use of BMPs may reduce overall cost	
Cost to operate and maintain	Established	Unclear for some systems: further work required
On-site flood control	Yes	Yes
Down stream erosion and flood control	No	Yes
Potential for water re-use	No	Yes
Potential for groundwater recharge	No	Yes
Potential for pollutant removal	Low	High
Public amenity benefits	No	Yes
Educational benefits	No	Yes
Performance lifetime	Established	Not established for some systems: further work required
Land take	Not significant	Dependent on type of system: varies between significant and substantial
Design criteria	Established	Not established for some systems: further work required

3.2 Factors affecting the use and selection of BMPs

There are a range of factors which can preclude or restrict to some extent the application of BMP structures for urban stormwater control and Figure 3.1 provides a general guidance matrix on a range of such prejudicial factors. Inspection of the figure shows that wetlands together with other wet storage facilities such as retention and extended detention basins, appear to have fewer overall restrictions although they can score badly against important factors such as space consumption (or land use) and adoption/management liability. The latter restriction is widely viewed by adopting authorities as a major problem in terms of implementing SUDS schemes and a recent Scottish survey has highlighted the significant deterrence to the use of SUDS (and especially ponds and wetlands) because of institutional concerns over adoption, maintenance, land take and safety issues (Wild *et al*., 2003). The major environmental restrictions arise in situations where the bedrock is very close to the surface or where the BMP structure is likely to be situated close to building foundations or where there is the likelihood of high sediment inputs over long periods of time. The most environmentally sensitive BMP options would appear to be infiltration options.

BMP	Gradient	High Water Table	Proximity to Bedrock	Proximity to Building Foundations	Land Take	Maximum Depth	Multifunctional Uses	High Sediment Input	Management and Liability
Extended detention basin	●	●	◌	●	○	●	●	◌	◌
Wet retention basin	●	●	◌	◌	○	○	●	◌	○
Constructed wetland	●	●	◌	◌	○	○	◌	○	○
Infiltration basin	◌	○	○	◌	◌	○	●	○	◌
Porous paving	○	○	○	○	○	○	○	○	◌
Grass swale	○	○	◌	◌	●	◌	○	○	●
Grass filter strip	◌	◌	◌	◌	●	●	○	○	●

KEY		
	○	May preclude BMP use
	◌	Can be overcome with careful site design
	●	Generally not a restriction

Figure 3.1 BMP restrictions evaluation matrix

Figure 3.2 provides a general guidance matrix to restrictions related to flow levels and frequencies, groundwater recharge potential, water re-use and downstream impact. The different types of storage systems (extended detention basins, wet retention basins, constructed wetlands and infiltration basins) are best able to attenuate peak storm flows but only infiltration basins are able to provide the linked benefits of volume control and groundwater recharge.

BMP	Peak Discharge Control			Volume Control	Groundwater Recharge	Potential Direct Water Re-use	Downstream Erosion and Flood Control
	RI 1:2	RI 1:10	RI 1:100				
Extended detention basin	●	●	◌	◌	○	?	◌
Wet retention basin	●	●	◌	◌	○	✍✍	●
Constructed wetland	●	●	○	◌	○	✍✍	◌
Infiltration basin	●	●	◌	●	●	✍	●
Porous paving (with reservoir structure)	●	○	○	●	●	✍	◌
Grass swale	◌	○	○	◌	●	✍	○
Grass filter strip	◌	○	○	◌	◌	✍	○

KEY: **RI** Return Interval (years)

○ Seldom or never provided ✍✍ Direct re-use potential

◌ Sometimes provided (but with careful design) ✍ Groundwater recharge

● Normally provided **?** Unknown

Figure 3.2 BMP stormwater control evaluation matrix

Grass swales and filter strips provide only limited flow attenuation capability or receiving water erosion protection but score highly in terms of groundwater recharge and pollutant removal capabilities. Most grassed channels and filter strips in the UK are located along road/highway margins and in private commercial/office developments with only limited application in residential developments.

An overall summary of the design applicability of various types of structural BMPs is given in Table 3.2 which suggests that infiltration systems, swales and retention basins might have some technological and sustainability advantages over other source control devices. There is concern over inappropriate design and construction resulting from inexperience and limited site investigation knowledge as well as the need for maintenance and landscaping specification for SUDS. In addition, the high cost of existing design manuals may inhibit wider stakeholder access to guidance and thus further restrict application.

Table 3.2 SUDS technology evaluation matrix

Criterion	Infiltration Systems	Porous Paving (with reservoir structure)	Grass Swales	Grass Filter Strip	Wet Retention Basins	Constructed Wetlands
Planning cost (Pre-planning and design)	+	o	+	o	+	-
Construction cost (Capital investment)	+	o	+	o	-	o
O & M cost (Including personnel, plant replacement and sediment disposal)	+	+	o	+	o	o
Technical implementation effort (excavation, lifetime O & M, decommissioning)	+	o	+	+	-	o
Water re-use (not including groundwater recharge)	-	-	-	-	+	+
Whole-life cost (Duration, affordability, flexibility for retrofitting etc)	+	-	+	+	+	o
Reliability against Failure (Forced and planned outage during lifetime)	-	o	+	+	+	o
Planning and Practical Experience (System performance knowledge)	o	+	o	-	+	-

KEY:

+ more advantageous as compared to other technologies

o neither advantageous nor disadvantageous as compared to other technologies

- less advantageous as compared to other technologies

4 DESIGN, O&M AND COSTING ASPECTS OF STRUCTURAL BMPS

4.1 BMP Design

4.1.1 Published Manuals

In the UK, it is only in recent years that design manuals for urban BMP treatment systems have been published, and even now they only provide detailed coverage for infiltration, dry/wet retention basins and wetland systems. General technical guidance on BMPs including design criteria principles, SUDS selection techniques and approval procedures are given in two CIRIA (C521 and C522, 2000) design manuals for Scotland & N Ireland and England & Wales, respectively, and there is also a more general "*Best Practice Manual*" (CIRIA Report C523, 2001). Detailed design manuals have been published for soakaways (BRE, 1991; *Soakaway Design*, BRE Digest 365, Building Research Establishment, Garston) and infiltration trenches (CIRIA, 1996; *Infiltration Drainage: Manual of Good Practice*, Report 156, Construction Industry Research & Information Association, London) and constructed pervious surfaces (CIRIA, 2002, "*Source Control Using Constructed Pervious Surfaces*"). The methods outlined in these two volumes derive dimensions required for a range of 10 year RI storm events based on design storm rainfall determined from Volume 3 of the Wallingford Procedure (Department of the Environment, 1981). However, despite the existence of these various guidance manuals, a recent Scottish survey indicates that they are not specific enough for most users, being limited in terms of design and engineering detail as well as appropriate case examples (Wild *et al*., 2003). In particular, the available manuals lacked information on adoption and maintenance issues. Nevertheless, the technical deficiencies in the manuals do not appear to have been a significant barrier to SUDS implementation within the UK generally.

A number of publications provide detailed design guidance for wetland systems including the 1998 CIRIA Report 180 (*Review of the Design and Management of Constructed Wetlands*) and the 2003 Environment Agency Technical Report P2-159/TR1 (*Constructed Wetlands and Links with Sustainable Drainage Systems*). An earlier WRc report (1996) "*Reed Beds and Constructed Wetlands for Wastewater Treatment*" also provides some limited but useful design information for urban stormwater wetlands.

The Highways Agency have included reference to the design and use of BMPs for the control and treatment of highway runoff in Volume 11, Section 3, Part 10; *Water Quality and Drainage* of the 1998 *Design Manual for Roads and Bridges* (DMRB). Volume 4, Section 2, Part 1 (HA 103/01) of the DMRB issued in 2001 also provides design detail for "*Vegetative Treatment Systems for Highway Runoff*". Design of fin and filter drains are covered in DMRB Volume 4, Section 2 Part 3 (HD 33/96) "*Surface and Sub-surface Drainage Systems for Highways*" and in "*Notes for Guidance on the Specification for Highway Works*" (Manual of Contract Documents for Highway Works, MCHW2, HMSO, London).

Ongoing CIRIA research projects include RP663 ("*SUDS Techniques: Hydraulic, Structural and Water Quality Issues*") and a proposal with industry to review and update technical SUDS design and construction guidance. HR Wallingford are also currently undertaking research on the "*Use of SUDS for High Density Developments*" in response to the increased housing density requirements set out in PPG3.

In France, general information on alternative techniques for stormwater drainage is given in *Techniques alternatives en assainissement pluvial: Choix, conception, realisation et entretien*

(Azzout *et al.,* 1994). More specific information on the design of stormwater retention basins is provided by the technical guide *Guide Technique des Bassins de Retenue d'Eaux Pluviales* (Bergue and Ruperd, 1994).

4.1.2 Determination of design treatment volume

Traditionally, EA regulatory consent requirement for stormwater discharges from new developments has been 5l/s/ha but throttle rates as low as 1 – 2l/s/ha need to be maintained during peak river flow periods to provide adequate receiving water protection levels (Kellagher, 2002). This would require a two-tier design discharge approach with total runoff split between a limited period of very low rates and a more extended high flow rate. The higher discharge rates would be dictated by the predicted greenfield runoff for high return period events, whilst the reduced discharge rates would be linked to the additional volume generated by the development compared to the greenfield condition.

One contentious and unresolved issue in the various UK design manuals relates to the determination of the appropriate design treatment volume required for pollutant removal under varying hydraulic retention times. Various methods have been advocated to determine such treatment volumes (V_t), mainly based on particle settling characteristics. The CIRIA C521 and C522 (2000) design manuals adopt the somewhat conservative Volume 3 Wallingford Procedure approach:

$$Vt\ (m^3/\text{total area, ha}) = 9.D(SOIL/2 + (1 - SOIL/2).\ I$$

where SOIL = WRAP (winter rain acceptance potential) soil index i.e 1 to 5
D = M5 – 60 rainfall depth (mm)
I = Impervious decimal fraction (0.0 – 1.0)

Typically this relates to a treatment volume of 70 – 100 m^3/ha for an average residential development and, for a wet retention basin on a 370ha development in SE Scotland, would equate to approximately 280 – 400 m^3/ha. The 1993 CIRIA "*Design of Flood Storage Reservoirs*" volume suggests a treatment volume based on the first 12 – 15mm of storm runoff distributed over the catchment area which would amount to 150m^3/ha for a wet retention basin on the same Scottish urban catchment. The 2003 Environment Agency "*Constructed Wetlands and Links with Sustainable Drainage Systems*" publication makes a similar recommendation but capture volume is based on the first 10 – 15mm of effective runoff and uses local hourly rainfall time series. An alternative suggestion is to utilise time series rainfall data to derive the capture volume of all runoff from 90% of storm events or the runoff volume generated by 25mm of rainfall over the catchment and to use the largest of these two depths as the design rainfall. The treatment volume can be calculated assuming all runoff from the impervious areas will drain to the treatment system and none from the pervious areas. If the 25mm design rainfall is used, the volume (in m^3) is thus 0,025 x catchment area (in m^2). If the impermeable percentage is extremely high or low, this estimation may be inaccurate. Based on the above approaches:

The design rainfall (R) should be the larger of:
? 10 – 15mm of effective rainfall runoff (based on local hourly rainfall series analysis)
? the one day, twice per year rainfall volume
? rainfall volume from 90% of all storm events
? 25mm rainfall volume distributed over the entire catchment

The treatment volume (Vt; m^3) is then calculated using:

$$Vt = (R \times I \times A) / 1000$$

Where R = Design rainfall (mm)
I = Impermeability index
A = Catchment area (m^2)

The CIRIA 2000b design manual recommends that a satisfactory standard of service for water quality should have a permanent pond volume (m^3) equal to 4Vt. The 1996 WRc wetland volume gives guidance for the surface area of the treatment system of between 1% to 5% of the total catchment area which would equate to about 130 to 350 m^3/ha. There is similar design guidance provided in US handbooks with the US Corp of Engineers STORM model being perhaps the most widely used. This is based on:

$$Vt = 10890.Sd.I \qquad \text{(where Sd = mean storm depth)}$$

and for the 370ha Scottish development this would derive a value of 380 m^3/ha for wetlands.

However, it should be remembered that “standard” SUDS design guidelines for the calculation of required storage volumes such as BRE (1991) or CIRIA (1996) are only acceptable if local conditions (e,g, rainfall, infiltration etc.) are fully taken into account and/or high safety factors are applied (Scholz, 2003).

With regard to the sizing of BMPs in cold countries, Caraco and Claytor (1997) recommend increasing the storage and treatment capacity of BMPs to cope with the large volumes of runoff generated in spring from a combination of meltwater and rainfall. As a snowmelt can occur over a period of several weeks, greater storage and treatment capacities are required compared to storm events alone. A “rule-of-thumb” is to oversize BMPs when the average annual snowfall depth is greater than the annual total precipitation depth, and it is suggested that no more than 5% of the annual runoff volume should be permitted to bypass treatment during this spring melt (Caraco and Claytor, 1997). Novotny *et al.* (1999) recommend capturing and treating 90% of the melt volume. In addition it is recommended that all runoff design facilities should incorporate some kind of pre-treatment to settle coarse-grained solids, have a maximum pond depth of 2.5 m, a maximum flow velocity of approximately 1.5 m/s anywhere in the system and use vegetated buffers (Caraco and Claytor, 1997, Claytor and Scheuler, 1996).

4.1.3 Swales

When calculating the design flow for a grassed swale, a runoff return period of 10 years has been considered suitable (Schwab and Frevert, 1985; SNRA, 1990). Erosion should be avoided by an appropriate selection of base slope, grass mixture, and cross-section. A base slope of less than 5% has been recommended (Schueler, 1987), with a typical value of approximately 2% (SNRA, 1998; Larm 2000). Prosser *et al.* (1995) concluded that grass provides a substantial resistance to erosion as most of the shear stress is exerted on the plant stems deflected beneath the flow, and as a consequence, very low velocities occur close to the bed soil surface (Montes, 1998). Bermuda grass, buffalo grass, Kentucky bluegrass or common grass mixtures are all reported to inhibit erosion at water velocities of approximately 1m/s in grassed swales with base slopes of less than 10% (Schwab and Frevert, 1985; Ferguson, 1998; Montes, 1998). The infiltration capacity of a grassed swale is dependent upon a range of factors such as groundwater level, soil porosity, sediment load and density of surface vegetation (Stahre and Urbonas, 1990). According to Schueler (1987), underlying soils should have a permeability of 12.7 mm/h or higher, and the groundwater table should be at least 0.6 m below the bottom of the swale. Stahre and Urbonas (1990) recommended a minimum saturated infiltration rate of 7.6 mm/h and that the seasonal high groundwater level be more than 1.2 m below the infiltrating surface. A swale can be used for stormwater infiltration as long as there is sufficient distance between the swale and the groundwater table. If the unsaturated zone is too shallow, there is a significant risk that pollutants will reach the groundwater resource.

Swale design has traditionally been governed by the demand for stormwater conveyance rather than water quality improvement. Based on knowledge of pollutant removal in grassed swales, Ferguson (1998) developed the following empirical design criteria:

? water velocity should be less than 0.15 m/s
? swale length should be at least 60 m
? residence time in the swale should be at least 9 minutes.

Yu *et al.* (2001) concluded that grassed swales should be a minimum of 75 m in length and have a maximum longitudinal slope of 3%. It has been found that pollutant concentrations decline exponentially along the length of the swale (Wang *et al.,* 1981; Coyne *et al*., 1998; Deletic, 1999), suggesting that the majority of pollutants are trapped in the first few metres of the swale. A similar behaviour is observed in filter strips.

Research by Barrett *et al.* (1998) concluded that long grassed medians are not required for the effective removal of pollutants from highway runoff as most of the pollutant removal had already occurred in the side slopes of the median. Instead, as discussed by Ellis (1999), factors other than swale length, such as vegetation density and flow conditions, may be more important when designing grassed swales for stormwater pollution control. Further work by Bäckström (2002) suggested that there is an exponential relationship between grassed swale sediment removal potential and mean hydraulic detention time, i.e. increasing the detention time increases removal efficiency. Furthermore, surface loading or specific swale area (i.e. the ratio between swale area and contributing impervious drainage area) might be used as design parameters when constructing grassed swales for pollution control.

4.1.4 Soakaways

Soakaways (or infiltration pits) provide attenuation of surface runoff by allowing gradual infiltration into the surrounding soil and are extremely widely used in the UK especially for road and highway runoff e.g over 60 soakaways are located in a 11km section of the M25 circular motorway (between junctions 18 and 24) around London. There are two major designs based on either the stone filled, perforated-ring soakaway or the chamber soakaway with both types usually incorporating a sump to trap coarse sediment. Soakaways in the UK are designed to receive a 2 hour storm having a return period (RI) of 10 years i.e 15 mm/hour. The infiltration rate should ensure that the soakaway is half empty within 24 hours of the completion of a runoff event.

Soakaway practice may provide little if any protection to groundwater from pollutants carried in the surface drainage, and especially for highly soluble contaminants such as herbicides, MTBE, metal species such as zinc, cadmium and platinum, as well as monocyclic aromatic hydrocarbons such as benzene or toluene or other organochlorine solvents. Whilst soakaways are invariably above the water table, even the presence of a thick non-saturated zone may not guarantee sufficient aquifer protection. In chalk for example, the pore space in the unsaturated zone is normally totally filled with water with only the fissures draining under gravity. Beneath a soakaway, the fissure space will rapidly fill after rainfall and the transit time to the water table may be only minutes. Tracer tests undertaken on soakaway drainage at the M1/M25 junction in Hertfordshire, UK, indicated potential travel times of about 2 km/day via fissure flow within the underlying chalk; the maximum recorded speed was 100 m/hour (Price *et al*., 1992). On the basis of the tracer behaviour, it was estimated that pollutant concentrations reaching abstraction wells some 3-km away from the soakaway injection point, were likely to be about 4 ?g/l for every tonne of pollutant reaching the soakaway structure.

4.1.5 Infiltration trenches

Infiltration trenches are essentially a linear version of soakaways and operate in an identical way. Infiltration trenches are filled with stone or rubble and in comparison to soakaways require lower volumes of infiltration material for a given water inflow. Narrower systems save on construction costs but one reason for their lower popularity in the UK, compared to soakaways, is the commonly perceived design problem associated with accommodating the required trench length and width into the land area available. However, the ability to maximise the infiltration surface area in these systems enables higher treatment efficiencies to be achieved. Infiltration trenches can be covered with grass or have surrounding grassed strips to protect the infill from excess sediment and thus act as interceptors between the roadway and the trench as well as enhancing the aesthetic appearance of the installation. A suitable covering also prevents the washing of the exposed surface medium during maintenance procedures.

4.1.6 Infiltration basins

Infiltration basins are designed to store surface water runoff and to allow it to slowly percolate through the soil of the basin floor or through a specially constructed under-drain system containing gravel and/or sand filter beds. Two under-drain configurations have been previously described involving a “reduced sand bed with gravel layer” and a “trench design” (Ellis and Revitt, 1991). The base may also consist of or include a geotextile such that the base material can be replaced if its porosity is reduced e.g. by contamination. The walls of the basin may be covered with a geotextile or simply consist of the natural soil, either with or without vegetation. Infiltration basins can be constructed to the required aesthetic shape and are generally between 0.5 and 3.0 m in depth with a freeboard of at least 200 mm above the maximum water level. The base should at all times be above the maximum water table. Infiltration basins may also include some type of pre-treatment structure such as a grit chamber, oil remover or clarifier.

It is common practice to incorporate vegetation cover, consisting of indigenous plant and grass species, throughout the basin with the length of the grass kept to approximately 150 mm by regular mowing. Infiltration basins are best suited to soils with infiltration rates exceeding 15 mm/hour (e.g sandy loams, sands, sandy gravels). An overall filtration rate of 5 $m^3/ha/m^2$ should provide for total solids removal efficiencies of between 64 - 98%. When infiltration basins are designed for rare frequency events (i.e. the basins are large), they can be incorporated as a landscape feature for example, as a playing field or a leisure park. The basin can be equipped with a regulated discharge to another outlet, generally the sewer system. The use of infiltration basins hence reduce peak flow volumes and flow rates.

Retention of pollutants within the first 30 cm of soil is very important. The use of limestone soil helps achieve this. Over time there will be a deepening of the pollutant front as the soil becomes chemically saturated. If a geotextile is employed, it should be placed at a maximum depth of 30 cm, although, areas of the basins under greater pressure e.g. water inlet and bottom zones, will require greater protection. In these areas, a geochemical semi-pervious barrier can be utilised (Didier and Norotte, 1999).

Research by Stenmark (1992) demonstrated that it was possible to use infiltration basins in the north of Sweden. However, it is essential that various cold climate and local conditions are considered when designing and maintaining these systems to enable optimum performance to be achieved. The infiltration basin should be designed to cope with a decreased capacity during the snowmelt period, due to both a lower hydraulic capacity and the possibility of ice formation in the facility. When calculating the volume of a basin the statistical design storm volume should be compared with meltwater inflow, with a corresponding decrease in hydraulic conductivity incorporated due to a higher viscosity at 0°C. Swedish guidelines (VAV P46, 1983) suggest a melt flow of 2 L/s per ha of contributing area (which includes frozen permeable surfaces) in northern Sweden. In addition, the capacity of the basin has to be sufficient to take the intensive part of the snowmelt without overflowing. It was found that the lower the hydraulic conductivity, the more important it was to consider the snowmelt. A generalised conclusion regarding when it was more important to consider snowmelt rather than rain events during the design of the infiltration basins could not be made because of the distribution of different types of surfaces within the drainage area. In non-cohesive soils ($K>2x10^{-5}$ m/s) the primary design load estimation criterion is usually based on rain flows, but the capacity of the basin during snowmelt should be checked using a decreased hydraulic conductivity due to the increased viscosity of the water (Stenmark, 1992). If soil is used, Caraco and Claytor (1997) recommend the selection of a soil with a minimum infiltration rate of approximately 1.3 cm/hour and a clay content of less than 30%. It has been noted that soils dry at the time of freeze-up will have a more effective porosity due to the lack of ice in pore spaces, and both Granger *et al.* (1984) and Novotny *et al.* (1999) have recommend keeping the top 30cm of soil dry before freeze-up to retain soil infiltration capacity at melt. It was also noted that flat slopes are essential to encourage infiltration and recommended that clogging should be minimised by, for example, pre-settling (Caraco and Claytor, 1997). Stenmark, 1992, also recommended locating infiltration basins in areas with vegetation and an untouched snow layer to insulate the basin thus decreasing frost penetration.

4.1.7 Sedimentation tank

Using data obtained from an experimental study (see section 5.2.3.2) in which a 1500 L sedimentation tank was located adjacent to the M1 motorway, Ellis and Revitt (1991) calculated the required dimensions of such a tank to provide 100% theoretical solids removal from runoff from a 1 km length of highway (15 m width) draining through 20 road gullies spaced 50 m apart. A tank of 0.57 m depth and a volume of 57.6 m^3 was predicted. Based on a length:width ratio of approximately 5 to 1, the sediment tank would have to be 21.97 m long and 4.55 m wide which would not be feasible in most instances. The size constraints together with the limited pollutant removal efficiencies (see Table 5.7) and the safety factors associated with large open tanks next to busy roads do not encourage the use of these systems.

4.1.8 Lagoons

Lagoons are similar to sedimentation tanks except that they are constructed by excavating natural earth basins which can be covered with vegetation whereas sedimentation tanks are entirely synthetic in construction. Lagoons may be lined where it is necessary to prevent infiltration and safety fencing is usually required.

4.1.9 Detention basins

Extended detention basins are naturally vegetated impounding systems which are dry during normal conditions (although a very shallow marsh may exist in the lowest levels of the basin) but provide storage of storm runoff during periods of heavy rainfall. A liner or membrane may be incorporated into the design if it is essential to avoid infiltration to groundwater. Associated with their flow attenuation characteristics, such detention basins also encourage sedimentation of the coarser suspended materials although fine solids will be re-suspended during high flows. In Herning, Denmark, constructed wetlands have been used in combination with conventional detention basins to save costs. Basins have been built to contain the equivalent of a rainfall depth of 2-4 mm over the contributing catchment. When a basin is full the overflow goes to a wet pond (built to hold 25 mm or more), which also receives discharges from separate stormwater systems. From here excess water is then discharged in a controlled manner to a nearby stream. The use of this combined system offers several clear advantages:

? the stream is protected against erosion from peak flows
? the overflow is less polluted following sedimentation and degradation processes in the pond
? treatment plants are no longer subjected to large volumes of water as the basin empties
? the system is much cheaper to construct than a concrete basin of the same volume

4.1.10 Retention ponds

The most widely used BMPs for the treatment of stormwater runoff in Sweden are retention and detention basins. However, pond design criteria and guidelines are often presented in only a very general manner, which may result in their misinterpretation. Design equations for a specific study seldom express both the required pond area and volume, and it has been suggested that design should be led by the pollutants targeted for reduction and by the level of treatment required. For example, the removal of nutrients usually requires larger systems than those targeting the removal of pollutants that are more strongly bound to sediments e.g. lead. The design should include control calculations for the residence time and water balance. A water balance should be carried out to ensure that the risk for overflow is acceptably low and that the base flow will be larger than losses due evaporation and infiltration. The residence time should also be optimised with respect to a variety of flow conditions. A series of guidelines put forward by various authors are set out in Table 4.1.

The requirements and conditions for pollutant removal from meltwater in cold climates are different from those for stormwater runoff under temperate conditions, which have been the focus of many BMP systems. For example, retention typically relies upon settling and biological activity for treatment. However, the treatment requirements are more complicated under winter conditions when an ice layer forms over the permanent storage pool and biological activity is slowed dramatically. Consequently, pollutant removal efficiencies in retention basins will be less effective under snowmelt conditions unless adaptations are made to accommodate meltwater runoff (Oberts *et al.,* 1989; Oberts, 1990; Marsalek, 1997). These adaptations are particularly important in areas receiving runoff from densely developed urban areas and roadways where solids are the predominant pollutants.

Relating the use of retention (and detention basins) to the characteristics of meltwater is an essential first step in their use. Early in the melt sequence, a highly soluble first flush occurs. Ponds can be used to store this for later infiltration, dilution, slow release or settling. The salinity often associated with meltwater reduces the settling velocity, oxygen levels and the partitioning coefficients for metals. The result of this is less settling of particulates, and possibly the release of metals from previously settled bottom material. Use of BMPs for snowmelt conditions, therefore, should start with the reduction of soluble pollutants and those associated with fine-grained particulate matter, both of which are difficult to accomplish. Following this process, the removal of particulate material, for which detention is better suited, can occur.

Table 4.1 Swedish design guidelines for retention ponds

	Size/comments	**Reference**
Water depth	Average depth 1.5-2 m Minimum depth 1.2 m Maximum depth 3.5 m	Urban Drainage and Flood Control District 1999; WEF and ASCE, 1998; SNRA,1998; SEPA, 1997; Hvitved-Jacobsen *et al*, 1994; Larm, 1994
Slide slope	= 1:3 (= 1:4 over permanent surface); concerning safety, maintenance and the reduction of pollutant. Minimum 1:2 if the ground is stable. Preferable 1:5 – 1:10, needs bigger area.	Urban Drainage and Flood Control District 1999; Persson, 1999; SNRA, 1998; SEPA, 1997; Hvitved-Jacobsen *et al*, 1994; Larm, 1994
Length: Width	>2:1 (= 3:1, recommended)	Urban Drainage and Flood Control District 1999; Persson, 1999; Larm, 1994
Absolute minimum area	= 150 m^2 (minimum width 8 m, minimum length 20 m)	Fransson and Larm, 2000
Recommended minimum area	>0.25 ha (2500 m^2)	Schueler, 1987
Permeability	Infiltration rate of $<10^{-9}$ m/s is preferable	Fransson and Larm, 2000; Urban Drainage and Flood Control District 1999
Drainage area	10-100 ha	Lönngren, 1995; Schueler, 1987
Vegetation	Can be planted in the shallow part of the pond. Water plants can cover up to 20-25 % of the surface.	SEPA, 1997, Urban Drainage and Flood Control District 1999; Schueler, 1992
Inlet	The inlet should be constructed to distribute the incoming water evenly into the pond, e.g. stones	Urban Drainage and Flood Control District 1999; Persson, 1999; Stahre and Urbonas, 1993
Inlet and Outlet	Stairs of stones at the in- and outlet can be used for aeration.	-
Outlet	The outlets should be designed for an emptying time of 12-24 h (max 48 h).	Urban Drainage and Flood Control District 1999; Persson, 1999; Urbonas, Roesner and Guo, 1996; 20-40 h according to Stahre and Urbonas, 1993
Outlet	Emergency exit dimensions are required for rain events of 25-100-year return intervals (several emergency exits can be constructed with the outflow higher up, from rain events for 2 year up to 100 year)	Urban Drainage and Flood Control District 1999
Outlet	A v-shaped weir or sewer at the outlet provides a flow compensation effect.	Persson, 1999
Outlet	Cleaning bars at the outlet pipe are preferable.	SNRA, 1998
Maintenance	Vehicular access to the inlet- and outlet should be provided.	Urban Drainage and Flood Control District 1999
Groundwater protection	The pond can be below the groundwater level. The benefit of this is that a permanent water body exists during the dry period.	-
Additional comments	A sedimentation pond may be provided as a	WEF and ASCE, 1998

	separate part or as a first part of the pond adjacent to the inlet. This should be about 10 % of the permanent water surface and the volume should be about 5-10% of the main pond volume.	

A critical factor for the design of wet ponds is the size of the runoff event to be captured and treated. If the design runoff is too small the treatment efficiency will be jeopardised since many runoff events will exceed the capacity of the facility. Traditionally, larger design rain events with return time of several years have been employed in the design, but if the design runoff is too large the water from smaller runoff events tends to empty quicker then desired for reaching acceptable sedimentation effects. The latter can be explained by a large outlet dimension. Research results (Urbonas, Roesner and Guo, 1996; Urbonas, Guo and Tucker, 1990) have shown that it is the smaller (generally producing less than 10 mm runoff) and more frequent rain event (with return time of around 1-4 months) that contribute to the largest part of yearly pollutant loads. It has been shown that there exists an optimal size to be estimated and that larger sizes than this can, in fact, result in decreased reduction efficiencies. Large ponds, therefore, may not provide the required residence time for the dominant number of smaller runoff events. A balance between capture volume and reduction efficiency is therefore required. A pond designed to maintain a 1-year-rain generally has a substantially larger volume than the volume required to capture and treat 90 % of the stormwater runoff reaching the pond in a year. With increasing watershed area and outlet dimension the runoff from smaller rain events will be treated with decreased efficiency. To compensate for this effect and to more effectively maintain smaller runoff events several outlet pipes of increasing dimensions can be used, the smallest placed at the permanent water level and the larger ones placed above this level. In this way the flows from smaller runoff events can for instance be emptied during 12-24 hours. Flows from larger intensive and less frequent rain events should only be treated when the main objective is flow compensation not pollutant reduction. In such cases control calculations should also be carried out for rain events with return times of 50-100 years depending on how the severity of the effects that flooding can cause (Larm 2000).

4.1.11 Filter drains

Filter drains consist of perforated drainage pipes normally laid along the edge of highways (in the verge or median strip) in trenches which are back-filled with granular material or lightweight aggregate fill and lined with a geotextile fabric. The filler material may be exposed at the surface or topped with turf or top soil.

4.1.12 Porous paving and reservoir structures

Porous surface materials collect rainwater directly as it falls. This stormwater can then either drain across the surface to the edge of the road or drain down through the surface to a porous reservoir structure below. Reservoir structures temporarily retain rainwater thereby reducing or eliminating runoff. In addition, they can improve water quality, support road traffic and reduce noise pollution. The concept of reservoir structures mainly relates to porous pavements, which first underwent trials in the 1970's (Thelen *et al.* 1978), but other applications also exist, for example, in school playgrounds and sport fields.

Figure 4.1 shows a variety of ways in which porous surfacing and reservoir structures have been configured. In the second diagram, all the pavement courses are made of porous materials and the soil is relatively permeable. In this design the surface layer serves to transport the rain to the porous underlying layers, which act as a temporary reservoir before the delayed evacuation of the water by infiltration into the subsoil. This design thus perform three functions, rainwater collection, storage and discharge. The type of reservoir structure most appropriate for a particular project will depend on how it is decided each of these functions should be performed. Table 4.2 gives some examples.

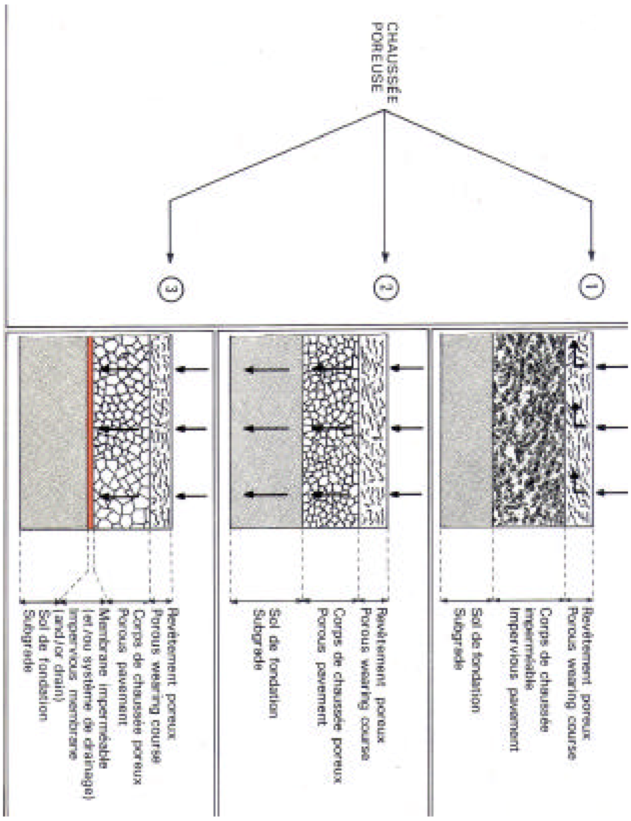

Figure 4.1 Basic reservoir structure

Table 4.2 Designs of reservoir structures

FUNCTION	TYPE OF IMPLEMENTATION	TECHNICAL SOLUTION
Collection of water	Distributed in space	-infiltration through a permeable material on the pavement surface.
	Localised	-infiltration channels -rainwater gullies with distribution pipe in the porous medium. -diffusion network for external input.
Storage of water	Spatially distributed throughout the structure	-porous material with adequate load bearing capacity.
	Localised in only part of the structure	-greater thickness of very porous material (adequate load-bearing capacity).
Evacuation of water	Distributed	-infiltration into pavement subgrade.*
	Localised	-drains to collector. -infiltration trenches to permeable levels. -calibrated orifice to collector..

*This solution requires special properties of the soil (permeability and sufficient bearing capacity in the presence of water) and special attention to the risks of ground water pollution.

4.1.12.1 Selection of materials

The porous materials usually used by road engineers are porous asphalt (to reduce traffic noise and increase wet-weather safety) and porous concrete (used mainly for the drainage of concrete pavements). Porous asphalt (or macadam) pavements consist of an open-graded asphalt mix (powdered/crushed stone with a bitumen binder) with a coarse surface texture and a high void ratio. The open texture with continuous pore spaces allows rainfall to immediately infiltrate the surface. It is usually laid some 50mm thick over new or existing impermeable road surfaces with stormwater flowing laterally across the highway within the porous asphalt layer to the kerb or to a filter drain. Porous asphalt can also be used in conjunction with an underlying reservoir structure.

The infiltration capacity of a newly constructed permeable asphalt surface has been shown to be between 500 and 700 mm/min (Goransson and Jonsson, 1990) and it has been reported that the infiltration rate on a newly-laid paving may exceed 1000 mm/hour. Results from laboratory tests simulating a permeable asphalt surface that had been continuously used for a period of 30 years indicated an infiltration capacity of 400 mm/min. All these values greatly exceed the approximate 1mm/min infiltration rate which is considered sufficient to cope with an intense rain storm. It has been recommended that the infiltration rate of the selected materials should be equal to or greater than the design rainfall intensity. It is, however, important to properly maintain the permeable road surface, especially during the construction phase. The surface should be protected against fine particles that will increase the rate of clogging. Sources of such particles include erosion from vegetated surfaces and flower-beds.

Porous materials used in reservoir structures include porous bitumen-stabilised materials (open materials with a lower bitumen content than porous asphalt), untreated crushed materials, secondary quarry crusher products (screened to eliminate the smallest parts), porous or grooved setts (used mainly in pedestrian zones) and honeycomb plastic materials. Table 4.3 compares the water storage (useful porosity) capability and relative costs of various materials.

Table 4.3 Properties of porous materials

Material	**Useful Porosity**	**Cost/m^3 of water storage**
Porous setts	10-20%	+++
Porous asphalt	10-20%	+++
Porous concrete	10-20%	+++
Porous bitumen stabilized materials	10-20%	+++
Crushed materials without sand	30-40%	+
Honeycomb plastic materials	>90%	++

Generally, the majority of the water storage is performed in a layer of untreated crushed materials or honeycomb plastic materials at the base of the structure. A pervious asphalt/crushed aggregate construction, known as the unit superstructure, was developed in Sweden (Hogland *et al.,* 1987) which includes the use of a geotextile between the soil and sub-base to prevent fine soil mixing with the aggregate. The presence of a drainage pipe to collect infiltrated waters is important where the surrounding soils posses low hydraulic conductivity values.

Mechanically, porous materials generally have a lower strength than non-porous materials. The complex modulus of porous bituminous materials is half that of conventional materials, but fatigue test results are similar. Crushed porous materials without binders must be made with hard aggregates and are regarded, mechanically, as intermediate materials. From the characteristics measured on these materials, it has been possible to establish typical pavement cross sections in porous pavements which allow for the anticipated traffic and subgrade conditions. It has been recommended that where the paving is only subject to light loads, the pavement can be constructed on the subsoil with a thin 100 mm bedding sand and gravel layer. For more heavily trafficked surfaces, the underlying construction layers should include crushed stone with the sub-base being at least 300 mm thick.

Damage to roads and structures within the road body, such as pipes and manholes, are also common problems in northern Sweden due to frost heave damage to the asphalt, storm water inlets and ice blockages in pipes. Many of these problems could be avoided if the road construction was homogenous with regard to the heat properties of the material used in the road sub-base, thereby reducing uneven frost heave. Movement of pipe trenches to the side of the road and replacement of stormwater pipes, which are closest to the surface and therefore most affected by frost, with the pervious asphalt construction mentioned above can also help to alleviate this problem (Stenmark, 1992).

4.1.12.2 Hydraulic approach

The use of porous paving and reservoir structures requires close liaison between engineers and developers in the initial planning stage as the layout of a development can have a significant impact on the possible use and performance of these systems. It is therefore essential that all the participants in the project be fully informed with regard to the technique and its mode of operation to avoid any misunderstandings.

As storage facilities, these systems need to be built either under or downstream of the surfaces from which they are collecting rainfall. Water storage capacity is larger in a horizontal structure than on sloping ground and the layout of development zones where such a type of drainage is planned should take this constraint into account (Raimbault 1992). This can be achieved by building roads parallel to contour lines for the maximum retention of stormwater, and then by joining these roads by sloping streets, which do not possess a storage capacity.

The construction of reservoir structures on level ground offers the advantage of storage without the risk of overflow. However, it also has the disadvantage that the emptying time is often too long. It is therefore desirable to ensure that the porous base of the structure slopes slightly (>1 %) to avoid local stagnations of water and to accelerate emptying. An appropriate slope can be constructed in one of two ways, depending on the shape of the surface occupied by the reservoir structure. For compact smaller areas, for example, car parks, small slopes over short lengths should direct the runoff to trenches with an outlet flow regulation device. During a period of intense rainfall, the free water surface will rise throughout the structure while remaining very nearly horizontal. During the emptying phase after the rain event has finished, the trenches act as outlets and cause a lowering of the free surface in their vicinity Figure 4.2 shows the cross section of a shopping centre car park system designed and built according to these principles. It also shows the shape of the free water surface during and after an intense rain event.

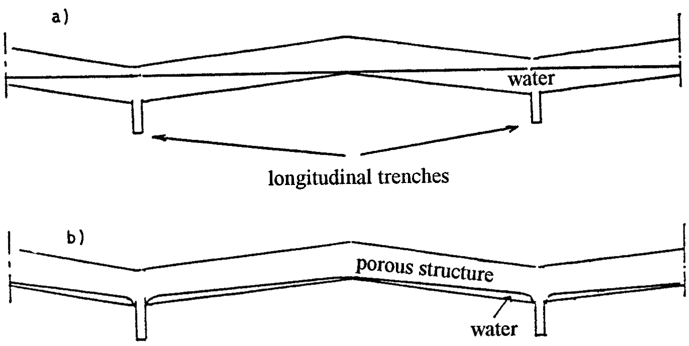

Figure 4.2 Cross section of a reservoir structure on flat ground

It is recommended that the design of reservoir structures in more extensive areas, such as horizontal streets, should include a longitudinal trench with a minimum slope to accelerate emptying. The crossfall of the street should be >1%. If a sewerage network is also planned for the street, the laying trench for this network may also be used for the storm drainage collection pipe (Figure 4.3). The slope of the emptying drain shown in Figure 4.3 could be the same as that of the sewage collector.

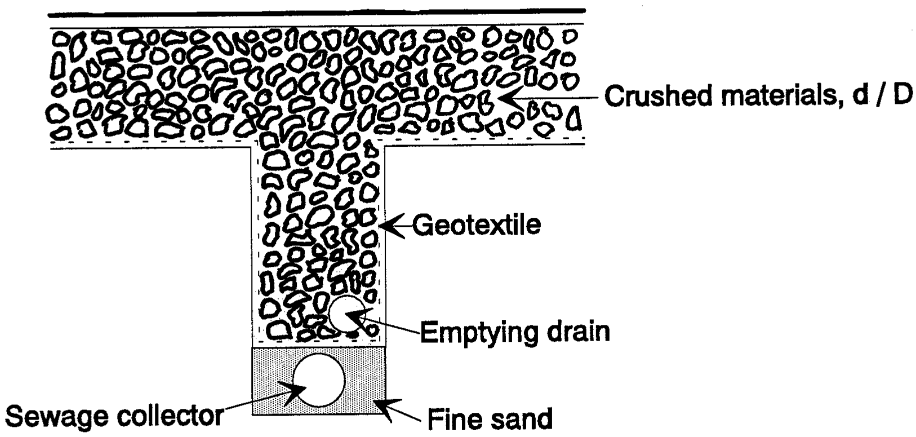

Figure 4.3 Cross section of a sewage collector laying trench used to drain a reservoir structure

When designing porous paving and reservoir structures on sloping ground it is proposed that basins be built in a cascade separated by water tight partitions which allow only limited flow rates to pass between them. This will provide sufficient storage capacity and avoid overflowing at the low points although the useful storage capacity provided by reservoir structures is smaller than the combined pore volume of the materials. To optimise the number of partitions and the storage capacity, the specific features of this type of drainage must be taken into account early in the design work of the development, since poor initial choices could forestall the use of this type of solution or reduce its effectiveness.

An example which illustrates this type of design is a shopping centre car park having a mean slope of 3 %, built in Chemillé, France (Figure 4.4). In view of the rain inputs from the parking lot itself and those from adjacent buildings, the parking lot was divided into three sub-basins. Regulation devices were installed between them so as to ensure uniform emptying of the whole system. The distribution of rain inputs and the capacities of the various reservoirs are shown in Table 4.4.

Table 4.4 Distribution of contributing inputs and capacities of the sub-reservoirs in a shopping centre/car park at Chemillé, France.

Sub-reservoirs: Feed area	Downstream	Intermediate	Upstream
Downstream parking lot	92 m^3		
Intermediate parking lot		70 m^3	
Upstream parking lot			72 m^3
West part of building			117 m^3
East part of building		144 m^3	
East road	55 m^3	13 m^3	
Service station	26 m^3		
Total input	173 m^3	227 m^3	189 m^3
Capacity of sub reservoirs	177 m^3	233 m^3	257 m^3

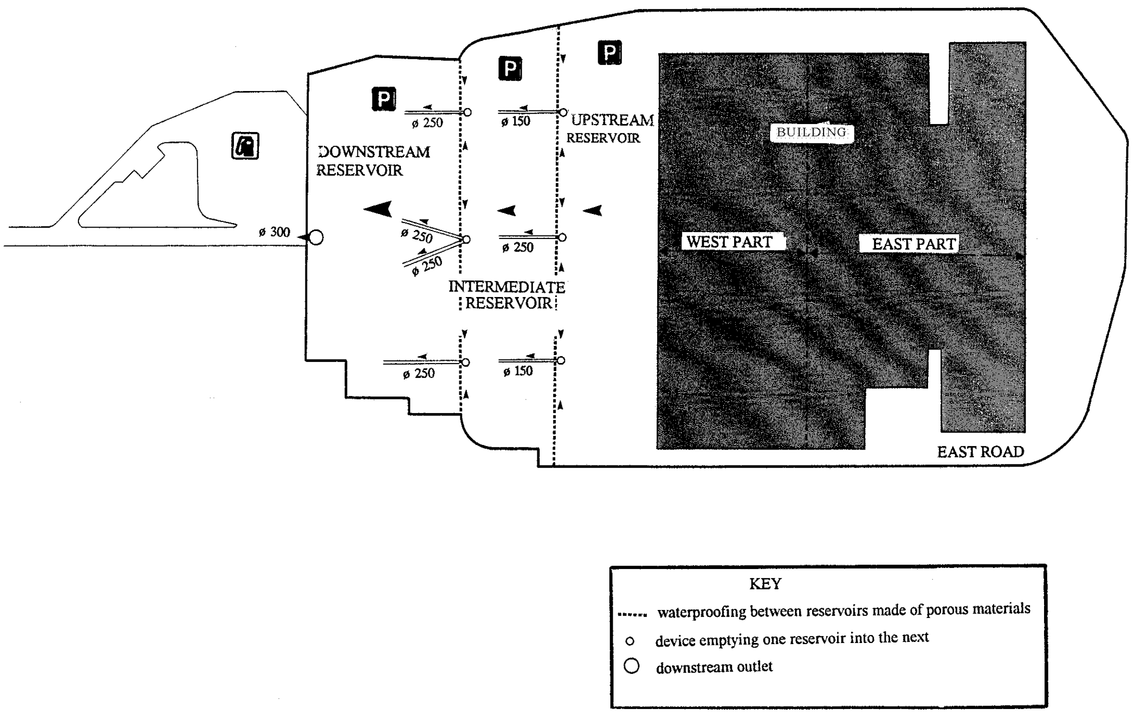

Figure 4.4 Plan of shopping centre with sloping car park having a partitioned reservoir structure

4.1.13 Flat roof storage systems

Flat roof storage systems are frequently used in France as a source control option for stormwater. A flat roof usually consists of several components including:

- a bearing material
- a vapour guard and thermal insulation material
- a water proof material (asphalt, fine gravel or soil and grass)

? protection for the water proof material
? a set of draining systems

A roof slope of less than 5% is recommended and it is suggested that this kind of device should not be used at altitudes above 900m. Two types of draining system are commonly used for flat roofs based on flow control devices and security overflows as shown in Figure 4.5. The role of the control devices is to limit the flow to the gutters and these usually consist of a set of calibrated outlets that are protected by grids and which preserve a specific water height or exist as a free overflow. The security overflows limit the water depth on the roof in order to meet the constraints of the waterproofing material and the strength of the bearing material.

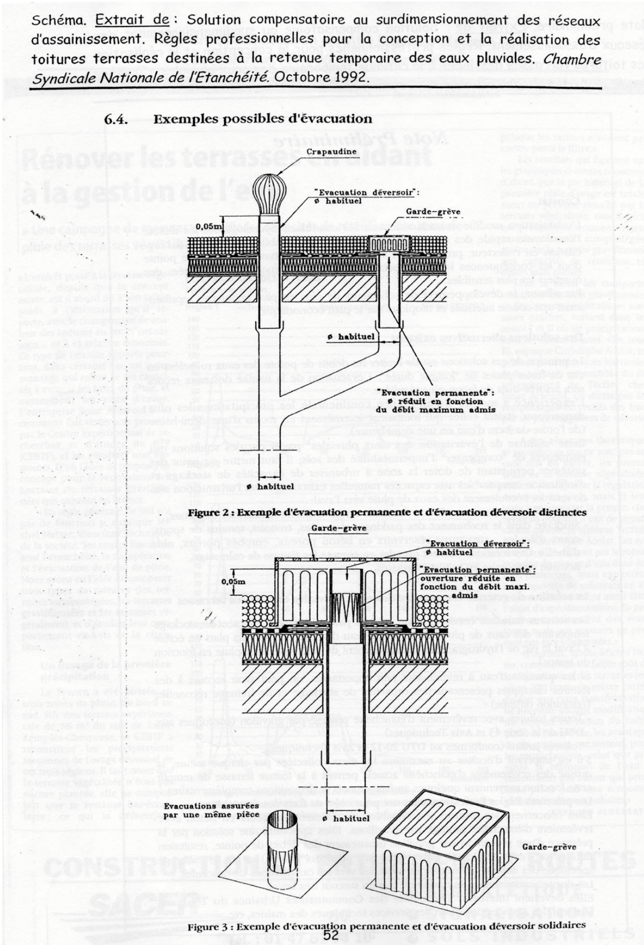

Figure 4.5 Flat roof drainage systems

It is recommended that every point on a flat roof should be less than 30 m from an outlet, and that each gutter drains a maximum roof area of 700m^2. The water depth on the roofs depends on the return period of the storm selected (usually a ten year return period) and the acceptable flow rate at the outlet of the building to the public drainage system. The optimum outflow from a flat roof is 3L/minute/m^2. Two annual technical inspections are required: one in late autumn to check that leaves have not obstructed the gutters, and a second prior to the summer season, in order to maintain the draining systems. The property owners have to meet maintenance costs associated with these inspections.

4.1.14 Gullypots

Gullypots in the UK mainly consist of a pot (or chamber) of 450mm diameter with a 90 litre storage sump extending to a total depth of 600mm below the outgoing pipework (as specified in British Standard 5911, 1982). These roadside stormwater collection systems provide the principal reception system for pollutants flushed from the urban surface, with a single gullypot typically receiving flows from between 50 – 300m^2 of impermeable "paved" surface".

A German innovation in gullypot design involves incorporating an extra filter which can be placed inside a gullypot to improve the treatment of stormwater from paved areas (Figure 4.6).

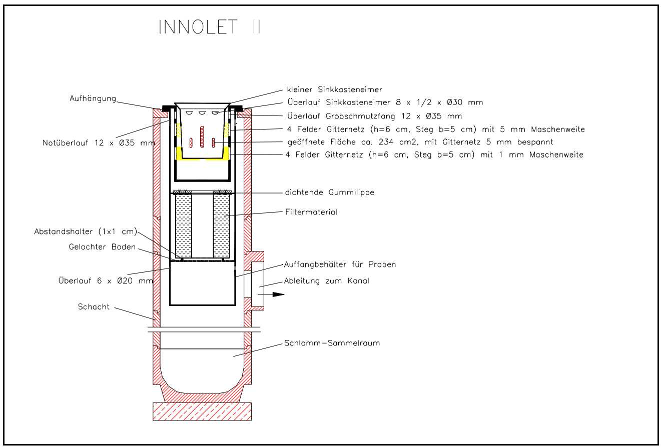

Figure 4.6 Section of a gullypot containing an additional filter

4.1.15 Rainwater harvesting

The technical standard DIN 1989 sets out the limits and design of measures for stormwater reuse in Germany.

4.1.16 Snow management strategy

Development of an optimal snow handling system involves evaluating the whole process to allow the best practice possible to be selected with the lowest environmental impact at the most reasonable cost. A snow handling strategy that takes the environment into account has been put forward by by Malmqvist (1985) and SEPA (1990). According to this strategy, cities and towns should be divided into different areas on the basis of the snow quality, which varies with location and time. The strategy involves dividing the city into white, grey and black zones, where the white zones represent areas with clean snow during the whole winter, the black zones represent dirty snow throughout the whole winter and the grey zones represent snow that is clean at the beginning of the winter but dirty at the end. This zoning must be carried out for each city individually since conditions, and therefore snow quality, will obviously vary according to local conditions. The snow that is most polluted should be transported to snow deposits that are appropriately located, designed and operated to minimise any negative environmental effects. In contrast, clean snow can be dumped at stormwater outlets. The use of this snow handling strategy would result in a significant reduction in the volume of snow dumped at depots in comparison to those deposits currently made (Mikkelsen *et al.,* 2002).

4.1.17 Design innovations

Researchers and practitioners in Germany have produced novel stormwater treatment systems by combining various elements of different BMP systems with a view to improving their performance and increasing their usability. For example, Figure 4.7 shows the design of two types of stormwater treatment systems developed in Germany which are described as superficial trench systems with a limited storage capacity. Figure 4.8 shows the design of a special type of swale-trench system, incorporating a pocket wetland, which has been specifically developed for stormwater management in residential streets (Marselek *et al.,* 2000).

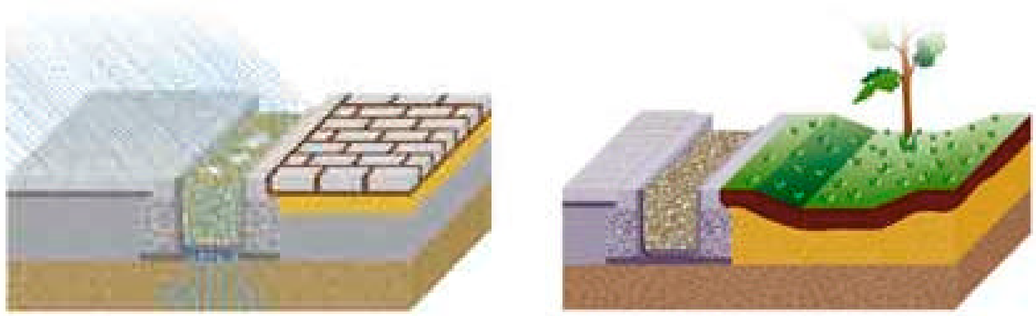

Figure 4.7 Modified superficial trench systems developed in Germany

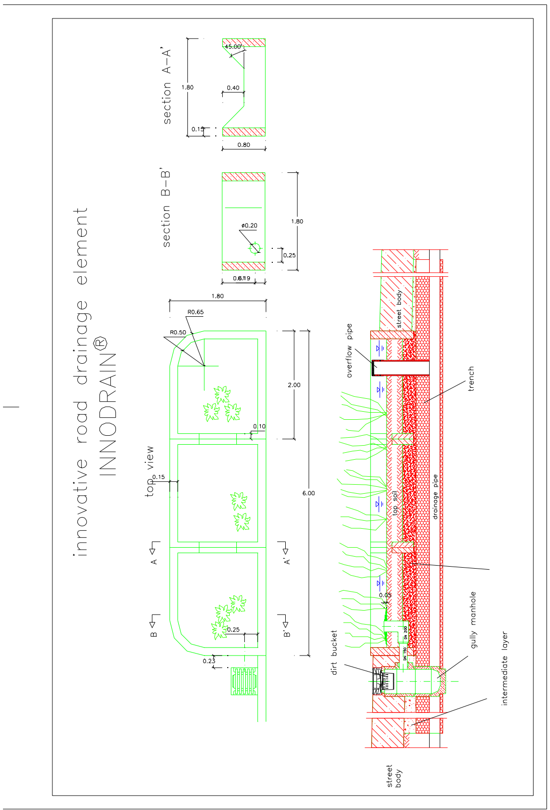

Figure 4.8 Design of a swale-trench system incorporating a pocket wetland

4.2 BMP Operation and Maintenance Procedures

There has been to date no clear guidance within England & Wales on the responsibility for the operation and maintenance (O & M) of SUDS/BMP, partly because such source control facilities can be regarded as being either drainage or landscape. This is a particular problem for infiltration systems and swales, which legally do not constitute "sewers" or "drains" and therefore can hinder adoption agreements with water companies. The recent 2003 Water Environment & Water Services Act does provide Scotland with a much clearer identification of O&M responsibilities and it is likely that Scottish Water may produce a "*SUDS for Adoption*" manual at some time in the near future which will provide detailed information and guidance for adopting authorities.

O&M can be considered as being a function of good initial design and construction, regular site after-care as well as appropriate long term administration and management. The work specifications and cost plans for most BMPs have rarely included formal Maintenance Agreements and associated schedules for post-construction O&M, even where the structures may have been formally adopted under a Section 106 Agreement. Whilst this attitude is changing with UK adopting authorities beginning to accept the need for O&M, the emphasis still tends to be on remedial (crisis) management rather than on regular good practice. Some authorities undertake independently contracted O&M inspection within the formal criteria of the 1975 Reservoirs Act to ensure minimum safety standards, although no "*form of record*" or "*supervising staff*" are required of the adopting authority if the storage facility falls outside the prescribed 25,000m^3 volumetric capacity of the Act. Most adopting local authorities require a commuted sum from the developer to cover O&M costs or alternatively a management company may be set up to maintain and manage the drainage and associated facilities with O&M costs taken from site rentals. Commuted sums taken through the local authority planning process are generally calculated over periods of 15 to 25 years and thus are unlikely to cover full lifetime costs (including final disposal and any de-commissioning costs). On commercially managed sites and business parks and on sites managed by housing associations, SUDS O&M can be paid for through annual rents or rates. However, it will be very difficult to levy a general community tax specifically for SUDS O&M or to pass such costs from the public to individual private owners.

The National SUDS Working Party (NSWG, 2003) has recently produced a SUDS Framework document for England & Wales which is currently out for consultation which will lead to a SUDS Code of Practice. The Framework covers planning and regulation, design standards, legal issues including adoption, ownership and O&M principles. Model Section 106 (Town & Country Planning Act, 1990) adoption agreements and outline maintenance agreements are included in the Framework together with model sewerage undertaker deeds and basic source hazard assessment for SUDS. The lack of detailed O&M specifications for individual (and combined) SUDS schemes is likely to cause problems given the lack of experience of SUDS operation by most adopting authorities. There is a potential liability on any owner or adopting authority in terms of nuisance or impairment of owner rights caused by ineffective SUDS operation due to lack of maintenance.

4.2.1 Infiltration basins

Basin maintenance requirements must be considered as part of the initial design, ensuring the allocation of an appropriate budget to cover both maintenance and data collection. The determination of various site conditions at the start of the design process, for example, soil hydraulic conductivity, mineral composition and pollutant concentration, are essential.

Problems associated with clogging have been reported in French investigations of the operation of infiltration basins (Gautier, 1998). The clogging process has been described as involving an initial slow phase associated with mechanical processes (e.g. surface deposits and pore obtrusion) onto which a second variable and reversible process then developed due to biological components. The second clogging phase was considered to be sensitive to seasonal changes. Monitoring the hydraulic resistance of a basin can provide information on the clogging process (Magali Deschesne, 2002). The amount and type of water depth measurements which can be taken will primarily depend on the budget allocated at the initial design stage. A low cost option is the use of a graduated rule, but this technique requires an on-site presence. As basin clogging can be quite a slow process, the use of sensors is more appropriate, enabling the collection and analysis of continuous data. A sampling frequency of several events per year is considered sufficient.

Monitoring of the concentrations of pollutants in the basin soils enables both the sediment toxicity and the migration of the pollutant front to be determined. As pollutant build-up and migration are slow processes, frequent sampling is not necessary. A good initial soil characterisation followed by the collection of samples at five year intervals is considered sufficient. Soil samples should be from the surface, just under the geotextile and at a depth of 20cm below the geotextile (when present).

The frequency of basin cleaning will depend on the hydraulic resistance and the quality of the soil. In the first case it may be necessary to remove surface layers of sediment which collect over the infiltration surface. Where there is a high level of soil contamination, there is a risk of salting out leading to further contamination. If the pollution front is very deep, there is a risk of groundwater contamination and appropriate maintenance will be necessary. The site-manager must evaluate the cleaning cost in relation to the volume of infiltration material requiring removal, the depth of excavation and the associated pollutant load. It should also be considered whether it is more efficient to carry out maintenance often to a shallow infiltration depth with an associated low level of toxicity or to clean less frequently but to a greater depth and with a comparatively higher level of toxicity.

4.2.2 Sedimentation tank

Sedimentation tanks have high cost maintenance requirements. A study of a sedimentation tank located next to a motorway in the UK concluded that tank desludging would be required at 5 yearly intervals.

4.2.3 Retention ponds

Results of a survey of 34 stormwater control ponds in Sweden by Farm (2003) showed that the maintenance of these systems was difficult due to poor access to the ponds. In 18 of the 34 ponds, vegetation covered 50% or more of the surface area. Vegetation plays an important role in sedimentation and filtration of particles in stormwater. The plants can also accumulate nutrients. However, too much vegetation may reduce the hydraulic function in the pond, increasing the retention time. This may result in algal blooms at certain periods of the year and, under these circumstances, some vegetation may need to be removed.

4.2.4 Constructed wetland systems

An outline O&M checklist recommended for stormwater constructed wetlands is given in Table 4.5 where there is a substantial amenity element associated with the BMP device. This O&M summary schedule covers a motorway service area having BMPs designed in a complex treatment train arrangement with extensive landscaping and water recycling. An alternative O&M template is given in Table 4.6.

Table 4.5 Operation and maintenance schedule for a motorway service station

HOPWOOD PARK MSA, M42
Maintenance Inspection Sheet

CONTACTS: Site Manager:
Landscape Foreman:
Landscape Architect:: Robert Bray 01453 764885

YEAR: 2001 **MONTH:**

SITE OPERATION	KEY	COMMENTS	TICK DONE	DATE	INITIAL
Main Building					
Cut all grass	F				
Weed all borders	M				
Spray hard areas	A				
Trim edges	A				
Screen Planting and Car Parks					
Cut all verges	F				
Weed shrub beds	M				
Spray hard areas	A				
Shrub pruning	A				
Trim edges	A				
Peripheral Planting					
Cut all verges	F				
Spray around woodland plants	A				
Check rabbit guards	M				
Cut meadow grass on mounds	A				
Ornamental Pond Feature					
Pond maintenance	A				
Maintain fountain	B				
SuDS Features					
• **Cut grass generally**	A				
• **Swale grass**	A				
• **Wetland & Ditch**	B				
• **Check inlets**	M				
• **Check outlets**	M				
• **Check drop manhole**	M				
• **Check valves**	B				

NOTE: Notify and rectify damage to SuDS. Inspection checklist: eg: grass weirs rip-rap blockages gullying of swales pontoon stilling area	COMMENTS:
Signature of Site Manager:	
Signature of Landscape Foreman:	

KEY: F = Fortnightly, M = Monthly, B = Bi-Annual, A = As Necessary

Table from: R Bray. 2001. Maintenance of Sustainable Drainage. 93 – 104 in C J Pratt, J W Davies and J L Perry (Edits): *Proc 1st National Conference on Sustainable Drainage*, June 2001. Coventry University, Coventry.

Table 4.6 Operation and maintenance inspection sheet: wetland operation, maintenance and management

Name/Location:…………………………………. Site status:……………………………..
Site Manager/Landscape Foreman:…………………………….. Reporting Office/Tel:…………………

Item	Frequency	Satisfactory or unsatisfactory	**Tick** (when work done)	**Date**	**Initial**
Wetland Vegetation					
maintain 50% surface area coverage of wetland plants after 2nd growing season	Annually				
new plantings	As necessary				
Dominant wetland plants; distribution according to landscape plan?	As necessary				
Evidence of invasive species	Annually				
Water depth; (maintain adequate water depths for desired wetland plant species)	As necessary				
Plant removal; dead plants and/or "choked" by sediment build-up	As necessary				
Evidence of eutrophication	As necessary				
Pre-Treatment Pool/Sediment Forebay					
sediment removal (Depth < 50% design depth	As necessary				
Inlet(s)					
riprap	Annually				
litter screens	Quarterly*				
blockages	As necessary*				
pontoons	Annually				
booms	As necessary				
stilling area	As necessary				
Outlet(s)					
riprap failure	Annually				
litter screens	Quarterly*				
drain pipes	Annually				
blockages	As necessary*				
endwalls/headwalls	Annually				
slope erosion	Annually				
drop manhole	Annually*				
valves	Annually				
Riser Pipe					
orifice obstruction	Annually*				
cracking/spalling/corrosion	Annually				
sediment accumulation in riser	Annually*				
control/drain valves	Annually				
Wetland Pool					
floatables/gross debris	Annually*				
visible pollution e.g. oil	As necessary*				
shoreline erosion	As necessary				
Peripheral Slopes/Buffer Zone					
grass mowing	As necessary				
erosion/rabbit and animal burrows	Annually				
prune shrubs/trim edges etc	Annually				
spraying (*Separate note below if undertaken*)	As necessary				
Other					
signage problems (vandalism, repair etc.)	As necessary				
boardwalks/seating	As necessary				
fencing	As necessary				
grafitti	As necessary				
condition of access route(s)	Annually				
complaints (*Separate note below*)	As necessary				
other public hazards (*Separate note below*)	As necessary				

NOTES/COMMENTS……
………
………
………
Signature:………………………………… **Position/Status:**……………………………. **Date:**………………..

*** = Also after Major Storms. Diagram from: J B Ellis, R B E Shutes and D M Revitt. 2003. "*Constructed Wetlands and Links to Sustainable Drainage Systems*"** Report P2-159/TR1, Water Research Centre, Swindon.

A review of 336 stormwater control systems in Seine-Saint-Denis, France, found that the management of storage functions in a range of systems including wetlands tended to be neglected (Table 4.7). The study also confirmed that underground basins were not properly maintained, as they were not visible and therefore ignored. Systems operating better than could be expected (based on the level of maintenance) were assumed to be newer systems. There was an assumption that the performance would change over a time period of a few years as the system aged.

Table 4.7 Type, maintenance and operating conditions of alternative structures in Seine-Saint-Denis in 1995

Techniques	Type in % of the total	Satisfaction in Maintenance	Satisfaction in operating conditions
Soakaway	3	64	73
Constructed wetlands	8	62	64
Open basins	23	51	70
Flat roof	4	50	64
Porous structures	11	37	39
Underground basins	47	30	56
Road infrastructure management via holding ponds	2	0	44
Porous paving	2	-	-

4.2.5 Porous paving and reservoir structures

The main O&M requirements of these systems are associated with the risk of clogging which can be measured in the porous top layer using variable head infiltration tests. The results shown in Figure 4.9 were obtained using this technique for a 700 m street which was rebuilt with a porous pavement in 1988. The first measurement series was carried out seven years after construction, and immediately after a remedial cleaning (Raimbault *et al.,* 1999). The depth of infiltration can be seen to decrease over time, with average values reducing from 0.85 cm/s to 0.15 cm/s over the 3 year monitoring period.

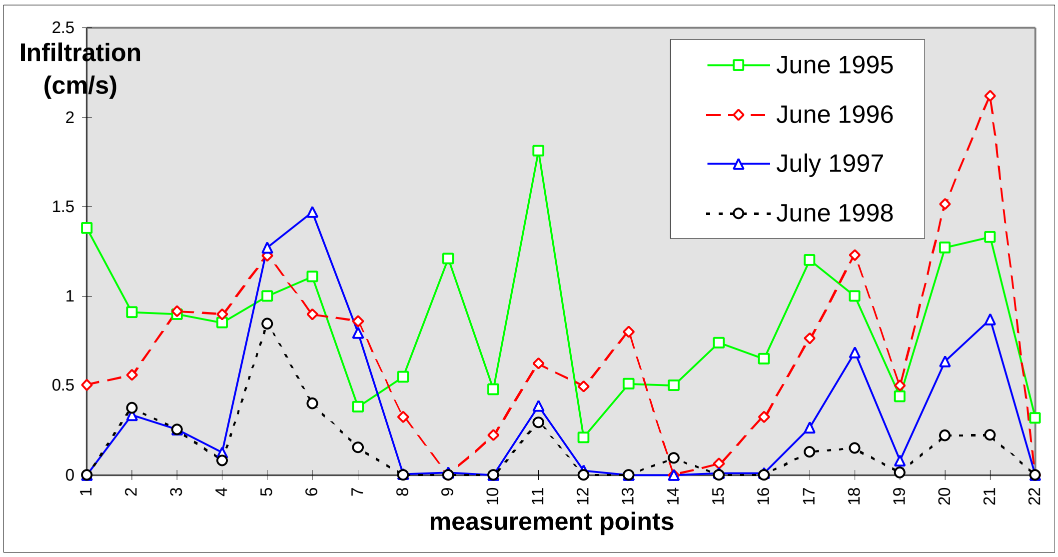

Figure 4.9 Variation of clogging in a street with reservoir structure over a 3 year period.

In a separate study, pervious asphalt samples collected from motorway hard shoulders were analysed with a gamma ray probe to determine the variation of density with depth (Pichon, 1993). Figure 4.10 presents the results, which show an increase in density with time only in the top two centimetres under the asphalt surface. From the results of both these studies, it can be concluded that clogging generally occurs in the upper part of the materials only. This behaviour of porous pavements as a coarse filter is supported by the reduction in stormwater pollutant loads on passing through these systems which has been widely reported in the literature (see section 1.1.1.1.1).

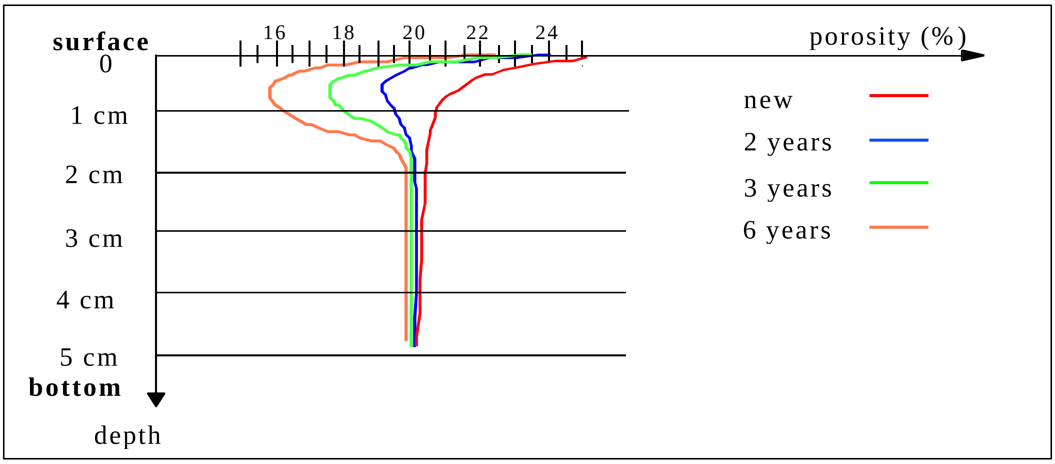

Figure 4.10 The location and extent of clogging in a porous asphalt top layer.

Like any environmental filter, porous paving requires some maintenance. A minimum six-monthly "brush and suction" cleaning is recommended in order to maintain the performance efficiency of the porous paving surface. However, the most efficient surface cleaning method may be through the use of manual and/or automatic jetting techniques combined with suction. Remedial cleaning is more delicate and requires a combination of spraying at high pressure and vacuuming using a specially adapted truck. However, this technique may not be successful if the clogging is advanced, and the solution in this situation may be to remove the top few centimetres of surface material.

A further approach to managing the risk of clogging, is to install safety manholes to allow stormwater to directly infiltrate into the base of the porous structure through orifices in the walls or through diffuser drains. Placement of these devices at the time of construction avoids major works at a later stage and acts as a guarantee for the developer but are less effective at removing pollutants from run-off.

Another issue to be considered is the stripping of surface aggregates which may occur on curved parts of the road, especially roundabouts and road junctions, which are subjected to large lateral forces from turning vehicles. Once stripped, these aggregates tend to clog the surfacing. An appreciation of this issue has led to a preference for the use of reservoir structures with a surface layer of conventional material in zones exposed to large shear forces. If this design is used, ventilation devices should be incorporated to avoid pressurisation of air as the structure fills with stormwater and provision made for the maintenance of diffusion drains.

4.3 BMP Costings

The construction and O&M costs of various types of BMPs developed by CERTU (1998) and used by consulting firms and civil engineers in France are given in Table 4.8. It is generally accepted that the use of stormwater control BMPs will result in a 20% saving in sewage costs. Savings in the region of 20-50% have been confirmed for retention ponds by various consulting companies. However, such savings are not always the case. Road infrastructure BMP measures can require the use of expensive materials (e.g. open-textured asphalt concrete) and the construction of porous structures. It has been calculated that construction using conventional materials (sewer and pavement included) costs 183 €/linear metre in comparison to 305-366 €/linear metre for reservoir structures. This latter value does not include the cost of the asphalt concrete for which a further 30% should be added. A survey by Baptista *et al.,* (2003) of 167 stormwater control sites (consisting mainly of retention basins) showed that the construction costs differed slightly from those put forward by CERTU (2003), with retention basins reported to cost more to both construct and maintain (Table 4.9). This study also confirmed that natural basins were generally less expensive to construct than concrete basins.

Table 4.8 The cost of various BMPs (not including land cost) according to CERTU (1998)

Technique	Cost in euros (1998)	Maintenance - cleaning	Observation
Flat roof	No overcost		
Soakaway	3 €/m² per treated area	0.15 €/m² per treated area	
Swale	7.6 to 15 €/m^3 stored or 15 to 30.5 € per linear metre	Dredge every 10 years, grass and leaves maintenance	
Retention basin	9.1 to 61 €/m^3	0.15 to 0.45 €/m^3/year	6 to 7% of investment in civil engineering
Detention basin	9 to 91 €/m^3 rural ? urban	Maintenance of the open space : 0.3 to 1.52 €/m^3/year	
Filter drain	30.5 to 38 €/m^3 (excavation + filling + geosynthetic membrane)	0.3 to 0.45 €/m²/year	
Porous road surface with reservoir structure	33.5 to 61 €/m^3	0.15 to 0.75 €/m^3/year	Depreciation time : 10 to 15 years for the open texture asphalt concrete
Open concrete tanks	76 to 152 €/m^3 70 % of civil engineering 30% of equipment	civil engineering 1.5% of the investment per year	Depreciation time : 30 years
Underground concrete tanks	152 to 533 €/m^3		
Porous paving	152 to 228 €/m^3	0.3 to 1.52 €/m^3/year	

Table 4.9 Economic indicators of stormwater drainage systems (Baptista *et al.,* 2003)

Techniques	Investment Cost in Euro 1999/m^3		Maintenance Euro 1999/m^3	Satisfaction and degree of acceptance by the stakeholders
	mean	standard deviation		
Underground storage tanks	224	1123	361	Underground basins seem to function less well than open ones
Water retention basin	140	152	3	Well perceived by the stakeholders
Dry retention basin: * Concrete open basins * Dry basin with plants * single purpose	136 225 108 146	174 201 157 203	1.61 5.6 0.83 -	The environmental impact is only seen under a visual aspect. The stakeholders don't seem concerned with the pollution

* multifunctional	113	87	-	

The removal efficiencies and costs of different French stormwater control measures to remove suspended solids are presented in Table 4.10 (Balades and Petitnicolas, 2002). It is suggested that measures for stormwater control can be grouped into two categories with the first group having excellent recovery yields associated with small management and investment requirements. The second category either reports low recovery rates for solids or includes systems also serving another function which requires costly investment.

Table 4.10 Particle pollution recovery cost according to various techniques

Technique	**Removal efficiency of particles <100 µm (%)**	**Cost of removal of particles <100 µm (€/kg)**	**Total cost (including eventual plant depreciation)**
Filter drain	80 – 90	0.6 to 0.91	0.83 to 1.18
Swales/ditches	80	0.01 to 0.015	0.05 to 0.1
Very open-textured asphalt concrete (declogging)	60 – 70	1.4 to 2.5	1.4 to 2.5
Holding pond	80	0.015 to 0.038	Dry : 0.47 to 1.25 Buried : 4.6 to 6.1
Lamellar decanters	50	0.12 to 0.33	1.67 to 3
Street cleaning	40 – 20	8.38 to 13.7	8.38 to 13.7
Roadside gully	10 - 15	1.37 to 3	Theoretical : 1.45 to 3.1 Real : ? 15

There is only limited data available on the relative costs of differing treatment systems to remove pollutants from urban stormwater runoff although capital costings for conventional drainage are well understood. Costs will vary between sites depending upon local conditions which will include engineering constraints (eg. site access, topography and size; lining requirements; construction techniques etc.) and land constraints (legal and land purchase costs; access provision; the size, type and layout of treatment devices etc.). In general terms, engineering constraints will tend to increase the design costs whilst land constraints will decrease costs but at the same time reduce performance. Table 4.11 provides a first-order cost estimation of the ranges of capital and maintenance costs associated with various treatment systems although the combined use of individual devices in a treatment train would give reductions of about 20 – 25% in overall costings. However, the table does not take into consideration the full lifetime costs which would include monitoring and disposal costs as well as any risk and environmental costs/benefits.

Table 4.11 Capital and maintenance costs for BMP treatment systems (Revitt and Ellis, 2001)

Treatment Device	**Capital Cost** (€'000s**)**	**Maintenance Cost** (€/per yr)	**Comments**
Gully/Carrier Pipe	220 – 320	1440	No fin drainage allowed for in costs
Filter/French Drains	230- 260	-	Requires replacement after 10-12 years
Grass Swale	20-60	500	With no off-site disposal of cuttings
Oil Interceptors	10-40	430-580	
Sedimentation tank	40-120	430-500	
Lagoon/Basin	70-150	720-2880	
Infiltration Trench/Basin	30-70	2800-3600	Requires infill replacement every 5-10 years
Retention (Balancing) pond	20-430	500-1440	With no vegetation or off-site dewatering and disposal of sludge and cuttings
Wetland Basin	20-230	2880-3600	Annual maintenance for first 5 years. (declining to €1200-€1400 p/year after 3 years)
Combined	140-430	2880-4300	Assume grass swale, oil/grit interceptor,

Treatment-Train			sediment forebay and wetland cells

The costs indicated in Table 4.11 for operational maintenance suggest they are insignificant compared to the initial capital investment although disposal of contaminated sediment as a hazardous waste (€70 – €90/m^3), replanting (about €4 – €7/m^2) and macrophyte harvesting could be expensive and labour intensive items.

The large range in costings shown for some treatment systems largely reflects local sizing requirements for particular devices which can strongly influence for example, the final costs of retention basin and wetland systems.

HR Wallingford are currently undertaking (on behalf of SDTIU under the Partners in Innovation scheme) a whole life costing study on SUDS and have developed a spreadsheet model to identify such (direct) costs (Woods Ballard and Malcolm, 2003). Figure 4.11 illustrates the approach for a number of UK retention ponds plotted against more detailed US studies to provide a comparison.

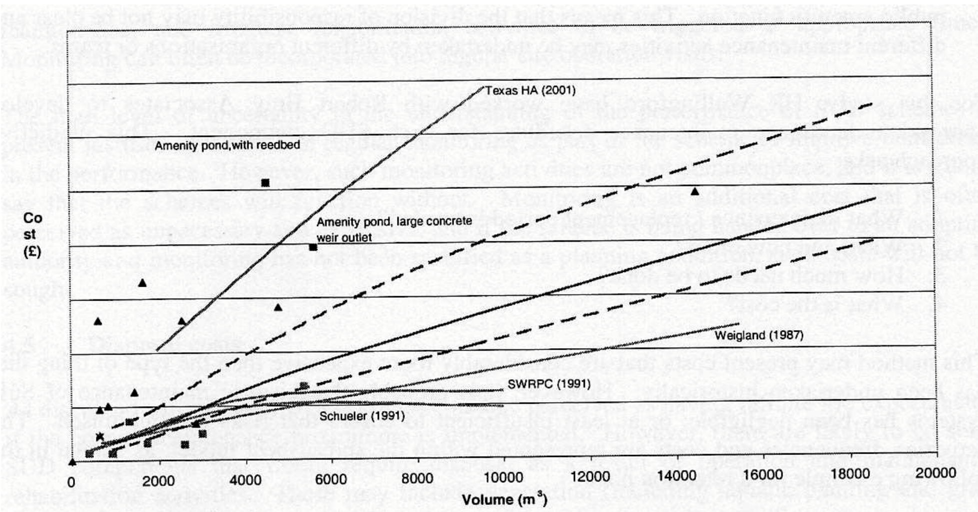

Figure 4.11 Retention pond costs from literature and UK schemes compared to model results

O&M costs can also vary from the levels indicated in Table 4.11. A UK cost comparison of BMP O&M with conventional drainage for the Oxford M40 motorway service area at Junction 8 completed in 1998 and which has a full suite of source control techniques, showed an annual 18% saving. A similar analysis for the Hopwood Park service area on the M42 motorway (see O&M schedule in Table 4.5) indicated a cost saving of 41% over a conventional kerb-gutter-gullypot system with oil interceptors. However, contractor estimates for the annual O&M schedule of a 1011m^2 wetland detention basin in Northampton, East England, varied from €17 500 to €36 000, allegedly requiring between 92 and 530 man hours of annual maintenance (excluding travel time). A wetland basin in Milton Keynes new town (SE England) which had become swamped with sediment, thereby losing some 70% - 60% of its effectiveness, cost over €72 000 to clean-out with the forebay alone costing €14 500. Another 793m^3 wetland pond cost the Milton Keynes Development Corporation €5 000 to clean-out. Cost-performance analysis using HydroWorks modeling for conventional drainage and the CIRISA (2000b) SUDS methodology, has suggested that SUDS are generally economically viable within those urban catchments (and especially Greenfield sites), having large areas or number of opportunities for their implementation, such as permeable soils and large open spaces (Walker, 2000).

None of the above costings make any reference to final disposal costs where the dredged sediment may be classified as hazardous waste due to levels of contained oil and metals. This can be a real and costly issue as indicated by the dredging and removal of a contaminated reedbed and associated sediment from a 18,128m^2 constructed wetland in NW London where on-site storage was required for sediment de-watering (down to 2% dry weight), prior to landfill disposal. Contained metal levels in the sediment averaged 219.8mg/kg, 841.0mg/kg, 778.9mg/kg and 12.5mg/kg for copper, lead, zinc and cadmium respectively. These levels are considerably higher than threshold loading limits as defined under 1986 EU legislation for biosolids and soil expressed in either annual or total accumulative loadings (see Table 5.5). Fencing, lighting, lagooning, berming and other security considerations were required as part of the on-site de-watering facility with costs for the disposal operation totalling nearly €360 000. Such O&M costings would be quite challenging to local authorities already under financial strain, and if they represent general O&M costing levels, may influence future decisions on adoption of BMP facilities. There is undoubtedly some concern about the long term capability of UK local authorities, who have adopted BMP facilities on the basis of their amenity potential, to sustain expenditure levels on O&M

Where adopting local authorities undertake a formal O&M inspection which is independently contracted under the criteria of the 1975 Reservoirs Act, such inspections are normally separate costable items. The London Borough of Harrow, for example, utilises such external agency reviews and as a general estimate, O&M for their stormwater storage ponds costs about €575/m^3 per annum with overall O&M costs for BMPs being some €2880/per annum per device.

In the UK, roadside gullypot emptying is undertaken by vacuum tankers on at least an annual (or twice annual) cleaning frequency, with arisings disposed of to landfill. Cleaning efficiency can range from 20% to 85% depending on local car parking conditions. During the emptying process, some 10% of the sediment originally present in the gullypot can be washed into the sewer line. Average unit costs range from €2 to €4 per gully. Manual sweeping (together with hydrojetting) remains the most effective street cleaning method and over 40% of UK local authorities continue to use this type of BMP. A recent innovation has been the introduction of 'rapid response teams' to deal with severely littered public areas. Average costs for street cleaning range from €7/km to €11/km.

An overview of the annual and maintenance costs for a wide range of stormwater control measures (including both BMPs and non-BMPs) in Germany is given in Table 4.12. Funding is raised from a separate stormwater fee based on the amount of paved area contributing runoff to the sewer system. Currently 60% of the population pays this fee but the percentage is growing. A different approach to the maintenance of stormwater measures was taken in a commercial area near Berlin, where the maintenance requirements were handed over to a private company.

In France, local municipalities provide the finance for stormwater control measures as part of their drinking water and wastewater system programmes. Water authorities, prior to 2002, were not allowed to finance stormwater control although they could help fund retention basins on combined sewer systems with a metric capacity of over 1000m^3. However, this situation has now changed and water authorities may finance source control BMPs according to the level of pollutant reduction with outflows of greater than 10 L/s/ha being costed at 600 €/m^3.

In Sweden, the advantages and disadvantages of different urban storm drainage systems have been discussed and during the first half of the 20th century the general view was that buried pipe systems were more economical than swales and ditches (Bäckman, 1984). Cost estimates made in 1925 showed that maintenance costs and land costs for swales where high in comparison to conventional piped systems and as a consequence, pipe systems were selected as the default alternative for urban storm drainage in Sweden. More recently, Finley and Young (1993) pointed out that the use of swale systems reduced costs due to the elimination of curbs and gutters. However, if swales are to be used for road drainage they normally require wider rights-of-way which may, depending on land prices, lead to a considerable increase in overall costs. The use of swales may also result in extra costs if special structures are required in conjunction with driveways and/or to maintain slopes (e.g. check dams) (Schueler, 1987; Li *et al.,* 1998). Several authors have suggested that adjacent property owners can be expected to maintain grassed swales situated in residential areas (e.g. Kercher *et al*., 1983; Schueler, 1987; Finley and Young, 1993), which would minimise the maintenance cost from a local government perspective. According to Bäckström (2002), grassed swales require lower amounts of natural resources in terms of energy than a comparable stormwater pipe system. The primary target for reducing energy use of a grassed swale would be the fuel consumption needed for transportation, excavation and grass mowing since these processes represent a major part of the total use of natural resources. The total cost of a grassed swale is largely dependent on site conditions, such as land price and quality of the parent soil, and it has been concluded that a grassed swale is more cost-efficient than a pipe system in areas with low land prices and good topsoil.

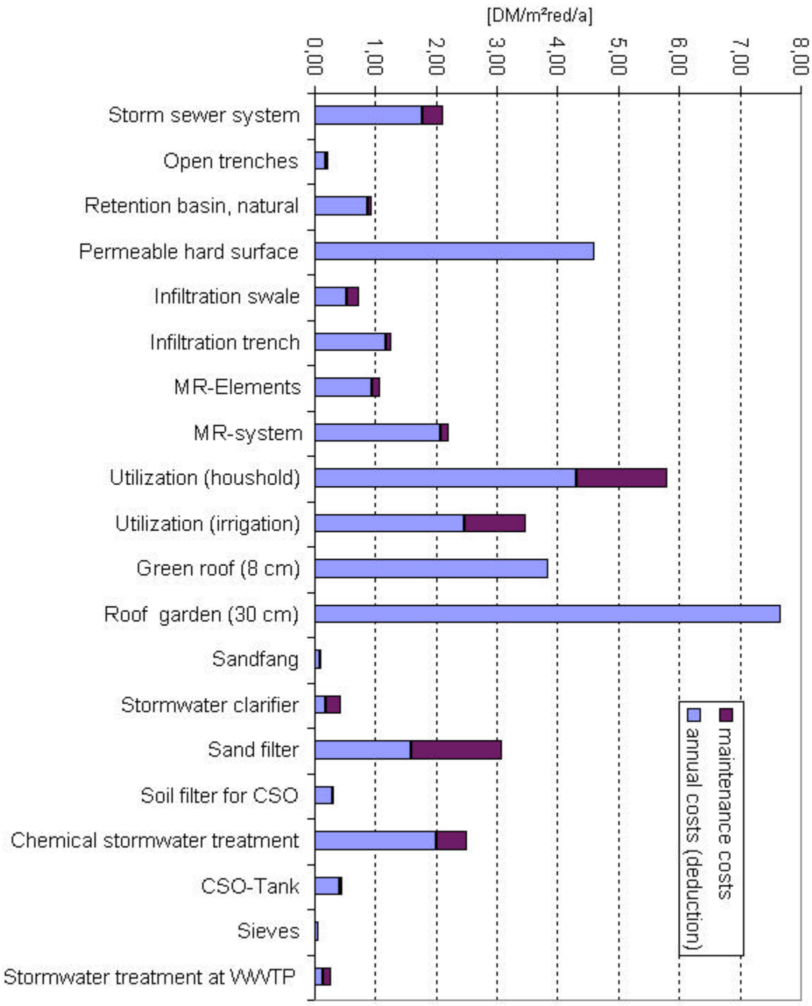

Table 4.12 Annual and maintenance costs for different stormwater management measures

5 BMP PERFORMANCE

5.1 Performance Indicators

Table 5.1 provides a general indicator summary of the ranges of pollutant removal percentages that have been reported from various UK urban BMP studies. The percentage removal efficiency is in most cases simply defined as: $(C_{in} – C_{out})/C_{in} \times 100$; where C_{in} and C_{out} are the inflow and outflow concentrations, respectively. Whilst total solids removal is generally good for most types of structural BMPs, there is considerable variation for other pollutant parameters with some showing rather poor removal capabilities.

The efficiency performance data, being based on the average difference between inflow and outflow storm event concentrations, may be misleading especially when inflow concentrations are low. For example, a wet retention basin experiencing 500mg/L TSS in the inflow and 100 mg/L in the outflow would yield an equivalent pollutant removal efficiency to a constructed wetland having 100mg/L and 20mg/L in the inflow and outflow respectively. Yet the final water quality for the latter BMP device is clearly superior and provides more effective and efficient protection of the receiving waterbody. The use of a percentage removal term is probably only really appropriate for sites and BMP facilities subject to high pollutant input concentrations.

The US EPA National Stormwater Best Management Practices Database recommends the use of a normal probability plot of the inflow and outflow pollutant event mean concentrations (EMCs), with the EMC distribution matched against set (or target) receiving water quality standards (or against any discharge consent conditions). This would enable performance to be described in terms of exceedance probability of target standards for differing flow conditions and/or return periods. This statistical methodology would also enable anomalous results (such as apparent negative efficiencies) to be identified, as well as determining whether a small number of large storms are biasing the resulting overall efficiency value.

It is clear that a comparative assessment of the performance of structural BMP options is currently limited by a lack of data and the uncertainties associated with the simplified methodology used to calculate percentage performance efficiency. In addition, for most wetland/retention systems, given the dynamic nature of flow into and out of wet basins having a permanent pool, the recorded inflow and outflow concentrations are not normally contemporaneous i.e. not generated by the same storm event. It is not yet feasible to provide definitive BMP designs to meet specified and consistent performance requirements for given storm and catchment characteristics or to meet specific receiving water standards and storm return periods.

Whilst accepting these reservations, it is still nevertheless possible from the data and information currently available to broadly identify representative pollutant removal (Table 5.1) and attenuation capacities (Table 5.2) for differing BMP devices. However, this can only provide a first-order screening evaluation of the robustness of the various BMP systems to achieve the stated functional objective. High design robustness gives a significant impact and probability of performing as intended. Low robustness and impact implies that there are many uncertainties with regard to how the BMP design will perform for that function.

Table 5.1 Performance efficiency and value of BMP treatment systems

Treatment Facility	Hydraulic Design Robustness	% Removal Efficiency						Maintenance Requirements	Habitat and Aesthetic Value
		TSS	Total Nitrogen	Bacteria	Hydro-carbons	Metals			
						Total	Dissolved		
Gully/Carrier Pipe System	High	10 - 30	-	-	5 - 10	10 -20	0	Low to moderate Costly to replace	None
Filter (French Drain)	Low - Moderate	60 - 90	20 - 30	20 - 40	70 - 90	70 - 90	10 - 20	Low to moderate Costly to replace Clogging potential	Inconspicuous Unobtrusive No habitat value
Infiltration Basin/Trench	Low - High	60 - 90	20 - 50	70 - 80	70 - 90	70 - 90	20 - 35	Moderate to high Costly to reinstate Susceptible to clogging	Inconspicuous, unobtrusive Limited habitat value
Swales	High	10 - 40	10 - 35	30 - 60	60 - 75	70 - 90	15 - 25	More costly than conventional drainage	Moderate visual appeal Selective planting can enhance habitat value
Sedimentation Lagoon	Low - Moderate	50 - 85	10 - 20	45 - 80	60 - 90	60 - 90	20 - 30	Moderate to high Costly to desludge	Some aesthetic value
Dry Detention Basin	Moderate to High	60 - 80	20 - 40	20 - 40		40 - 55	0 - 15	Moderate	Limited
Extended Detention Basin	High	30 - 60	5 - 20	10 - 35	30 - 50	20 - 50	0 - 5	Moderate	Moderate visual appeal Can enhance habitat value
Detention Basin 6-10 hour detention 16-24 hour detention	High High	40 - 80 50 - 90	20 - 40 20 - 40	40 - 50 60 - 75	30 - 60 50 - 75	30 - 60 45 - 85	5 - 10 10 - 25	Moderate to high Moderate to high	High aesthetic appeal Moderate to high habitat value especially if vegetated
Retention Basin	High	80 -90	20 –40	40 - 60	30 - 40	35 - 50	10 - 20	Moderate	Moderate
Wetland	Moderate - High	70 - 95	30 - 50	75 - 95	50 - 85	40 - 75	15 - 40	Moderate to high Costly to replace plants	High visual and habitat appeal

Table 5.2 Wetland and Dry/Wet Storage Basin Indicators

	Pollutant Category				Flood Abatement		Amenity	
	Floating debris	Sediment and litter: Coarse	Sediment and litter: Fine	Dissolved	Runoff reduction	Peak Flow Reduction (with appropriate overflow control)	Open space & recreation	Landscape quality, habitat & biodiversity
Natural wetlands	+	+ +	+ +	+	+	+ +		+ + +
Constructed wetlands	+	+ + +	+ +	+		+ +	+	+ +
Extended detention basins	+	+ +	+			+ +	+ +	+
Dry detention basins	+	+ + +	+		+ + (Infiltration basin)	+ + +	+ +	
Wet retention basins	+	+ +	+ +	+		+ +	++	+ +

Key: **+** minor impact; **+ +** medium impact; **+ + +** major impact.

Table 5.3 provides a semi-quantitative (but nevertheless still subjective) approach to the evaluation of wetland BMP systems which considers various factors that influence selection, design and performance. The scoring system is based on the procedure developed by the US Environmental Protection Agency which scores all positive aspects of each system type from 1 (lowest) up to 5 (highest; having the most desirable conditions) and negative aspects with increasingly negative values from -1 to -5. All parameters were weighted equally (weighting factor = 1) with the exception of those relating to the "applicability" to differing urban land uses. These three land use columns were allocated a weighting factor of one-third each. Thus constructed wetlands score extremely highly in terms of final water quality and flow control but have high O & M requirements and can influence downstream temperatures and therefore have low scores for these two parameters. The scores and group rankings are again based (and therefore biased) on information and data gathered from the international literature and on personal experience. Despite their bias and subjectivity, the composite average rating scores reveal an overall group ranking that attempts to integrate most of the aspects that must be considered in stormwater runoff drainage design. However, they do not incorporate institutional issues such as the attitude of water companies to the adoption of non-pipe systems, the legal and administrative difficulties posed by multiple ownership or long term effectiveness.

Table 5.3 Evaluation of Wetland and Dry/Wet Basin Effectiveness Potential

	Water Quality	Flow Rate Control	Runoff Volume Reduction	O & M Needs	Failure Potential	Applicability for Given Urban Land Use: Low-Medium residential	Applicability for Given Urban Land Use: High Residential and Low/medium Commercial	Applicability for Given Urban Land Use: High Density Commercial and Industrial	Design robustness: Hydrologic and Hydraulic	Design robustness: Water quality	Potential for Groundwater Contamination	Potential for Temperature Increases to Discharges	Weighted Rating Average	Group Ranking
Constructed wetlands	5	5	2	-3	-1	4	5	2	4	3	-2	-3	**0.88**	**I**
Extended Detention Basins	4	5	1	-2	-2	4	4	3	4	4	-2	-2	**1.06**	**I**
Retention Basins	5	5	1	-2	-1	4	4	3	4	4	-2	-4	**0.97**	**I**
Detention Basins (With Infiltration)	4	5	5	-4	-4	5	5	2	3	4	-4	-1	**0.64**	**II**
Natural Wetlands	2	3	1	-2	-1	?	?	?	4	2	-1	-2	**?**	**III**

5.2 BMP Performance Data

5.2.1 Filter strips and swales

5.2.1.1 Swales

Roadside and median grass-lined depressions and channels are now commonly used as low-cost practices in North America, Australia, France and Germany to convey impermeable runoff although they may have land uptake costs which are difficult to meet in some restricted highway situations. Swale techniques have been slow to take-off in the UK and only comprise some 15 - 18% of all BMP source control devices, principally in association with new industrial/commercial estates. The 1997 Scottish SUDS database (see Section 2.2) lists a total of 16 swales of which only four have any monitored data. Two sites at Dundee estimate initial wetting losses at 1.2 to 5.0mm in comparison to 0.3 – 0.4mm for the adjacent road surfaces. The corresponding pairs of percentage runoff rates are 6.5% - 37% and 41% - 53% respectively. At both grass channel sites, increased lag times before runoff and reduced peak flows have been observed. Pollutant concentrations have been in general very low, with significant removal of SS and other chemical determinands (e.g hydrocarbons reduced by 36%), although there is some evidence of increased metal outflows (Jefferies *et al*., 1998).

Table 5.4 shows the range of pollutant removal efficiencies that have been noted for grass swales.

Table 5.4 Swale pollutant concentrations, loadings and removal efficiencies

Pollutant Parameter	**EMC and Range** (mg/l)	**Load** (kg/ha/yr)	% **Removal Efficiency**
TSS	25.0 (7.0 - 47.0)	–	86 (55 - 91)
Total Zinc	0.032 (0.011 - 0.143)	7.05 (1.85 - 9.2)	83 (63 - 93)
Total Lead	0.079 (0.014 - 0.144)	0.78 (0.25 - 2.61)	54 (17 - 76)

It is clear that whilst in general, good removal rates can be achieved by such systems, there is still considerable variability in performance. Very little removal is achieved for soluble metal species, nutrients or bacteria and it may be that swales can only provide an efficient performance for solids, oils and heavy organics such as leaf litter etc. Solids removal performance increases as flow TSS concentrations increase but with inflow concentrations below 30-40 mg/l, little reduction can be expected. Irrespective of these reservations, comparison of the data in Table 5.4 and Table 5.5 implies that pollutant loadings accumulating within conventional swale channels are generally well below most national criteria for biosolid disposal to land. Table 5.5 gives "trigger" or threshold loading limits as defined by various national US and European agencies expressed in either annual or total accumulative loadings.

The UK ICRCL values are those quoted for parks and open spaces whilst the Dutch values are those defining clearly contaminated land. Even adopting the maximum loading rates shown in Table 5.4 and comparing with the most restrictive criteria of Table 5.5 would suggest operational site lives of well beyond 50 years especially if regular and proper maintenance are provided. However, the relatively low loading limits specified for cadmium might provide a more critical restriction.

Table 5.5 Loading criteria for biosolid disposal to land

Pollutant	**UK ICRCL** (mg/kg)	**EU 1986 Directive**				**Dutch Ministry of Public Housing** (mg/kg)	**Swedish EPA** (Moderate pollution) (mg/kg)	**US EPA** 503 Regulations (kg/ha/yr)	**Canada Ontario Ministry of Env.** (Lowest Effect Level) (mg/kg)
		Biosolids (mg/kg)	UK 90% (1996/97) Biosolids Limit	Soil (mg/kg)	Application Loading 10 yr average (kg/ha/yr)				
Zinc	300	2500 - 4000	1076	150 - 300	30	720	175 - 300	140	110.0
Lead	2000	750 - 1200	288	50 - 300	15	530	30 - 100	15	31.0
Cadmium	15	20 - 40	3.4	1.3	0.15	12	1.7 - 2.0	1.9	1.0
Copper		1000 - 1750	758	50 - 140	12		25 - 50		25

The use of swales (and ditches) in cold climate countries, such as Sweden, offer a further advantage through their potential as snow deposit areas (Lindwall and Hogland, 1981), and both systems are reported to have a good capacity to convey melt-water during the snowmelt period (Lindwall and Hogland, 1981). It is expected that the majority of particle bound pollutants will remain in the swale or ditch, while the majority of dissolved pollutants will leave with the meltwater (Viklander 1997). However, conveyance problems may occur due to ice-growth and ice-blocking of inlets, outlets and ducts under roads.

The positive effects of vegetation, e.g. flow retardation and uptake of pollutants, are less apparent during the snowmelt period, which may cause a higher risk of erosion. Removal of suspended solids in swales was found to be higher during the growth season compared to the dormant season (Walsh *et al.,* 1997), with the higher removal rates being associated with the combined filtering capacity of the dead and live grasses in the swale. However, smaller removals of nutrients and organic material were observed during the growth season, possibly due to decay of last seasons vegetation. Söderlund (1972) found that less suspended solids were trapped in a vegetated waterway during snowmelt events (30 % removal) compared to rainfall events (75 % removal). This phenomenon was explained by the lower flow resistance and lower filtering effect during the winter season due to the deterioration of the vegetation layer (Bäckström, 2002).

Variations in swale pollutant removal efficiency are also thought to be associated with variations in the influent pollutant concentrations. When inlet pollutant loading rates are high, grassed swales retain significant amounts of pollutants, mainly due to the sedimentation of particulate matter and associated pollutants. Large particles are trapped to a higher degree than small particles. When grassed swales receive stormwater with low pollutant loadings, they may release rather than retain pollutants. Thus it may be concluded that pollutants, once trapped in a swale, are not permanently bound to either the vegetation or soil (Bäckström, 2002).

5.2.1.2 Filter strips

There are few reports of the individual performance of filter strips in the UK but the pollutant removal efficiency of a filter strip receiving runoff from a car park in the US has been described by Yu *et al* (1987). Optimum removal rates were achieved within 18 to 25 m slope lengths but the density and height of the grass sward were also important factors influencing pollutant removal effectiveness. Sheet flow over the grass surface was achieved using a level spreader and the associated average percentage removal efficiencies were 71%, 38%, 10%, 25% and 50% for TSS, P_{tot}, N_{tot}, Pb and Zn respectively. The achievement of maximum contact and residence times through the use of level spreader devices to obtain sheet flow over the grassed surface is a desirable factor in the use of these systems (Schueler, 1987; Livingston *et al*, 1984). Grassed filter strips and swale channels are being increasingly used as “first stage” treatment systems for the runoff from car parks and residential streets in the US prior to an additional treatment system such as a detention pond or an infiltration basin (Schueler, 1987; Yu and Benelmouffok, 1990). A 10m grass filter strip has been installed as an initial receptor for surface runoff from a heavy goods vehicle (HGV) parking area on the Hopwood Park Motorway Service Station at Junction 2 on the M42 in Oxford. The first 10mm first-flush volume is directed over the filter strip to intercept silt prior to discharge into an infiltration trench. No problems have been reported although the grass surface is occasionally heavily oiled and the combined filter strip and collector trench collectively show reductions of 94% for total zinc, 82% for total copper and 97% for lead as well as 99% and 98% reductions for SS and BOD respectively (Bray, 2001).

5.2.1.3 Filter drains

The traditional role of filter drains has been to intercept highway discharges as well as subsurface seepage from the non-saturated (vadose) zone and transport the flow to a suitable outlet point. However, they also provide a treatment facility and the results of an experimental study carried out adjacent to the M1 motorway, north of Luton, England, are shown in Table 5.6. The effective removal of both conventional and toxic pollutants by a 55 m length of filter drain is clearly indicated. The operational lifetime of filter drain systems has been estimated to be 10 years at most due to the build-up of oil, grease and sedimentary material which blocks the voids in the filler material.

Table 5.6 Mean percentage annual removal efficiencies for a UK motorway filter drain treatment system

Pollutant	Percentage removal efficiency
TSS	85
Pb_{tot}	83
Zn_{tot}	81
Zn_{diss}	56
COD	59
Oil	70
PAH	70

A 750 m filter drain in Aberdeen, Scotland receiving inflows from 44 roadside gullies alongside the A944 highway has been monitored as part of the Scottish SUDS database. The 150-300 mm drain is surrounded by single-sized filter material within a geotextile wrapping and has a 150 mm soil cover. The percentage runoff outflow from the perforated pipe under-drain ranged from 0.85 – 196.0%, with a mean value of 42% (the events over 100% were mainly die to snowmelt). The lag time between peak of rainfall intensity and peak flow varied from zero to 11.5 hours, with a mean value of 3.5 hours. Although reductions in TSS of 74.3% have been recorded, water quality has been highly variable showing strong seasonal differences.

5.2.2 Infiltration Systems

5.2.2.1 Soakaways

Although concerns have been expressed over the use of soakaways with regard to the potential for groundwater contamination, the majority of research (albeit very limited in extent) would suggest that pollutant concentrations peak at a soil depth of 0.4 - 0.5 m immediately below the base of the soakaway, and decline exponentially with depth to background levels. The uniform depth-concentration profiles also suggest that the pollutant decay rates are influenced strongly by the available total organic carbon and clay-silt percentages. High concentrations of total organic carbon and heavy metals were associated with fine organic accumulations in the first 400 mm of sediment at the base of two soakaways investigated by Pratt (1996) at Brandon, Suffolk, UK. Similar results were reported in a study of a motorway soakaway on the M25 at junction 20 (near Kings Langley, Herts). Total quantified PAH in the basal soakaway sediments were recorded as 100,333 ?g/kg with an estimated annual loading of 0.20 – 0.33 kg per annum being delivered to the soakaway (Barker *et al*., 1999). Below the base of both the Brandon and M25 soakaways, the pollution levels appeared to approach those of background levels. It was suggested from both the above studies that the formation, and continued presence, of a sludge layer at the base of the soakaway is important in terms of retaining pollutants by filtration and sorption. This inevitably results in a significant build-up of metals, PAH and halogens in the lower layer and if the site becomes saturated with the pollutant species, they would migrate with the runoff water to the unsaturated zone and to the groundwater. In addition, soluble components have the potential of being leached out to groundwater. Experimental work undertaken on a laboratory scale soakaway has suggested that up to half the available soakaway volume might be filled with sediment after 8 years of operation based on the cumulative annual mass of suspended solids discharged to the system (Pokrajac and Deletic, 2002).

Soakaways have been widely used in the UK for treating runoff from the impervious surfaces and roofs of individual properties. They are also used for the disposal of highway drainage, particularly when connected to single or multiple gully pots. The installation of multiple soakaways (or soakaway fields) has also been used to increase the storage and infiltration capacity for highway runoff prior to overflow but the practice could lead to downstream build-ups of persistent pollutants. Where soakaway drainage is being disposed directly to ground overlying Groundwater Resource Protection (GRP) zones, interception facilities will be required. Under such circumstances, drainage from extensive stretches of highway (perhaps as much as 1 km) can be brought to lined oil interceptors and then to a group or "field" of soakaways. On the M40 and M25 motorways, the interceptors are sized to hold the equivalent of 6 minutes flow at the design discharge rate and have follow-on soakage lagoons to accept drainage overspill if all the soakaways should fill.

5.2.2.2 Infiltration trenches

An infiltration trench which forms part of a combined stormwater treatment system at the Hopwood Park Motorway Service Station (Oxford, UK) is reported to have performed extremely well with regard to the removal of heavy metals, SS and BOD levels (see section 5.2.1.2 for data), despite a problem with silt infilling which was also noted. A 1m deep drainage blanket system has been installed below a traditional block-paved road/parking area in Cirencester, Wiltshire, which receives roof and road gully drainage but no information on its performance is available. An infiltration trench in Aberdeen, Scotland, is currently being monitored for both flow and pollutant attenuation, although again no information has yet been published.

5.2.2.3 Infiltration basins

An infiltration system in Luton, Bedfordshire, UK, receiving peak discharges of 2.4 m^3/s from a 26 ha residential site, showed incremental annual accumulation of zinc, copper and cadmium (averaging 0.8 - 1.5 mg/kg for Zn) at all depths in the basin but with an exponential mobilisation of soluble species with depth. The exhaustion of the basin buffer capacity for acids make the long-term fixation in the underlying soil almost impossible. The results of this study imply that average hydraulic conductivities in the unsaturated zone below infiltration systems should range from 10^{-4} m/s to 10^{-6} m/s, with the first 30 cm of the infiltration system having a minimum hydraulic conductivity of 10^{-5} m/s. In addition, the top 0 - 30 cm of the infill structure should be capable of maintaining a long term pH value of 5.5 - 8.0. This will reduce the probability of metal mobilisation and breakthrough arising from alkaline reactions

due to the presence of water-soluble organic complexes. Finally, the groundwater level should be more than 1 m below the base of the infiltration device to ensure that the unsaturated zone can effectively adsorb downward moving colloidal metal species.
The current evidence would suggest that the best use of infiltration basins is as final polishing systems in which the major treatment function is achieved by a preceding sedimentation or biofiltration system which in turn is fitted with a front-end oil/sediment trap. Infiltration basins are in effect a type of filter drain or soakaway having an expanded surface area. They are not suitable for spillage containment and have few ecological benefits. Although the use of infiltration basins has been recommended in Germany and France, their use in the UK is limited due to the high costs of construction and maintenance in relation to their pollutant removal abilities.

Infiltration systems in cold countries may have problems with ice clogging during winter and, as a result, the infiltration capacity can be heavily reduced during the snowmelt period. However, the evaluation of an infiltration basin over a winter period reported there was a minimal risk of total ice blockage with temperatures down to -15°C (Stenmark, 1991), and that the infiltration basin operated well during the snowmelt period. Bäckström and Viklander (2000) have also reported that both moderate runoff control and high pollution control can be achieved by using infiltration systems in cold climate regions.

Färm and Renman (1999) evaluated the performance of the infiltration component of a stormwater management system in Västerås, Sweden. The complete system consisted of a detention pond, infiltration system and constructed wetland, and the drainage area included a 4.3 ha highway area with a daily mean traffic density of 20,000 vehicles/day. The results from the infiltration system showed that the calcium silicate rock infiltration material clogged during winter, and that water was then unable to pass through the filter surfaces. The clogging was probably caused by cementation of the material (Mikkelsen *et al.,* 2002).

5.2.3 Storage Facilities

5.2.3.1 Flat roofs for storage

The water and sewerage department of Seine Saint-Denis County, France, demonstrated the potential of flat roofs for rainwater storage in an experiment conducted on three types of storage system (open sky storage, storage in porous materials and storage under flagstones). The flat roof was able to store the water depth associated with a ten-year return period storm (i.e. a depth of 40 mm). The edges of the roof measured 25 cm, and the strength of the bearing material was 400 kg/m^2. The system included two flow control devices for the drainage of rainwater, each of which consisted of two 1 cm diameter outlets which limited the flow rate to 0.5 l/s.

5.2.3.2 Storage tanks/chambers

Data on the performance of a sedimentation tank receiving runoff from a major motorway in the UK are given in Table 5.7 (Ellis and Revitt, 1991). The relatively poor treatment efficiencies found in this study have been supported by French motorway studies (Ruperd, 1987; Ranchet and Ruperd, 1983) in which removals of 36%, 38%, 61%, 48% and 22% were obtained for COD, BOD, TSS, total lead and nitrate, respectively.

Table 5.7 Mean percentage annual removal efficiencies for a UK motorway sedimentation tank treatment system (Perry and McIntyre, 1986)

Pollutant	Removal efficiency (%)
TSS	52
Pb_{tot}	40
$Zn_{to}t$	47

Zn_{diss}	15
COD	35
Oil	28
PAH	45

Due to the combination of size restrictions (see section 4.1.7), limited pollutant removal capabilities (Table 5.7), high maintenance requirements (see section 4.2.2) and safety concerns of locating large open tanks next to busy roads, these systems would only be a preferred option if available land was to be so restricted as to necessitate a vertical sided structure or if there should be safety reasons to avoid an open water lagoon.

5.2.3.3 Lagoons

The UK motorway study referred to in section 5.2.1.3 also investigated the performance of a 28m long by 2m wide polythene lined lagoon for the treatment of runoff from a 3172 m^2 area of road surface. The lagoon had a holding capacity of between 3 and 5 m^3 according to the height of an adjustable outlet pipe. The high pollutant removal efficiencies recorded for this system are shown in Table 5.8.

Table 5.8 Mean percentage annual removal efficiencies for a UK motorway lagoon treatment system

Pollutant	Percentage Removal Efficiency
TSS	92
Pb_{tot}	90
Zn_{tot}	71
Zn_{diss}	25
COD	54
Oil	>70
PAH	>70

(Table from: R Perry and A E McIntyre. 1986. Impact of motorway runoff upon surface water quality. 53 – 67 in J F Solbe (Edit): *Effects of Land Use on Freshwater*. Ellis Horwood Ltd., Chichester.)

The results can be compared with those found for other treatment systems in the same location (see Table 5.6 and 5.7) from which it can be seen that the lagoon was more efficient than the French drain which in turn was more efficient than the sedimentation tank. The high treatment efficiencies of the lagoon were attributed to over-design of the system with contributing factors being water loss due to seepage. Soakage lagoons at the junction of the A1(M) and M25 motorways to the north of London have shown persistent surface oil and scum problems despite the installation of booms and gate valves and recently some €86 500 was spent de-silting both lagoons. Regular maintenance is essential to retain the long term effective performance of sedimentation lagoons with the maintenance frequency being dependent on the storage provision made for silt. However, such open water systems are rare stormwater BMP forms in the UK.

5.2.3.4 Detention basins

Detention ponds completely empty between storm events, and therefore the residence time of stormwater is shorter in a detention basin than in a retention pond and settling of particles and biochemical degradation of dissolved constituents is comparatively less efficient (Ferguson, 1998). However, a potential advantage of detention basins are that they can be used as a snow deposit area in cold countries during the winter months, although this could cause severe problems during the snowmelt period when large volumes of melt-water flow into the basin. (Bäckström and Viklander, 2000).

5.2.3.5 Extended detention basins

Extended detention basins are detention basins which detain stormwater runoff for an extended period of time. Associated with their flow attenuation characteristics, detention basins encourage sedimentation of the coarser suspended materials although fine solids will be re-suspended during high flows. US investigations have also demonstrated low removal efficiencies for soluble pollutants. No data has been reported for any UK extended detention basins although such facilities have been installed at North Weald, Essex and in Dundee, Scotland.

A series of French motorway studies (Balades *et al,* 1985; Cathelain *et al,* 1981; Ruperd, 1987) have investigated the performance of detention basins and removal efficiencies in the ranges of 0-73%, 0-75%, 0-73%, 1-67%, 0-48% and 7-86% were reported for BOD, COD, TSS, total Pb, total Zn and oil, respectively. The removal efficiencies were generally at the lower end of these ranges and the reasons given for the poor performances were the re-entrainment of solids during high flows (2.5 to 3.1 m^3) through the basins. The use of front-end oil separators and sediment chambers were found to be beneficial to overall pollutant removal performance yielding solids removal efficiencies of at least 50%. Stahre and Urbonas (1990) quote long term efficiencies for extended detention basins having 48 hour detention times of 50 - 70% for TSS and hydrocarbons, 20 - 40% for BOD, 75 - 90% for lead and 30 - 60% for zinc. Even 4 - 10 hours detention is alleged to offer up to 50 - 60% TSS removals. However, as most detention basins often have less than 2 hours detention time, the pollutant removal efficiencies are usually rather mediocre with TSS in the range of 15 - 20% and BOD/COD generally less than 10%.

5.2.3.6 Retention basins

Retention basins (or balancing ponds) contain a permanent pool of open water (usually occupying 50 to 75% of the surface area) around which emergent macrophyte vegetation may be introduced. Such planting will assist in the treatment process by providing biological removal of pollutants, particularly those in the dissolved phase. This re-inforces the removal of particulate associated pollutants through sedimentation within the relatively still water body which should be sized to contain at least 4 times the treatment volume in order to provide retention of approximately 3 weeks during the wettest conditions.

The time-based trap efficiency of a 25000 m^3 balancing pond receiving discharges from a 60.7 ha residential development in NW London is given in Table 5.9 together with a bench-top determination of settleability. It is clear that even a few hours retention can provide a base-level treatment of stormwater runoff but that extended retention times are required to remove nutrients and organic loadings. For a retention time of 12 to 15 hours, the reductions which can be expected include some 60% of total SS, hydrocarbons, total coliforms and lead; 40% of BOD, phosphates and copper; and 10 – 20% of other pollutants such as cadmium, nitrate and ammoniacal nitrogen. The operational performance of the balancing pond under stormflow conditions is shown in Figure 5.1 and the potential for siltation at the inlet is clear from the high slug SS concentrations recorded at this location.

Table 5.9 Trap Efficiency of Wet Retention Basins

Pollutant	Imhoff Settleability (24 hrs average %)	Balancing Pond 2 hr Removal (%)	Balancing Pond 6 hr Removal (%)	24hr Balancing Pond Removal (Average %)
TSS	68	34	82	46 - 84
BOD	32	13	48	29 - 53
Pb	62	30	66	46 - 78
Oil/Hydrocarbons	69	18	62	20 - 78
Total P	46	20	58	20 - 70
Total Coliforms	71	60	72	54 - 73

(Table from: M J Hall, DL Hockin and J B Ellis. 1993. *Design of Flood Storage Reservoirs*. CIRIA, London)

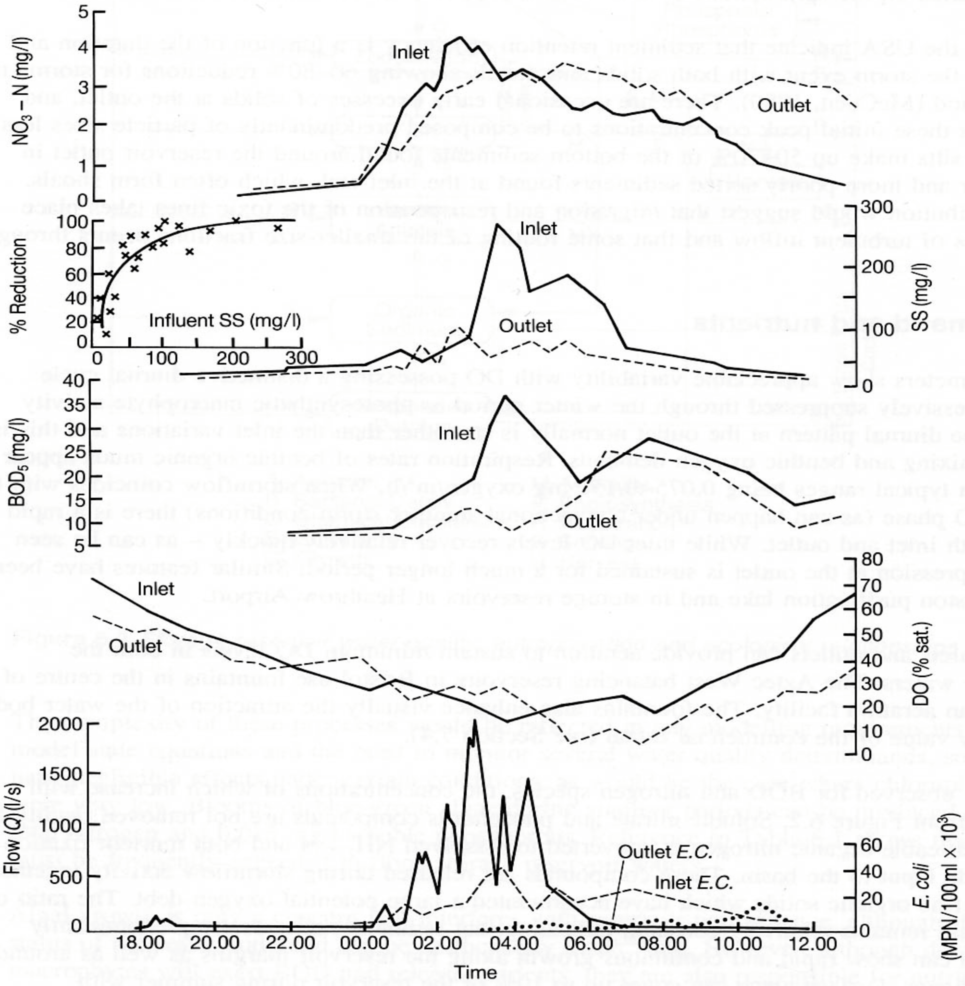

Figure 5.1 The Operational Performance of a Wet Retention Basin
(Figure from: M J Hall, D L Hockin and J B Ellis. 1993. *Design of Flood Storage Reservoirs*. CIRIA, London.)

The inset graph to Figure 5.1 also demonstrates that as inlet SS concentrations increase, a larger proportion of the suspended solids is able to settle out and for an influent value greater than 100 mg/l, reductions of greater than 80% can be consistently achieved. However, at low influent concentrations, removal percentages decrease very rapidly to reach an irreducible background minimum concentration level. At such very low inlet concentrations, it is possible for the retention basin to record negative removal efficiencies. However, such increased outlet flow concentrations can also result from the mobilisation and flushing of pollutants loosely bound to the sediment (and plant roots/tissue) as can be seen from inspection of the nitrate pollutograph in Figure 5.1.

Two wet retention basins within the Dunfermline, Scotland DEX development receiving highway runoff are included in the Scottish SUDS database monitoring programme. Using a vortex flow outlet control, good peak flow reduction was achieved unlike a simple pipe outlet which yields a much poorer performance. Visual observations indicated a good sedimentation performance especially for coarse and sand size solids. However, problems of litter and sludge shoal accumulations have been encountered confirming the potential for inlet silting as implied from Figure 5.1. The (retrospective) inclusion of marginal vegetation (to a maximum of 25% cover) and islands (to amend flow characteristics) within balancing ponds has been shown to markedly increase the treatment efficiency without prejudicing the overall peak storage capacity.

Although retention ponds are frequently used for stormwater control in countries with cold climates, the performance of these systems is not generally well understood. Research in Sweden on the performance of two retention ponds concluded that the ponds could effectively control pollution (Table 5.10) and that removal efficiencies increased with the specific storage of the pond up to approximately 250m^3/impervious ha (equivalent to a depth of 2.5 mm) (Pettersson *et al.,* 1999). However, the pond sediments were found to be highly polluted and therefore to ultimately require proper disposal e.g. to a controlled landfill site. This finding also led to the conclusion that ponds should be regarded primarily as treatment facilities and not as habitat for wildlife. The concentrations of heavy metals in the outflow were found to be critically high compared to Swedish guidelines for lakes and streams (German, 2001). These findings were supported by a literature survey carried out to identify future stormwater treatment systems for a part of Copenhagen which was being redeveloped (Moller, 2001).

In cold weather countries, formation of an ice-layer in a retention pond forces inflowing meltwater under the ice which can result in the scouring of fine bottom material. When the somewhat pressurised volume under the ice is exceeded, water flows over the ice surface and the storage volume is eliminated because of the impervious ice layer. The ice also restricts the air-water exchange, limiting the availability of oxygen to the water column which is being progressively depleted throughout the winter due to organic decomposition. The cold water flowing during the melt periods has a higher viscosity, thus reducing settling velocities of particles being carried into retention facilities. This decreases sedimentation and enables mobilisation of associated contaminants further down-stream. Research by Jokela and Bacon (1990) has indicated that settling velocities are 50% faster at a water temperature of 20 °C compared to 4 °C. It is anticipated that the impact of ice cover and low water temperatures would be similar in constructed wetland systems.

Watt *et al.,* (1997) have investigated the winter regime in a retention pond with a surface area of 0.52 ha and average depth of 1 m situated in Ontario, Canada. The results of studies carried out over a period of two winters indicated the low potential of bottom sediment scouring and pollutant release from the sediment. Anaerobic conditions occurred during two days at the end of a period (one to two months) of constant freezing conditions. There were indications of density stratification in the pond during winter. Studies on a stormwater retention pond in Sweden with a surface area of 350 m^2 and an average depth of 1.2 m showed that the amount of dissolved oxygen decreased when the pond was ice-covered and no inflow or outflow of stormwater took place (Pettersson, 1996). The concentrations of dissolved heavy metals (Zn, Pb, Cu and Cd) increased during the same period.

Table 5.10 Removal efficiencies in two Swedish stormwater ponds (Pettersson *et al.,* 1999)

Pollutant	The Järnbrott Pond		The Krubban Pond
	Pond	System*	
TSS (mg/l)	70	42	84
Zinc (µg/l)	30	24	82
Copper (µg/l)	30	24	75
Lead (µg/l)	48	30	82
Cadmium (µg/l)	11	12	50
Nitrogen (mg/l)	7	80	33
Phosphorus (µg/l)	40	27	74

***** Removal efficiency considering the by-pass upstream of the pond.
(Mikkelsen, *et al*., 2002)

Oberts *et al.,* (1989) have investigated the treatment performance of four different retention ponds in Minnesota, USA. The data collected during snowmelts indicated that the ponds have a wide range of pollutant removal abilities (Table 5.11). The data also show that there is a marked reduction in the ability of the retention ponds to treat snowmelt runoff in comparison to rainfall runoff (with the exception of the Woodbury pond which was notably undersized). An explanation for this could be the different characteristics of meltwater in comparison to stormwater runoff. For example, studies of metal partitioning in a stormwater pond have indicated that more metals are in the dissolved phase during snowmelt events, a finding thought to be associated with the higher conductivity of meltwater due to the presence of road salts (Pettersson, 1999). Research by Oberts (1994) and Oberts and Osgood (1991) found that the removal efficiencies of all the monitored substances decreased during winter months with the lowest removal efficiencies reported for nutrients. It was noted that the ponds could become stratified during winter conditions because of thermal and dissolved solids concentration gradients. This phenomenon was studied in Canada, where it was concluded that wind was an important parameter in determining the flow pattern during baseflow conditions without ice cover, and that a stable stratification occurred in the pond due to temperature and salinity gradients (German *et al.,* 2003, Marsalek *et al.* 2000).

Table 5.11 Pollutant removal ability (%) of ponds in treating runoff in Minnesota

				Percent pollutant removal Snowmelt events (Rainfall events)				
Pond	**TSS**	**VSS**	**TP**	**DP**	**COD**	**TKN**	**NO3**	**TPb**
McCarrons	58	58	41	38	50	22	13	40
(0.97 ha)	(91)	(95)	(78)	(57)	(90)	(88)	(60)	(85)
Lake Ridge	72	63	10	6	-	10	19	18
(0.38 ha)	(90)	(70)	(61)	(11)	-	(50)	(10)	(73)
McKnight Basin	85	48	30	11	-	10	8	59
(2.24 ha)	(85)	(67)	(48)	(13)	-	(31)	(24)	(67)
Woodbury	-60	-46	-17	-12	-	-27	4	-40
(0.15 ha)	(46)	(32)	(24)	(21)	-	(14)	(18)	(42)

5.2.3.7 Constructed Wetlands

Wetlands (both natural and constructed) have been widely used for the of treatment of sewage and for urban, industrial and agricultural runoff although with less extensive applications for highway runoff. Sub-surface wetlands provide limited flood storage and therefore, where significant flood storage is required, should be combined with a separate storage facility. The balance between storage and treatment requirements will depend on the land availability and where space is limited, the constructed wetland could be designed to only treat the first flush contained in the initial 5-10 mm of effective runoff. Table 5.12 indicates the average range of pollutant removal efficiencies that have been reported in the literature for constructed wetlands receiving highway runoff in the UK, France, Canada and the United States.

Table 5.12 Percentage pollutant removal rates in constructed wetlands

Wetland Type	**TSS**	**Faecal Coliforms**	**N_{tot}**	**P_{tot}**	**Pb_{tot}**	**Zn_{tot}**	**BOD/TOC**
Subsurface Flows	85 (67-97)	88 (80-97)	44 (25-98)	50 (20-97)	83 (5-94)	42 (10-82)	-
Free Surface Flows	73 (13-99)	92 (86-99)	33 (10-99)	43 (2-98)	69 (41-83)	58 (31-75)	15 (5-32)

A 3900m^2 biofiltration (surface flow) wetland receiving runoff from the M25 London Orbital Motorway recorded consistent metal removal efficiencies of about 90% confirming the potential treatment effectiveness of such systems. Solids removal performance increased as flow TSS concentrations increased but with inflow concentrations below 30 - 40 mg/l, only minimal reductions were achieved. A 1050 m^3 constructed wetland on the A34 Newbury

Bypass draining 16,000 m^2 of road surface showed similar good TSS (90%) removal rates but metal removal efficiencies were highly variable particularly for zinc and copper. This variability in performance (which can be noted from Table 5.12) has variously been attributed to short-circuiting, short detention and contact times, pollutant speciation mechanisms and remobilisation, seasonal vegetation effects etc.

5.2.3.8 Combined stormwater runoff treatment systems

A stormwater treatment system, consisting of an oil separator, sedimentation basins, grassed filter strip and ponds, was constructed in Flemmingsberg/Huddinge, Sweden, in 1994-95 (Lännegren, 1998). The catchment area was 9.6 km^2 and the detention time was approximately six days. The results of a three-year monitoring programme showed that lead and zinc concentrations were reduced by this system, while copper, mercury, chromium, suspended solids, COD and TOC concentrations increased. BOD remained constant. It was also noted that the wetland had a positive effect on the wildlife, with 10 to 12 different bird species and a variety of fish observed in and around the wetland area (Mikkelsen *et al.,* 2002).

A combined stormwater control system at Lake Magelungen, Sweden, began operating in 1992 (Rosen, 1996). The catchment area of 81.5 ha includes a city centre, roads and a sports arena. The system includes a 1000 m^2 grassed filter strip and a 10,000 m^3 banked basin in Lake Magelungen. Sampling was carried out over a two year period to study the reduction of phosphorus and nitrogen. The discharge of P from the grassed filter strip varied depending on the season, from washout (during the summer) to a reduction of 70-80%. The removal of nitrogen also varied, with the lowest reduction observed during the summer and a higher removal of particulate bound N in comparison to the dissolved fraction. The conductivity and metal concentrations increased across the surface of the grass filter. It was concluded that, rather than retaining the pollutants, pollutants were being washed out and the grass filter was therefore taken out of use. These problems could be explained by difficulties experienced in spreading the flow equally over the surface, which resulted in channelling across the surface. The results for the pond showed that the main removal process was sedimentation (Rosen, 1996). The results also showed that denitrífication was occurring in the sedimentation basin (Mikkelsen *et al.,* 2002).

The monitoring of oxygen and flow downstream of a combined detention pond and constructed wetland system in Herning, Denmark, has shown that the receiving water can cope with the limited discharge from this system. The available data, although limited, shows a 40-70% reduction in concentrations of COD and nutrients, with concentrations discharged from the ponds often being lower than those discharged from wastewater treatment plants (Mikkelsen, *et al.,* 2002).

Research on a wetland in Minnesota, USA, demonstrates some of the issues associated with accurately determining treatment performance of these systems. Table 5.13 shows the treatment performances of a 2.5 ha, six-chambered, low-head wetland treatment system on receiving meltwater, and the treatment performances of the same wetland system during the first two rainfall events following this snowmelt event (Oberts and Osgood, 1988). The wetland outlet was frozen shut for the entire winter, resulting in the slow accumulation of all small mid-winter events and baseflow in the final wetland chamber (approximately 1 ha). When the melt began, flow entering the final wetland chamber was detained until a small opening in the outlet culvert gradually allowed all of the accumulated meltwater to discharge. Material that had settled out of the accumulated meltwater during the extended detention period had, however, settled onto several layers of ice that had built-up over winter. These settled pollutants were then largely washed through the system by the first of the two rainfall events as the ice layers remained as an impervious surface over which the rainfall runoff freely flowed. Keeping the outlet open to prevent the formation of an ice layer over the entire wetland, and then allowing detention to occur in contact with the wetland soils could have enhanced the treatment under these conditions.

Table 5.13 Wetland treatment system melt/spring rain performance

	TSS	VSS	TP	DP	COD	TKN	NO3	TPb
Snowmelt	82	78	68	68	74	53	54	71
Two rainfalls after melt	4	15	6	-5	10	22	-20	39

5.2.4 Alternative road structure

5.2.4.1 Porous paving

Given that as much as 60% of the typical urban surface is taken up as “vehicle habitat” use with some 10 parking spaces available per average single car, it is not surprising that alternative forms of hard-standing have been developed to reduce the environmental impact of increasing traffic densities. Work in the 1980s on a concrete block-surfaced car park at Nottingham Trent University using differing types of sub-base materials demonstrated 34% - 47% reductions in total runoff discharges with initial wetting loss before drain discharge being 2.4 – 3.2 mm. Considerable improvements were also achieved in water quality with the porous paving limiting TSS discharges from near zero to 50 mg/l maximum with hydrocarbons only found at trace levels. The work showed that pollutant retention occurred in the 50 mm layer immediately above the geotextile liner on which the porous blocks were placed. Observations on a similar concrete block surfacing at Shire Hall, Reading indicated a mean infiltration rate of 2600 mm/hour, six years after installation without any maintenance (Pratt, 1995). The surfacing allows the immediate infiltration of rainfall-runoff into the construction with the sub-base providing storage, treatment and pathways for downward percolation into the underlying soil or to perforated underdrains. The volume of water that can be stored and the outflow rates are dependent on the void ratio of the sub-base gravel or crushed stone. The presence of dirt and oil spillage on the paved surface significantly reduced the infiltration rates for both the blocks and the gaps between them.

A 1500 m^2 porous paved car park installed at the Scottish Civil Aviation Authority HQ in Edinburgh, whilst costing out some 15% more expensive than conventional "blacktop" asphalt, is showing significant attenuation (22% flow reduction) of the outlet hydrograph with the first discharge only occurring several hours after the start of rainfall. In addition, TSS, COD and BOD outflow values are consistently below 20, 10 and 2 mg/l respectively with hydrocarbons below detection levels. Studies conducted on permeable pavements at the M40 Wheatley, Oxford service station and at the Wokingham Tesco car park site, demonstrated average storm peak reductions of 88% and 81% respectively with attenuation extended on average by a factor of 14 (Abbott *et al*., 2003). Newman *et al*., (2001) have also shown that properly installed permeable paving with the gravel bedding reinforced with lightweight clay aggregates or porous concrete granules, can provide considerable oil and water retention. Experimental paving surfaces have given infiltration rates of some 4500 mm/hour with overall oil retention capacities of 9542 g/m^2 which would give an operational life of over 40 years and an outflow effluent from the pavement of about 0.6 - 0.8 mg/l. The use of pre-fabricated plastic/polypropylene geo-cellular units under the sub-base bedding layer has been shown to optimise oil and sediment removal capturing some 20 – 40% of the oil applied to the paved surface (Newman *et al*., 2003).

A porous concrete block-surface car park at the Bank of Scotland, South Gyle, Edinburgh showed outflow discharge to be under 50% of total rainfall-runoff with initial wetting loss being 1.65 mm. Lag times were typically within a range of 40 – 140 minutes. Both heavy metal (<0.068 – 1.7 ?g/l) and hydrocarbon (<3.5 mg/l) concentrations in the porous paving effluent were markedly reduced over raw surface runoff concentrations. A 6250 m^2 porous concrete-block surfaced car park at the M40 Wheatley Motorway Service Area near Oxford has provided similar observations to those in Scotland with outflows from the porous pavement being only 4% – 47% of the rainfall volume with lag times of up to 2 – 3 days. Block infiltration was assessed as varying between 250 – 14,000 mm/hour although after 10 months of operation, this had reduced to zero. Infiltration through the gaps was however maintained at rates of 11,000 – 229,000 mm/hour. The results of these and similar studies elsewhere in Scotland have led SEPA to accept that oil interceptors are not required on permeable car parking areas which have an approved engineering sub-base.

A 4-year study carried out near Nantes, France, monitored the flow rate upstream of a drain collecting runoff from 255 m of street surface. A cross-section of the porous pavement structure is given in Figure 5.2, while Figure 5.3 displays the responses of both the pavement containing a reservoir structure and a reference basin site to a heavy storm event.

Examination of the complete data set demonstrated that the greatest proportion of water infiltrating into the pavement was not discharged via the drain. An analysis of drain operation in relation to daily precipitation height is given in Table 5.14. The absence of outflow indicates that the stormwater had infiltrated into the soil, been retained by aggregates and/or evaporated. The proportion of stormwater discharged by the drain varies from 0% to a maximum of 12.5%. Over the entire 4-year study period, the drain only served to discharge 3.3% of total rainfall.

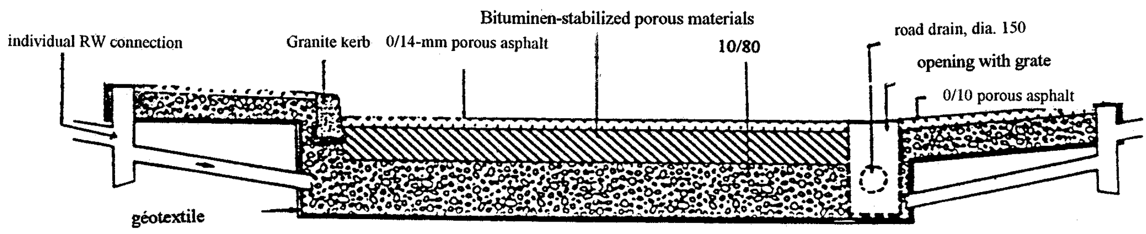

Figure 5.2 Cross-section of a street fitted with a reservoir structure

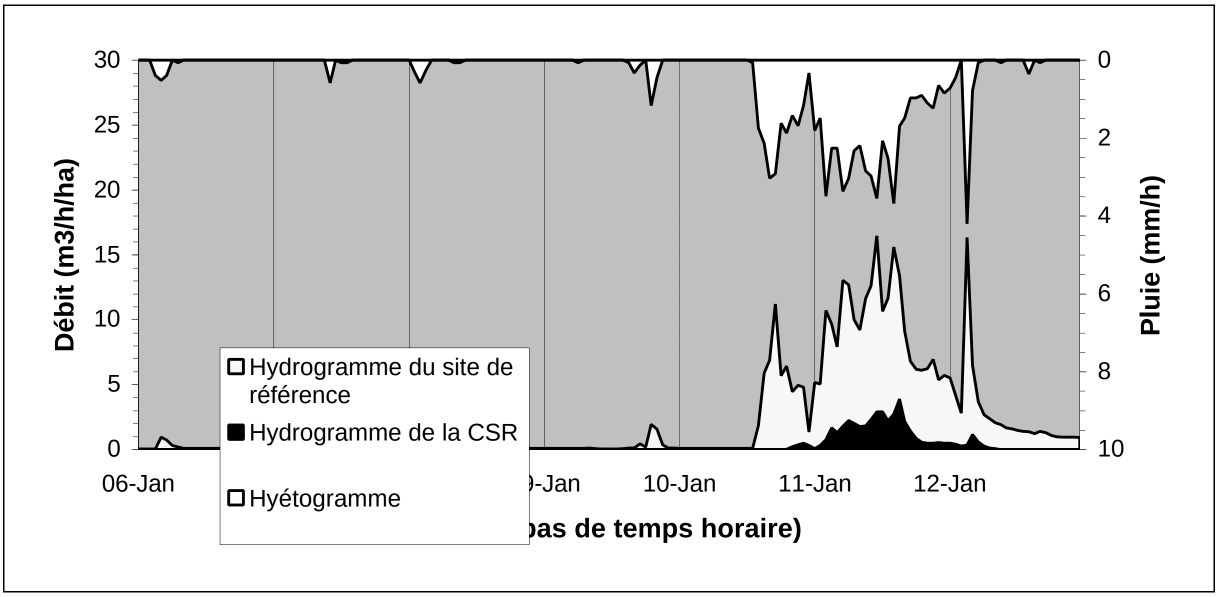

Figure 5.3 Comparison of responses to a given rainfall event between a reservoir structure and a conventional suburban catchment basin

Table 5.14 Analysis of drain outflow in relation to rainfall data

Daily rainfall limit (mm/day)	Number of days of rainfall higher than the limit	Number of days of rainfall higher than the limit without outflow	Number of days without outflow/Number of days of rainfall
1.8	273	166	60.8 %
10	60	22	36.7 %
20	19	6	31.6 %

An average per-event "pseudo-infiltration" was obtained by calculating the volume of water not recovered by the drain with respect to two different measures: elapsed flow time between beginning of the rainfall event and end of the flow period (or end of the rainfall event when flow is zero), and surface area of the porous pavement. The extreme values of these ratios are listed in Table 5.15. They are aligned with values of soil permeability measured both in situ and in the laboratory which, depending on measurement point, vary from 1 to 6×10^{-7} m/s. The extreme pseudo-infiltration values can differ by up to a factor of 40. This variability seems to be caused by variations in the hydrated state of the soil, which in turn depends on the meteorological conditions prior to a precipitation event.

Table 5.15 Extreme values of per-event losses

Rain events	Infiltration/rainfall duration (mm/h)	Pseudo-infiltration 10^{-7} m/s	% non flowed
With outflow	min. 0.5	0.5	
	max. 3.6	16.9	87
Without outflow	max. 5.8	19.8	100

1.1.1.1.1 Effects on stormwater quality

To study the impact of reservoir structures on the quality of stormwater runoff, an experimental site was built in 1991 in Rezé, France, (Raimbault and Métois, 1992, Legret *et al.,* 1996, Legret and Colandini, 1999). The quality of stormwater runoff collected at the outlet of the reservoir structure was compared with that from a nearby catchment drained by a conventional separate system. An analysis of the materials and soil sampled in and under the reservoir structure was also performed. Samples were collected over a 4 year period, which included the analyses of approximately 40 storm events.

The results of water quality analysis of samples collected at the outlet of the reservoir structure following the start of a storm event (first flush) and the outlet of the conventional drainage system (composite sample) are presented in Table 5.16. The data shows that concentrations of suspended solids, lead, zinc and cadmium were reduced by 61%, 81%, 67% and 62%, respectively, indicating that the reservoir structure acts as a kind of filter system. On average, 96.7% of the storm water volume infiltrated into the soil below the reservoir structure (Colandini, 1997).

The pollutant loadings in the drainage from both catchments were calculated for storm events which were simultaneously sampled downstream of both catchment areas. The pollutant loadings data for both catchments (expressed as mass per hectare of contributing area) are presented in Table 5.17. The efficiency of the reservoir structure is determined in relation to the reference catchment area and presented in Table 5.17 as mean difference (%). This data clearly demonstrates the efficiency of the porous pavement, and the results are supported by several other studies. Baladès *et al.* (1992) observed pollution load reductions of 50%, 93% and 89% for suspended solids, lead and COD, respectively, for a 56-cm thick reservoir structure in comparison to a conventional pavement. Ranchet *et al.*

(1993), in comparing the performance of a conventional pavement to a 16 cm thick porous concrete pavement, reported reductions of 70% for suspended solids, 78% for lead and 54% for COD. A study carried out in Sweden investigated the impact of a porous pavement on snowmelt and reported a reduction of 95% for suspended solids and from 40-50% for lead (Hogland *et al.,*1987).

Table 5.16 Comparison of runoff water quality from a reservoir structure with a composite reference sample

	pH	COD (mg/l)	SS (mg/l)	Hc (mg/l)	Pb (µg/l)	Cu (µg/l)	Cd (µg/l)	Zn (µg/l)
Reservoir structure								
Nber Samples	28	31	31	8	31	32	31	28
Mean	7.5	<22	13	<0.02	3.7	8.7	0.5	52
Range	6.1-8.7	<20-36	0.6-139	-	0.6-33	3.5-22	0.04-3.5	11-340
Std. Dev.	0.7	5	27	-	6,2	4.5	0.8	69
Reference catchment								
Nber Samples	16	18	19	3	19	19	19	19
Mean	7.2	<23	33	<0.02	20	9.6	1.3	158
Range	6.2-8.1	<20-43	5-86	-	6-63	4.5-44	0.3-3.2	110-229
Std. Dev.	0.6	6	25	-	15	8.7	0.8	34

Table 5.17 Pollutant loadings discharged from the reservoir structure and the reference catchment area (per hectare)

	SS.	Pb	Cu	Cd	Zn
	(kg/ha)	(g/ha)			
Reservoir structure					
Minimum	0.32	0.17	0.57	0.001	3.2
Maximum	20.9	3.6	6.3	0.27	29.9
Mean	3.5	0.88	3.0	0.08	11.3
Standard Dev.	6.0	1.0	2.1	0.08	8.2
Reference catchment					
Minimum	1.3	1.9	1.1	0.11	34.1
Maximum	26.0	16.7	11.6	0.88	58.5
Mean	8.5	5.6	3.0	0.35	41.8
Standard Dev.	7.8	4.2	3.0	0.22	8.5
Mean difference (%)	**59**	**84**	**-**	**77**	**73**

Data from several experimental studies in France of various designs and types of reservoir structure are summarised in Table 5.18. From this data it can be concluded that the filtration of stormwater runoff through reservoir structures improves water quality, regardless of surfacing permeability, while the presence of a porous surface material enhances this effect.

Table 5.18 Comparison of the performance of different types of reservoir structures receiving stormwater runoff

Site	Characteristics	Reduction of pollution (%) as concentrations SS	COD	Pb	Zn	BOD
Classerie street (Rezé)	Porous asphalt + porous bituminous-bound graded aggregates	61		81	67	
Le Caillou park (Bordeaux)	Porous asphalt + porous concrete	36	79	86		
ZAC of Verneuil ZONE I	Porous asphalt + porous bituminous-bound graded aggregates	81	63	76	35	45
ZONE II	Conventional asphalt + porous bituminous-					

	bound graded aggregates	68	48	77	45	39
ZONE III*	Different reservoir structures	1	14	50	16	7

* = data from this site is thought to have been influenced by infrastructure work

Analysis of clogging material, crushed material, the geotextile material and the underlying soil, indicated that metals were primarily located in the porous surfacing of the reservoir structure and that the porous layers under the surfacing had only a minor effect on the retention of particulate pollution. Furthermore, the infiltration of stormwater into the porous asphalt over a period of more than 8 years did not cause any migration of particulate-bound metals within the reservoir.

The overall findings from these French studies are summarised below.

? From a hydrological perspective, it appeared that more than 96 % of the annual rainfall infiltrated into the soil underneath the reservoir structure significantly reducing both peak flow and runoff. The quality of water discharged from the reservoir structure was of a higher quality than that discharged from a neighbouring reference catchment area. In addition, there was no evidence of soil contamination under the structure after 8 years of operation.
? From a mechanical perspective, despite water infiltration, the behaviour of the reservoir structure was comparable to that of a conventional impervious structure.
? From an acoustic perspective, after 10 years and two maintenance operations (unclogging) the structure had retained sufficient porosity to achieve an acoustic absorption coefficient of 10-15%.
? From a performance perspective, the main problem was related to the clogging of surface porous materials. To maintain optimal performance regular cleaning would be required, indicating that the use of these systems involves additional costs and constraints in comparison to conventional pavement structures.
? The use of reservoir structures is primarily suited to the construction of large car parking facilities.

Another type of paving material is Grasscrete, a type of modular pavement well suited to overflow car parks which require a grass surface that must be sufficiently hard wearing to withstand regular vehicle use. Such grass-concrete surfaces possess infiltration rates between 0.2 to 1.0 mm/s (well in excess of most design storm rainfall intensities) and can hold up to 5 mm rainfall within one hour for subsequent evaporative loss. Filtration-sedimentation and adsorption processes within the structural reservoir of the surfacing material can limit TSS outflows from near zero to 50 mg/l and typically remove between 40 - 60% bacteria, 70 - 90% heavy metals and hydrocarbons. Pre-cast pavers over lattice slabs offer the dual advantages of on-site infiltration and easy maintenance. The inevitable accumulation of silt in the surface layers of the "reservoir" construction and "clay-bridging" between particles during wetting-drying cycles will lead to clogging and failure of the structure although minimum lifetimes for properly installed and maintained structures can be of the order of 10 to 15 years. The pre-cast blocks and modular pavement can be easily lifted allowing the underlying gravel bed layer and geotextile to be replaced before reinstating the paving surface.

Several researchers have reported that porous pavements with reservoir structures may be suitable for the control of both stormwater quantity and quality in regions with a cold climate (Hogland and Niemczynowicz, 1986; Hogland and Wahlman, 1990; Stenmark, 1995; Bäckström, 1999, Bäckström and Viklander, 2000). These studies found that the porous surface maintained its draining function during snowmelt and that the porous pavement was more resistant to freezing and frost actions in comparison to impermeable road constructions. However, Fujita (1994) has suggested that porous pavements should be constructed with drainage pipes to avoid the risk of damage during freezing.

5.2.4.2 Porous Asphalt and Whisper Concrete

Porous asphalt surfacing has become popular because it forms a highway surface which generates less vehicle noise; it reduces splash and spray and hence also reduces aquaplaning whilst enhancing driver visibility; and provides a durable, high-speed road surface. It can also perform a stormwater treatment function, with a study by Stotz and Krauth, 1994, reporting a retention of approximately 50% for suspended solids demonstrating its filtration ability.

Full scale trials are now taking place in the UK on a 2 km section of the M23 near Gatwick Airport of "whisper concrete" inlays to overcome the problem of rutting on asphaltic highway surfaces subject to heavy trafficking. Serious rutting of the inside lane of motorways and trunk roads can pose hazards due to increased risks of aquaplaning resulting from retained water as well as yielding increased solids, bitumen and oils to the surface runoff. The "whisper concrete" composition of the inlay makes it appear very similar to asphalt and it will reduce maintenance costs, extend durability and lifetime of the surface as well as reducing noise and combating the effects that any future increase in vehicle axle weights might have on highway life.

5.2.5 Street cleaning

Street cleaning is a common practice throughout Europe. However, the effectiveness of this process as a stormwater source control measure is unclear as the pollutant load conveyed by runoff remains very high and, in most instances, unacceptable in comparison with the quality-based objectives of receiving watercourses. Figure 5.4 shows the relative cleaning effectiveness of varying types of street sweeping procedures in the UK, based on field data for a NW London catchment. The build-up of sediment against the kerb edge is indicated as well as the lack of removal of the fine solids fraction (< 63?m), with which most of the pollutant load is associated, meaning that there is considerable deflationary re-distribution of fines back across the road surface as well as an almost infinite contaminated sediment “reservoir” available for stormwater transport to the roadside gully during wet weather events.

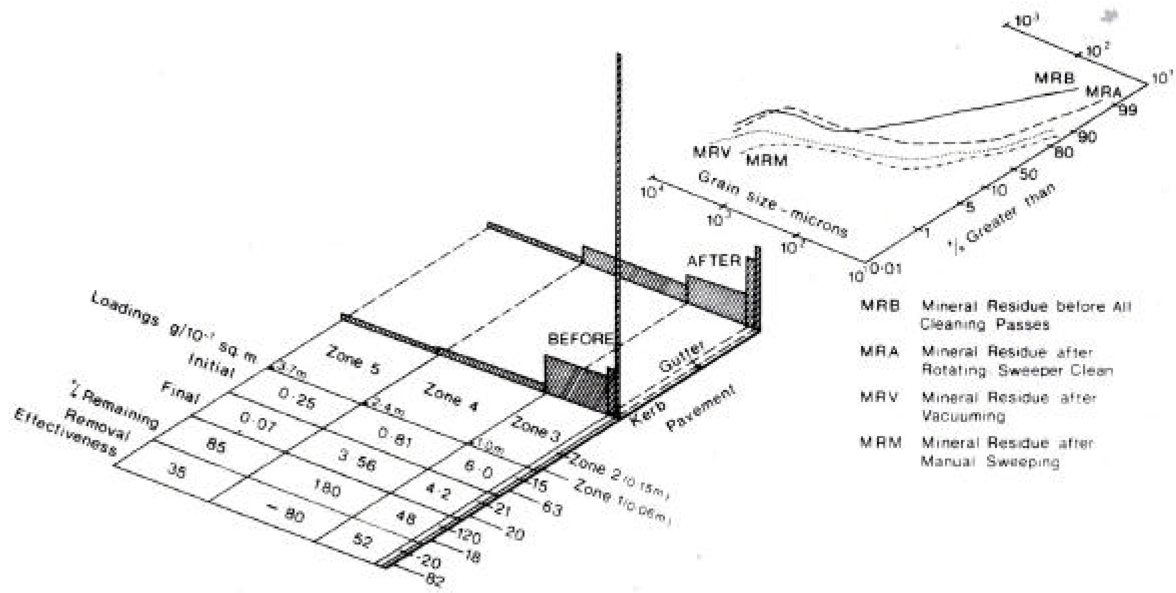

Figure 5.4 Street surface particulate distribution and cleaning effectiveness

Berga (1998) carried out a major study in the metropolitan area of Bordeaux, France, to determine the levels of pollution conveyed by rainfall and street-sweeping operations. Based on annual estimations of the average annual mass of sediment collected during conventional street sweeping and the total mass of solids discharged at the street outfall during a year, the split between street cleaning and storm runoff as conveyance processes for the removal of sediments in a street with a bi-monthly vacuum cleaning programme, dense urban traffic patterns and surfacing with a high level of micro-roughness was 55% and 45%, respectively.

The results of grain size distribution analyses of sediments accumulated on pavement surfaces indicated a very high proportion of fines (particles <100 µm) immediately after conventional vacuum cleaning. The lead, copper, cadmium and zinc contents of these sediments were found to be strongly correlated with particle size, with highest concentrations associated with particles <80 µm. The highest metal pollutant concentrations were therefore found immediately after vacuum cleaning with a decrease after a week of sediment accumulation. The study was not able to determine whether the very fine particles were capable of being conveyed by stormwater runoff, other than concluding that storm events occurring during the sampling period did not prevent sediments from "re-concentrating". The sediments collected by street cleaning equipment were also subjected to grain size distribution analyses. All of the sweeping debris samples collected contained a low level of fines.

As stormwater can mobilise surface sediments accumulating between two conventional street cleaning operations, increasing the frequency of street cleaning must be beneficial. The magnitude of this pollution conveyance depends not only on rainfall intensity and runoff flow rates, but also on the duration of the rainfall event. Following a durable wetting of pavement surfaces, sediments may even be mobilised by storm events of a low intensity, hence increasing the frequency of street-cleaning operations would not be sufficient unless the street cleaning equipment was capable of producing a comparable wetting capacity to that of rain in disaggregating sediments prior to suction but with an energy surpassing that of the rain.

German (2001) investigated the impact of increasing the frequency of street cleaning as a stormwater pollution control measure in Sweden. Samples were collected over a six week period: streets were swept daily for the first three weeks (sweeping period 1) and on work days only during the second three week period (sweeping period 2).

The collected data (Table 5.19) shows that the increased amount of sediment removed was not proportional to the increase in cleaning effort. There could also be problems in implementing intensive street cleaning as a pollution control measure due to the problem of parked cars and disturbance to traffic. In this study, sampling was carried out on a street where parking was not allowed. However, there are also advantages with street cleaning that have not been taken into account here, such as a decreasing need to use chemical weed control because of frequent mechanical brushing of the surface (German, 2001). Overall, Mikkelsen *et al.* (2002) concluded that street cleaning with modern sweeping equipment could be an effective pollutant control measure.

Table 5.19 Masses of removed particulate material and heavy metals in street sweeping sediment

Sweeping period	All (kg)	Sediments <0.25 mm (kg)	Cr (g)	Ni (g)	Cu (g)	Zn (g)	Pb (g)
1	37.9	6.3	0.4	0.1	1.5	1.2	0.2
2	46.6	10	0.5	0.2	2.5	2.5	0.4
1+2	84.5	16.3	0.9	0.3	4	3.7	0.6

An additional point is that interest in sustainability and recycling has increased the required levels of reuse of various materials, including sand or other substrates used to provide friction on roads during winter. However, swept sediments should not be re-used without taking into account their quality. For example, Viklander (1996) demonstrated that a large proportion of the pollutants present in snow stay in the sediments after snowmelt. Further work by the same author (Viklander, 1997) found that the levels of zinc and copper in a city centre exceeded the US EPA levels for dredged sediment disposal (USEPA, 1974). Some kind of treatment would therefore be necessary prior to reuse, for example, sieving to remove the smallest particle fractions which normally contain the highest concentration of metals. The characteristics of such sediments and their impact on the environment need further investigations before any recommendations can be given (Viklander, 1997).

5.2.6 Snow management

5.2.6.1 Transportation to snow deposits

Snow removed from streets and parking areas is normally either deposited on land or in water. If the snow is deposited directly into a watercourse all the substances contained in the snow can disperse into the water body. Particle-bound substances form sediments on the bottom, while the dissolved fractions tend to enter biological systems.

For snow which is transported to a land deposit, the dissolved substances generally leave the snow with the meltwater (Viklander, 994, Westerström,1995, Colbeck, 1981) which may have a different recipient to that of stormwater. Sediments, as well as the majority of particle-bound pollutants, remain at the surface of the deposit area i.e. gravel (Viklander, 1994, Lockery *et al.,* 1983), and studies have shown these sediments to be heavily contaminated (Droste and Johnston, 1993). Such sediments are either left for a long period of time, with the probable slow dispersion of substances into the environment, or are cleared from the deposit area and transported to another deposit such as a controlled landfill site or are re-used as filling material. The mobility of metals depends on a range of factors such as soil type, humus content, water quality and the geochemical environment. If the pH of the soil decreases, the capacity to attach metallic ions also decreases and adsorbed ions may be released. High salt concentrations are also known to decrease the adsorption of heavy metals. Milne and Dickman (1977) showed that the lead concentrations in sediments at a snow deposit area in Ottawa, Canada, were more than an order of magnitude greater than those of uncontaminated sediments. Research has also established that although some sodium chloride does leach from snow deposit soils during the summer months, the majority of both salt and lead continues to accumulate from year to year (Scott, 1980, Viklander *et al.*, 1998).

5.2.6.2 Treatment of meltwater

If the snow handling strategy set out in Section 4.1.16 is followed, the quantity of snow deposited will be significantly reduced but the snow that is deposited will contain higher levels of pollutants. If the meltwater from these deposits needs to be treated, it should not be directed to the municipality treatment plant since snowmelt can occur over a short period of time, generating large volumes of water which can inundate a treatment plant. Increases in the incoming flow to treatment plants of up to 300% have been reported during the melt period (Bengtsson *et al*., 1980). In addition, the meltwater has a low temperature (close to 0^{o}C) which has negative effects on both the efficiency of treatment as well as on the practical management of the plant. The concentrations of oil, other organic substances and heavy metals in meltwater differ from those in conventional sewage water, resulting in poor treatment and a risk that the sludge from the treatment plant could become contaminated by metals and hydrocarbons transported by the meltwater.

Another factor which must be taken into consideration is the possibility of infiltration into the ground below the snow deposit. The ground under the main snow deposit in Luleå, Sweden, was found to be partly thawed during the spring (Viklander, 1994), with the consequence that meltwater could, and probably did infiltrate. However, it was also noted that the water saturated soil caused a significant part of the meltwater to be transported as surface runoff. The optimal treatment system for meltwater will be dependent on a range of factors such as its typical characteristics, temperature, metals, hydrocarbons and salt content. During the melt period there are large variations in flow which will probably require some type of detention, but how this detention will affect the pollutants and particles transported in the meltwater has yet to be investigated (Viklander *et al.,* 1998)

5.2.6.3 Snow remaining within the city

Snow left in city centres and in housing areas may be classified into snow on cleared and uncleared surfaces. The meltwater from uncleared surfaces may run off into a storm water system, a local watercourse or infiltrate into the ground. Snow on a grass surface will result in the same environmental impact as rain. However, it should be emphasised that meltwater from a large grassed area, such as a park, could cause an acid shock impact due to the potentially large volume of runoff.

The cleared snow is either located on impermeable surfaces, grass surfaces or ditches. For snow on grass surfaces and in ditches, the pollutant pathways will be similar to those for a snow deposit. Meltwater from impermeable surfaces either enters the stormwater network or runs off directly to a receiving watercourse. The concentrations of pollutants in the snow will probably be considerably higher than the concentrations of pollutants in the meltwater that reach the drainage system. This is associated with melt intensity which largely determines the composition of the meltwater; during a long thaw period with low levels of flow, the particles are left at the ground surface, while short thaws with large flows carry the solids away from the street area. Sediments left on the road surface are either swept away, re-suspended in the air or carried away by the next storm event. Some of the sediments are swept up in spring when the snow has melted.

The pathways of snow, sediment and pollutants will not only depend on the snow handling strategy but also on the design of the city and the volumes of snow which differ from year to year. A consequence of the variation in snow volume is that the amount of snow transported to the snow deposits will vary, and consequently the paths of sediments and pollutants in the city also vary (Viklander *et al.,* 1998).

6 ENVIRONMENTAL ADVANTAGES AND SUSTAINABILITY ASPECTS

It is now widely recognised that urban stormwater BMPs must be referenced against those parameters related to all three functional elements of the sustainable urban drainage system triangle i.e. water quantity, water quality and ecology/amenity. Thus not only technical factors but environmental/ecological as well as social/community interests must be considered in the design of structural BMPs. Such integrated approaches to urban drainage involve a variety of stakeholders who need to work within a given planning and regulatory framework (Figure 6.1).

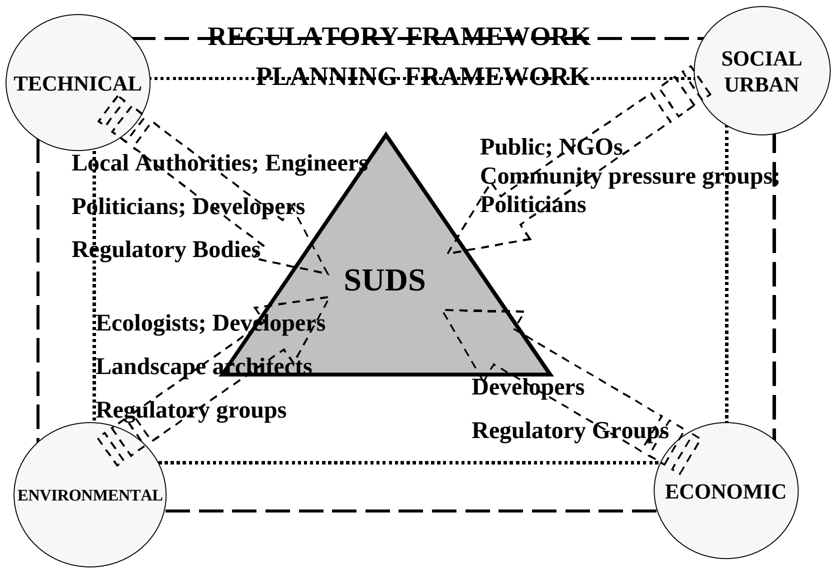

Figure 6.1 The BMP triangle and relation to stakeholder interest and sustainability criteria

In addition, the multi-disciplinary teamworking approach encouraged by BMPs makes it appropriate to evaluate the sustainability of BMP systems against the prime factors of technical, environmental, social/community and economic acceptability.

6.1 Environmental Advantages

In the UK, the 1991 Land Drainage Act and the 1995 Environment Act require that due consideration should be given to environmental conservation and enhancement in drainage improvement works and new development. Improved water quality and landscaping of urban BMP structures enhance aesthetic values for direct recreational and passive amenity use as well as encouraging local community stewardship although such intangible values for urban stormwater control and management are difficult to measure and cost. Nevertheless, it is generally accepted that landscaping and amenity upgrading associated with BMP structures will stimulate the perceived attractiveness of the wider surrounding drainage area. Figure 6.2 provides a qualitative matrix comparing the relative environmental opportunities offered by differing BMP options including wildlife, landscaping and amenity provision.

BMPs	**Receiving Water Low Flow Status**	**Aquatic Habitat Creation**	**Wildlife Habitat Creation**	**Landscape Enhancement**	**Recreational Benefits**	**Hazard and Safety Reduction**	**Aesthetics**	**Community Acceptance**
Extended detention basin	○	◌	◌	◌	◌	◌	◌	◌
Wet retention basin	○	●	●	●	●	◌	◌	●
Constructed wetland	◌	●	●	●	●	◌	●	●
Infiltration basin	●	○	○	◌	◌	●	○	◌
Porous paving	●	○	○	○	○	●	○	●
Grass swale	◌	○	◌	◌	○	●	◌	●
Grass filter strip	◌	○	◌	◌	○	●	◌	●

KEY ○ Seldom or never provided: ◌ Sometimes provided (but with careful design modification): ● Normally provided

Figure 6.2 BMP Environmental and Urban Community Amenities Evaluation Matrix

The potential environmental and community amenity benefits accruing from wetland BMP options are clear from the Figure 6.2 matrix although early consideration in the design and planning process is required if these benefits are to be actually achieved as they are difficult and costly to retrofit into existing structures. UK surveys, for example, have shown that public attitudes towards wetlands and wet retention basins are much more positive than for other BMP types, particularly with regard to valuing their wildlife and amenity benefits (Table 6.1). This is despite the fact that mean plant species richness of stormwater wetlands being some 20 – 40% less than “minimally impaired” ponds but is equivalent to ordinary countryside ponds (Ponds Conservation Trust, 2003). As shown in Table 6.1, the ecological value of wetlands receiving discharges from motorway areas and industrial estates is of much lower ecological standard than residential wetlands, with 12% of recorded plant species being alien and including highly invasive species such as *Crassula helmsii*. Overall there is little evidence that SUDS schemes are adding significant numbers of high quality ponds to the national landscape. In particular, there is a need to evaluate the ecological effectiveness of treatment train schemes and the significance of “standing water” SUDS schemes as national habitat resources.

Table 6.1 Conservation Value of Urban Wetlands

	M42 Hopwood Park MSA wetland	Milton Keynes Mount Farm Wetland	Welsh Harp (N London) wetland	Livingston Caw Burn (Industrial estate) wetland	Dunfermline (DEX Commercial Park) Wood Marsh
Invertebrates					
Number of species	37	58	40	24	38
Number of uncommon species	-	1	3	0	0
Conservation value	High	High	High	Moderate	High
Plants					
Number of native species	5 -13	24	17	13	25
Number of uncommon species	-	1	4	0	4
Conservation value	High	High	Moderate	Moderate	High

Sources: Welsh Harp Conservation Group, 1992; Milton Keynes Development Corporation, 1992; Pond Action, 2000; Bray, 2001b.

The matrix criteria identified in essentially relate to BMP stormwater systems intended for residential and or commercial/industrial use rather than to highway runoff systems where recreational, amenity and aesthetics are not seen as being of any major significance. The main difficulties indicated in the matrix are associated with health and safety and with downstream receiving water protection of low flow and thermal regimes where rapid changes in temperature due to incoming stormwater may present difficulties to fish and other aquatic species.

An example of the increasing influence of environmental issues and social considerations on stormwater management is illustrated by information from Sweden which suggests that the acceptance of vegetated systems as a stormwater control measure was partly because of low cost and partly because the public generally liked “green” solutions that could be incorporated into a natural landscape and also serve as public amenity areas.

Source control BMPs are seen as providing UK water companies, waterway authorities and the regulatory agencies with opportunities to “protect and improve” the urban environment and to make contributions towards achieving national Biodiversity Action Plans (BAPs). Water authorities for example, Severn Trent Water, have undertaken audits of their 20,000 hectare holdings to determine ecological value and to identify opportunities for conservation gain with the BAP process driving corporate targets as part of the wider need to meet future Water Framework Directive management plans. The Environment Agency has also developed a specific SUDS policy objective (Policy Number EAS/2/1/1) to achieve “*environmental enhancements, including improvements to wildlife habitats, amenity and landscape quality*”.

There are some concerns in the UK that the successful environmental/ecological development of BMP sites, as indicated in Table 6.1, could lead to formal planning designation as Special Protection Areas (SPAs), Special Areas of Conservation (SACs) or even Sites of Special Scientific Interest (SSSIs). Such designation might then prejudice their prime flood or water quality control functions especially in terms of required O&M activities. Whilst this might not be an immediate or even probable threat, it is much more possible that the EU Conservation of Wild Birds Directive (79/409/EEC) and the Habitats Directive (92/43/EEC) pose more serious and long term management problems. Even the presence of a protected bird, insect, invertebrate or floral species specified within the Directives within a BMP site would be sufficient to endanger the required management and O&M activities to maintain the drainage and/or water quality function of the BMP structure. The “blanket” application of such wildlife protection legislation would inevitably result in less BMPs and in existing BMP structures being operated and managed in such a way that the conservation value is minimised.

Table 6.2 attempts to evaluate a range of different types of stormwater control systems with regard to potential multifunctional use and cost.

Table 6.2 Evaluation of stormwater management systems with regard to multifunctional use and cost

Water Functions Techniques		Landscape	Swimming	Recreation	Fish farming	Irrigation	Animal watering	Industry	Perimeter water protection
Sweeping		????	????	????	????	????	????	????	????
Alternatives methods	**tank structure**		?	?	?	?	?	?	?
	porous coating		?	?	?	?	?	?	?
	trenches	??	??	??	??	??	??	??	??
	swale/ ditch	??	??	?	?	?	?	?	
Holding basins	**retention basin**	?	??	??	??	??	??	??	
	retention basin		???	????	????	????	???	???	
	underground tank		????	????	????	????	????	????	????
Roadside gully			???	???	???	???	???		
Decanters			???	???	???	???	???	???	

In developing this table the optimal decision making processes of the various stakeholders have been considered to enable the best solutions at the lowest possible cost to be identified. Qualitative decisions have been taken bearing in mind that the water may have contrasting functions such as landscaping, swimming, recreation, fish farming, irrigation, animal watering and industry, and the perimeter of water protection for groundwater uses. The chart uses shades of grey to indicate performance efficiency in comparison to determined objectives, and stars to indicate cost in relation to the level of treatment achieved (i.e. value for money).

6.2 Sustainability Aspects

The biggest challenge is to convince stakeholders and particularly customers and financial regulators, that full-cost water and drainage services will provide demonstrable sustainable whole-life investment. It must also be recognised that decisions in the field of urban stormwater runoff are no longer taken exclusively by drainage engineers; a variety of stakeholders need to be involved in the decision process in order that the preferred solution is acceptable to all user and interest groups (Figure 6.1). Unfortunately, the evaluation of BMP options for the control and treatment of polluted impermeable surface runoff has been, to date, mainly empirical and subjective in nature. There has been little development and application of robust quantifiable sustainability criteria and indicators. This is particularly the case in respect of the evaluation of long-term performance, life-time costing and receiving water impacts.

Methodologies are needed to support decisions taken on preferred drainage options which allegedly derive reduced costs for urban stormwater and highway drainage infrastructure whilst maintaining socially acceptable levels of service, enhancing community benefits and minimising environmental impacts. A basic structured approach to a multi-criteria, multi-objective methodology for the assessment of water resource systems was proposed within the 1998 UNESCO International Hydrological Programme (American Society of Civil Engineers & UNESCO, 1998). This study recommended a holistic conception of decision-making processes incorporating sustainability criteria and guidelines covering the economic, ecological, social and environmental factors which influence investment in and construction of water resource systems. Thus technical, environmental/ecological, social/community and economic factors become prime potential sustainability criteria to facilitate comparisons between, and accreditation of, drainage options with regard to capital cost, resource use, acceptability, performance, maintenance etc (Figure 6.1). It is therefore appropriate, if not necessary, to evaluate the sustainability of urban source control drainage systems against multi-criteria and multi-objectives placed within an overall decision-support framework.

The primary components in the structure of any decision-making process must reference and define generic performance criteria together with appropriate supporting multi-criteria decision-making parameters. Table 6.3 provides such a generic listing of primary criteria for the four categories shown in Figure 6.1 and which define the action field for BMPs. The listed criteria are sufficiently flexible and dynamic to be adapted and refined to meet changing circumstances and constraints within differing organisations, regulations and customers. The multi-criteria methodology must also be capable of evaluating the "do-nothing" option as well as that offered by conventional drainage systems. In addition, it must be recognised that the final decision may well be driven or at least constrained by specific local considerations and hence result in a preferred option which may not be the most sustainable.

Table 6.3 Primary criteria for assessing SUDS sustainability

SUSTAINABILITY CRITERIA	
CATEGORY	PRIMARY CRITERIA
TECHNICAL & SCIENTIFIC PERFORMANCE	System performance (Quality and Quality) System reliability System durability System flexibility and adaptability
ENVIRONMENTAL IMPACTS	Water volume impact Water quality impact Ecological impact Resource use Maintenance, service provision and responsibilities
SOCIAL AND URBAN COMMUNITY BENEFITS	Amenity; aesthetics, access and community benefits Public information; education and awareness Stakeholder acceptability (perception and attitude to risks and benefits Health and safety risks
ECONOMIC COSTINGS	Financial risks Affordability Life cycle costs

The primary criteria listed in Table 6.3 can be further sub-divided and developed by the use of secondary indicators and benchmark standards which allow the criteria to be quantified and compared against national sustainability targets. This sort of approach, if adopted, would not only be consistent with governmental sustainability agendas but also with complementary, multi-criteria methodologies which are being developed within the water industries of a number of countries to support water asset resource investment (Ashley *et al*., 2001).

7 REFERENCES

Abbott, C L., Weisgerber, A and Woods Ballard, B. (2003) Observed hydraulic benefits of two UK permeable pavement systems. 101 – 111 in C J Pratt., J W Davies., A P Newman and J L Perry (Edits): *Proc 2nd Nat. Conf. on Sustainable Drainage*. Coventry University, Coventry.

Ashley, R M., Smith, H., Jowitt, P W., Butler, D., Blackwood, D J., Davies, J W., Gilmour, D and Foxon, T. (2001) A multi-criteria analysis/risk management tool to assess the relative sustainability of water/wastewater systems: SWARD (Sustainable Water Industry Asset Resource Decisions). 221 – 231 in C J Pratt., J W Davies and J L Perry (Edits): *Proc. 1st Nat. Conf. on Sustainable Drainage*. Coventry University, Coventry.

Anchorage Bowl OGS Performance Modelling, Document No. WMP AP r98002, Municipality of Anchorage Watershed management Program, December 1999

ATV-A 138 (2002) ATV-Arbeitsblatt A138: Planung, Bau und Betrieb von Anlagen zur Versickerung von Niederschlagswasser, Januar 2002.

Azzout, Y., Barraud, S., Cres, F N and Alfakih, E. (1994) Techniques alternatives en assainissement pluvial: Choix, conception, realisation et entretien" Tex et Doc, Lavoisier, Paris. 371pp.

Bäckman, H. (1984) A historical perspective on sewage pipes in Swedish cities (Avloppsledningar i svenska tätorter I ett historiskt perspektiv). Geohydrologiska forskningsgruppen, Meddelande nr 74, Chalmers University of Technology, Gothenburg, Sweden. (In Swedish).

Bäckström, M. (1999) Porous pavement in a cold climate. Licentiate thesis 1997:21, Division of Sanitary Engineering, Lulea University of Technology.

Bäckström, M. and Viklander, M. (2000). Integrated stormwater management in cold climates. Journal of Environmental Science and Health, Vol. A35, No. 8, 1237-1249.

Bäckström, M. (2002). Grassed Swales for Urban Storm Drainage. Doctoral thesis 2002:06. Division of Sanitary Engineering, Luleå University of Technology, Luleå, Sweden.

Baladès J.D. and Petitnicolas F. (2001) Les strategies de reduction des flux pollutants par temps de pluie a la source: approche technico-economique. Novatech, pp367 – 373.

Baladès, J.D., Cathelain, M., and Marchandise, P. (1985) Chronic pollution of intercity motorway runoff waters. Water Science and Technology 17 (6-7): 1165-1174.

Baladès J.-D., Bourgogne P., Madiec H. (1992). Evaluation des flux de pollution transitant dans un type de solution compensatoire. Conf. Novatech, Lyon, pp. 66-75.

Woods Ballard, B. and Malcolm, M. (2003) Whole life costing for sustainable drainage schemes, p181-192 in C J Pratt, J W Davies, A P Newman and J L Perry (Edits): Proc 2nd Nat.Conf. on Sustaoinable Drainage. June 2003. Coventry University, Coventry.

Baptista, M., Barraud, S. and Alfakih, E. (2001) Analyse de donnees pour l’elaboration d’indicateurs technico-economique de systemes alternatifs en assainissement pulvial. Novatech pp63-70.

Barker, J., Burgess, W., Fellman, L., Licha, T., McArthur, J. and Robinson, N. (1999) The Impact of Highway drainage on Groundwater Quality. Rs Report No. 3, Jackson Env Inst., University of East Anglia, Norwich, ISSN 1465-458X.

Barret, M.E., Walsh, P.M., Malina, J.F. and Charbeneau, R.J. (1998). Performance of vegetative controls for treating highway runoff. Journal of Environmental Engineering, Vol. 124, No. 11, pp. 1121-1128.

Bengtsson, L., Johnsson, A., Malmqvist, P.-A., Särner, E., and Hällgren, J. (1980). Snöhantering i tätort. [Snow handling in built-up areas.], BFR report R 27:1980, The Swedish Council for Building Research, Stockholm. ISBN 91-540-3191-5. [In Swedish]

Berga P. (1998) Optimisation du nettoyage des voiries, Rapport CETE du Sud-Ouest, Ministère de l'Equipement, Bordeaux, 40 p.

Bergue, J-M. and Ruperd, Y. (1994) Guide Technique des Bassins de Retenue d'Eaux Pluviales. Tec et Doc, Lavoisier, Paris.

Bray, R. J. (2001) Environmental monitoring of sustainable drainage at Hopwood park Motorway Service Area M42 Junction 2. 58 – 70 in C J Pratt, J W Davies and J L Perry (Edit): Proc.1st Nat. Conf on Sustainable Drainage. Coventry University, Coventry.

Bray, R. J. (2001b) Maintenance of Sustainable Drainage; Experience on two EA Demonstration Sites in England. 93-104 in C J Pratt, J W Davies and J L Perry (Edits): Proc. 1st Nat. Conf on Sustainable Drainage. Coventry University, Coventry.

Bray, R J. (2003) Sustainable drainage solutions for local authority school sites. 51 – 61 in C J Pratt., J W Davies., A P Newman and J L Perry (Edits): *Proc 2nd Nat. Conf. on Sustainable Drainage*. Coventry University, Coventry.

BRE, (1991) Soakaway Design. Digest 365. Building Research Establishment, Garston, Watford, Herts.

Caraco, D. and Claytor R. (1997) Stormwater BMP Design Supplement for Cold Climates. Center for Watershed Protection, Ellicott City, Maryland, USA.

Cathelain, H., Friant, G. and Olie, J.L. (1981) Les Eaux de Ruisellement de Chaussees Autoroutieres. Bull. Liason de Labs. Des Ponts et Chaussees, 116, 9-24

CERTU (1999). Chaussées Poreuses Urbaines. Guide technique. Ministère de l'Equipement-CERTU Ed., Lyon, 150 pp

CIRIA. (Hall, M J., Hockin, D L and Ellis, J B) (1993) Design of flood storage reservoirs. Butterworth-Heinemann (also CIRIA), London.

CIRIA. (Butler, D and Clark, P). (1995) Sediment management in urban drainage catchments. Report 134. Construction Industry Research & Information Association, London.

CIRIA (1996) Sustainable urban runoff management. Report 20. Construction Industry Research & Information Association, London.

CIRIA, (1996) Infiltration Drainage: Manual of Good Practice, Report 156, Construction Industry Research & Information Association, London.

CIRIA (1998) Report 180 Review of the Design and Management of Constructed Wetlands

CIRIA (2000a) Sustainable urban drainage systems: A design manual for Scotland and N Ireland. Report C521, Construction Industry Research & Information Association, London.

CIRIA (2000b) Sustainable urban drainage systems: A design manual for England & Wales. Report C522, Construction Industry Research & Information Association, London.

CIRIA (2001) Sustainable urban drainage systems: Best Practice Manual. Report C523, Construction Industry Research & Information Association, London.

CIRIA (2002) Source control using constructed pervious surfaces. Report C582, Construction Industry Research & Information Association, London.

Claytor, R.A. and Scheuler, T.R. (1996) Design of stormwater filtering systems. Center for Watershed Protection, for the Chesapeake Research Consortium Inc.

Colandini, V. (1997). Effets des structures réservoirs à revêtement poreux sur les eaux pluviales : Qualité des eaux et devenir des métaux lourds. Thèse de Doctorat, Université de Pau et des Pays de l'Adour, 171 pp.

Colebeck, S. C. (1981) A simulation of the enrichment of atmospheric pollutants in snow cover runoff. Water Resources Research, 17(5): 1383-1388.

Coyne, M.S., Gillfillen, R.A., Villalba, A., Zhang, Z., Rhodes, R., Dunn, L., and Blevins, R.L. (1998). Fecal bacteria trapping by grass filter strips during simulated rain. Journal of soil and Water Conservation, Vol. 53, No. 2, pp. 140-145.

Deletic, A., (1999). Sediment behaviour in grass filter strips. Water Science and Technology, Vol. 39, No. 9, pp.129-136.

Deschesne, M. (2002) Connaissance et modélisation du fonctionnement des bassins d'infiltration d'eaux de ruissellement urbain pour l'évaluation des performances techniques et environnementales sur le long terme.

Design Manual for Roads and Bridges (1998) Water Quality and Drainage, Volume 11, Section 3, Part 10.

Design Manual for Roads and Bridges (2001) Vegetative Treatment Systems for Highway Runoff, Volume 4.

Didier, G. and Norotte, V. (1999) Assainissement pluvial : par infiltration : acquisition de connaissances, nouveaux procédés de traitement pour l'aide au choix, à la conception et à la gestion de politiques d'infiltration. Rapport final de coordination du programme de recherche (génie urbain et environnement).

Droste, R.L., and Johnston, J.C., (1993) Urban snow dump quality and pollutant reduction in snowmelt by sedimentation, Canadian Journal of Civil Engineering, 20: 9-21.

Ekvall, J. (1998): Rening av vägdagvatten med lamellavskiljare. Stockholm Vatten AB, Rapport nr 46/1998. (In Swedish with an English summary).

Ellis, J. B. (1999) The use of vegetative controls for the treatment of highway discharges in Ellis, J.B. (Edit): Impacts of Urban Growth on Surface and Groundwater Quality, pp 357-363. Publication No. 259, IASH Press Ltd, Wallingford.

Ellis, J B and Revitt, D M. (1991) Drainage for roads: Control and treatment of highway runoff. Report NRA 43804/MID.012, National Rivers Authority, Reading.

Ellis, J B., Shutes, R B and Revitt, D M. (2000) Best Practice in the Use of Constructed Wetlands for Pollution Control. R&D Project Report P-2-159, Environment Agency, Reading, Berks.

Environment Agency (2003) Technical Report P2-159/TR1 Constructed Wetlands and Links with Sustainable Drainage Systems.

Environment Agency (2003) Framework for Sustainable Drainage Systems (SUDS) in England and Wales.

Färm, C., and Renman, G. (1999): Removal of pollutants from road runoff - The Vallby system in Sweden. 8ICUSD, Sydney, Australia, 1841-1846.

Färm, C. (2003) Investigation of detention systems for stormwater runoff regarding maintenance, operation and handling of sediments. 1st International Conference on Urban Drainage and Highway Runoff in Cold Climate, Riksgränsen Sweden, pp 213-221

Ferguson, B.K. (1998) Introduction to stormwater – concept, purpose, design. John Wiley & Sons.

Finley, S.M. and Young, G.K. (1993) Grassy swales to control highway water quality runoff. Transportation Resrarch Record, No. 1420, U.S. Transportation Research Board.

Fransson, T. and Larm T., (2000) Dimensionerande förutsättningar för hantering av vägdagvatten. PM VBB VIAK, Stockholm. (In Swedish)

Fujita, S. (1994) Infiltration structures in Tokyo. Water Science and Technology30 (1): 33-41.

Gautier, A. (1998) Contribution à la connaissance du fonctionnement d'ouvrages d'infiltration d'eau de ruissellement pluvial urbain, Thèse INSA, Lyon, France.

German, J. (2001): Stormwater sediments, removal and characteristics. Licentiate Thesis, Department of Water Environment Transport, Chalmers University of Technology, Göteborg, Sweden.

German, J., Svensson, G., Gustafsson, L.-G. and Vikstrom, M. (2003) Modelling of temperature effects on removal efficiency and dissolved oxygen concentrations in stormwater ponds. 1st International Conference on Urban Drainage and Highway Runoff in Cold Climate, Riksgränsen Sweden, pp 223-233.

Goransson, K. and Jonsson, H. (1990). Environmental influence from using porous top pavement - a literature study. VATTEN 46:27-35. (In Swedish)

Granger, R.J., Gray, D.M. and Dyck, G.E. (1984) Snowmelt infiltration to frozen prairie soils. Canadian Journal of Earth Science, 21(6): 669-677.

Hall, M. J., Hockin, D.L. and Ellis, J.B. (1993) Design of Flood Storage Reservoirs. CIRIA, London)

Hogland, W. and Niemczynowicz, J. (1986) The unit superstucutre – A new construction to prevent groundwater depletion. Proc. Budapest Symposium on Conjunctive Water Use, July 1996. IAHS publ. No. 156.

Hogland, W. and Wahlman, T. (1990) The unit superstructure – effects on hydrology and road construction. Report R90:1990, Swedish Council for Building Res., (In Swedish).

Hogland W., Niemczynowicz J., and Wahlman T. (1987) The unit superstructure during the construction period. Sci. Total. Environ., 59, pp. 411-424.

Hvitved-Jacobsen, T., Johansen N.B. and Yousef Y.A. (1994). Treatment system for urban and highway runoff in Denmark. The Science of the Total Environment 146/147, s. 499-506.

Jefferies, C., McKissock, G M., Logan, F., Gilmour, D and Aitken, A. (1998) Preliminary Report on Swales in Scotland. Scottish SUDS Working Party, SEPA (SNIFFER), Edinburgh.

Jokela, J.B. and Bacon T.R. (1990) Design of urban sediment basins in Anchorage. Cold regions Hydrology and Hydraulics, American Society of Civil Engineers, NY, pp.761-789.

Kellagher, R. (2002) Guide for the drainage of development sites. HR Wallingford

Kercher, W.C., Landon, J.C., and Massarelli, R., (1983). Grassy swales prove cost-effective for water pollution control. Public Works, USA, 1983, Vol. 114, No. 4, pp.53-54.

Lännegren, C. (1998) Flemingsbergsvikens våtmarksanläggning. Erfarenheter och drift under de tre första åren. Stockholm vatten. (In Swedish).

Larm, T, (1994). Dagvattnets sammansättning, recipientpåverkan och behandling. VA-FORSK rapport nr 1994-06. (In Swedish)

Larm, T. (2000). Watershed-based design of stormwater treatment facilities: model development and applications. Doctoral Thesis, Division of water Resources Engineering, Royal Institute of Technology, Stockholm, Sweden.

Legret, M., Colandini V., and Le Marc C. (1996) Effects of a porous pavement with reservoir structure on the quality of runoff water and soil. Sci. Total. Environ., 189/190, pp. 335-340

Legret, M. and Colandini V. (1999). Effects of a porous pavement with reservoir structure on runoff water : water quality and fate of heavy metals. Wat. Sci. Technol., 39, pp.111-117.

Li, J., Orland, R., and Hogenbirk, T. (1998). Environmental road and lot drainage designs : alternatives to the curb-gutter-sewer system. Canadian Journal of Civil Engineering, 25, pp. 26-39.

Lindwall, P. and Hogland, W. (1981). Operation aspects on stormwater infiltration. BFR report R14:1981. Swedesh Council for Building Research. (In Swedish).

Livingstone, E., Cox, J., Sanzone, P. and Gourlie, N. (1984) The Florida Development Manual: A Guide to Sound Land and Water Management. Florida Department of Environmental Regulation, Tallahassee, Florida, USA.

Local Authorities Associations. (1989) Highway Maintenance: A Code of Good Practice. Association of County Councils, London.

Lockery, A.R., Gavrailoff, T., and Hatcher, D. (1983) Lead levels in snow dumping sites along rivers in downtown Winnipeg, Manitoba, Canada, Journal of Environmental Management, 17: 185-190.

Lönngren, G, (1995) Våtmark: renare vatten och renare liv. MOVIUM, Sveriges Lantbrukaruniversitet, Alnarp. (In Swedish)

Malmqvist, P-A. (1985) Environmental effects of snow disposal in Sweden. Proc. Of Workshop Minimizing the Environmental impact of the Disposal of Snow from Urban Areas, June 11-12, 1984. Report EPS 2/UP/1, October 1985. ISBN 0-662-14390-6

Marsalek, P.M. (1997) Special characteristics of an on-stream stormwater pond: winter regime and accumulation of sediment and associated contaminants. M.Sc. thesis, Dept. of Civil Engineering, Queen's University, Kingston, Ontario, Canada.

Marsalek, J. (2003) Road salt in urban stormwater: an emerging issue in stormwater management in cold climates, 1st International Conference on Urban Drainage and Highway Runoff in Cold Climate, Riksgränsen Sweden, pp 65-74

Mikkelsen, P. S., Adeler, O.F., Albrechtsen, H.-J. & Henze, M. (1999). Collected rainfall as a water source in Danich households – what is the potential and what are the cost? Wat. Sci. Tech. 39, (5), 49-56

Mikkelsen, P. S., Viklander, M., Linde J. J., Malmqvist P-A., (2002) BMPs in Urban Stormwater Management in Denmark and Sweden. Proc. Eng. Fnd. Conf. Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation, Aug 19-24 2001, Snowmass Village, Colorado/USA, pp 354-368. American Society of Civil Engineers.

Milne J. B., and Dickman M. (1977) Lead concentrations in algae and plants grown over lead contaminated sediments taken from snow dump in Ottawa, Canada, Journal Environmental Science Health, A12(4/5): 173-189.

Milton Keynes Development Corporation (1992) Monitoring Studies of Milton Keynes Balancing Lakes. Vols 1-6. Urban Pollution Research Centre, Middlesex University. Milton Keynes Development Corporation, Milton Keynes.

Möller, J. (2001) Treatment systems for urban runoff water in Ørestad. M.Sc. thesis (in preparation). Environmetn & Resources DTU, Technical University of Denmark.

Montes, S. (1998) Hydraulics of open channel flow. American Society of Civil Engineers, Usa, ISBN 0-7844-0357-0.

Newman, A P., Pratt, C J., Coupe, S J and Cresswell, N. (2001) Oil bio-degradation in permeable pavements by inoculated and indigenous microbial communities. 425 – 432 in C J Pratt, J W Davies and J L Perry (Edits): Proc 1st. Nat. Conf on Sustainable Drainage. Coventry University, Coventry.

Newman, A P., Shuttleworth, A., Puehmeier, T, Wing Ki, K and Pratt, CJ. 2003. Recent developments in oil retarding porous pavements. 81 – 89 in C J Pratt., J W Davies., A P

Newman and J L Perry (Edits): Proc 2nd Nat. Conf. on Sustainable Drainage. Coventry University, Coventry.

Novotny, V., Smith, D.W., Kuemmel, D.A. Mastriano, J. and Bartosova, A. (1999) Urban and Highway Snowmelt: Minimising the Impact on Receiving Water. Water Environment Research Foundation, (WERF) Project 94-IRM-2.

NSWG (2003) Framework for sustainable drainage systems (SUDS) in England & Wales. Environment Agency, Bristol.

Oberts, G.L. and Osgood, R.A. (1988) Lake McCarrons Wetland Treatment System: Final report on the function of the Wetland Treatment System and the impacts on lake McCarrons. Metropolitan Council, St. Paul, Minnesota, publication No. 590-88-095, 227pp.

Oberts, G.L., Wotzka, P.J. and Hartsoe, J.A. (1989) The Water Quality Performance of Select Urban Runoff Treatment Systems. Metropolitan Council, St. Paul, Minnesota, publication No. 590-89-062a, 170pp.

Oberts, G.L. (1990) Design considerations for management of urban runoff in wintry conditions. In Proceedings, International Conference on Urban Hydrology under Wintry Conditions, Narvik, Norway.

Oberts, G.L. (1994) Influence of snowmelt dynamics on stormwater runoff quality. Watershed Protection Techniques, 1(2):55-61.

Oberts, G.L. and Osgood, R.A. (1991) Water quality effectiveness of a detention wetland treatment system and its effect on an urban lake. Environmental Management 15 (1): 131-138

Perry, R. and McIntyre, A. E. (1986) Impact of motorway runoff upon surface water quality. In J F Solbe (Edit): Effects of Land Use on Freshwater. Pp 53-67 Ellis Horwood Ltd., Chichester.

Persson, (1999). Hydraulic efficiency in pond design. Thesis for the degree of Doctor of Philosophy. Department of Hydraulics, Chalmers University of Technology, Göteborg, Sweden.

Pettersson, T.J.R. (1996) Pollution reduction in stormwater detentions ponds. Chalmers University of Technology, Sweden, Dep. Of Sanitary Eng., Licentiate theses, Report 1996:3.

Pettersson, T.; German J.; Svensson, G. (1999) Pollutant removal efficiency in two stormwater ponds in Sweden. Proc. 8th Int. Conf. on Urban Storm Drainage, Sydney, Australia.

Pichon, A. (1993). Colmatage de milieux poreux en génie civil : cas des enrobés drainants de l'autooute du Nord, LMSGC LCPC/CNRS, thèse de doctorat, Université Paris VI.

Pokrajoc, D and Deletic, A. (2002) Clogging of infiltration drainage systems. In *Proc SOM 2002*, 26 – 28 November 2002, University of Bradford, Bradford.

Pond Action (2000) An Assessment of the Ecological Value of Sustainable Urban Drainage Systems in Scotland. report by Pond Action, Oxford Brookes University. Scottish Environment protection Agency, Stirling.

Ponds Conservation Trust (2003) Maximising the ecological benefits of SUDS schemes. Ponds Conservation Trust, Oxford Brookes University, Oxford.

Pratt. C J. (1995) Infiltration drainage: Case studies of UK practice. Project No. 22, Construction Industry Research and Information Association, London.

Pratt, C J. (1996) Research and Development in Methods of Soakaway Design. J. Insy. Water and Env Mangt, 10, 47-51.

Price, M., Arkinson, T.C., Barker, J.A. and Monkhouse, R.A. (1992) A tracer study of the danger posed to a chalk aquifer by contaminated highway runoff. Proc. Inst. Civil. Eng., (Water, Maritime and Energy), 96, 9-18.

Prosser, I.P., Dietrich, W.E., and Stevenson, J. (1995). Flow resistance and sediment transport by concentrated overland flow in a grassland valley. Geomorphology, Vol. 13, pp.71-86.

Raimbault, G. and Métois, M. (1992) Le site experimental de structure réservoir de Rezé. Conf. Novatech, Lyon, pp. 213-222.

Raimbault G. (1992) Structures réservoirs et topographie des aménagements urbains. Conf. Novatech, Lyon, pp. 400-409.

Raimbault G., Nadji, D. and Gauthier, C. (1999). Stormwater infiltration and porous material clogging. 8th ICUSD, Sydney, pp. 1016-1024.

Ranchet, J. and Ruperd, Y. (1983) Moyens d’Action pour la Pollution due aux Eaux de Ruisellement en Systeme Seperatif et Unitaire. Trib. Cebedeau, 36, 117-130.

Ranchet J., Penaud F., Le Grand R., Constant A., Oborg P., Soudien B. (1993). Comparaison d'une chaussée pavée et d'une chaussée drainante du point de vue de leur comportement hydraulique et de leur impact sur la dépollution des eaux de pluie. Bull. Liaison Labo P. et Ch., 188, pp. 67-72.

Revitt, D.M. and Ellis, J.B. (2001) Drainage, Runoff and Groundwater. 67 – 102 in : Guidelines for the Environmental Management of Highways. Institution of Highways & Transportation, London.

Revitt, D.M., Ellis, J. B. and Llewellyn, N.R. (2002) Seasonal removal of herbicides in urban runoff. Urban Water 4, 13-19.

Rosen, K. (1996) Försöksanläggning för rening av dagvatten vid sjön Magelungen - Resultat efter tre års drift 1993-1995. Stockholm vatten.

Ruperd (1987) Efficacite des ouvrages de traitement des eaux de Ruisellement. Service Tech. L’Urbanisme, Div Equip Urbains, Paris, France.

Sansalone, J.J. and Buchberger, S.G. (1996) Characterisation of metals and solids in urban highway winter snow and spring rainfall runoff. Trans Res Record, 1523: 147-159.

Scholz, M. (2003) Design, operation and maintenance optimization of sustainable urban stormwater ponds. 31 – 41 in C J Pratt., J W Davies., A P Newman and J L Perry (Edits): Proc 2nd Nat. Conf. on Sustainable Drainage. Coventry University, Coventry.

Schueler, T. (1987) Controlling urban runoff. Met Washington Council of Governments, Washigton DC.

Schueler, T. (1992) Design of stormwater wetland systems: guidelines for creating diverse and effective stormwater wetland in the mid-Atlantic Region. Metropolitan Washington Council of Governments, Washington, DC. USA.

Schwab, G.O. and Frevert, R.K. (1985) Elementary soil and water engineering. John Wiley and Sons, Inc.

Scott, W.S., (1980) Occurrence of salt and lead in snow dump sites, Water, Air and Soil Pollution, 13: 187-195.

SEPA, (1990) Snöupplag, lokalisering och drift, [Snow deposits, location and operation], The Swedish Environmental Protection Board, Report 3785. [In Swedish]

SEPA, (1997) Guidance document for evaluation of surface water best management practices. Draft May 1997. Prepared for Scottish Environment Protection Agency (SEPA) by Sir Frederick Snow & Partners Ltd and Camp Dresser & McKee Inc.

SEPA, (1997) Urban Best Management Practice Database. Tech. Report EQI, 17 December 1997, (G.McKissock), Scottish Environment Protection Agency, East Region, Edinburgh.

SNRA (1990) (Swedish National Road Administration) (1990). Hydraulic design of ditches, culverts, pipes, and basins. Swedish National Road Administration, publication 1990:11. (In Swedish).

SNRA (Vägverket), (1998) Rening av vägdagvatten – Preliminära råd vid dimensionering av enklare reningsanläggningar. Samarbetsprojekt mellan Vägavd. vid Vägverket i Borlänge och Statens geotekniska institut (SGI). (In Swedish).

Söderlund, G. (1972). Stormwater treatment by a vegetated ditch. Research report, Allmänna Ingenjörsbyrån, Stockholm, Sweden, October, 1972. (In Swedish).

Stahre and Urbonas, B. (1990) Stormwater detention for drainage, water quality and CSO management. Prentice-Hall, New Jersey, United States.

Stahre and Urbonas, B. (1993). Stormwater. Best management practices and detention for water quality, drainage and CSO management. PTR Prentice Hall, Englewood Cliffs, New Yersey, USA.

Stenmark, C. (1991) The function of a percolation basin in a cold climate. Proc. 5th Int. Conf. In Urban Storm Drainage, Suita, Osaka, Japan, July 1990, 809-814.

Stenmark, C. (1992) Local disposal of storm water in cold climate. Licentiate Thesis 1992:24, Luleå University of Technology.

Stenmark, C. (1995) An alternative road construction for stormwater management in cold climates. Water Science and Technology, 32(1): 79-84.

Stotz, G. and Krauth, K. (1994). The pollution of effluents from pervious pavements of an experimental highway section : first results. Sci. Total Environ., 146-147, pp. 465-470.

Thelen E., Fielding, and Howe L. (1978) Porous pavement, The Franklin Institution Press. Philadelphia, Pensylvania.

Urbonas, B., Guo, and Tucker, (1990). Optimization of stormwater quality capture volume. Proceeding of an Engineering Foundation Conference, ASCE, October 1989 in Switzerland, Published in New York, Urban stormwater quality enhancement.

Urbonas, B., Roesner, and Guo (1996). Hydrology for optimal sizing of urban runoff treatment control systems. Water quality International, January/February 1996, London, England.

Urban Drainage and Flood Control District (1999) Urban storm drainage. Criteria manual. Volume 3 – best management practices. Denver, Colorado. USA

US EPA, (1974) Proposed guidelines for determining acceptability of dredged sediments disposal in EPA Region VI., Dallas, USA.

VAV P46, (1983) Lokalt omhändertagande av dagvatten – LOD. Anvisningar och kommentarer. Svenska vatten- och avloppsverksföreningen, VAV. (In Swedish).

Viklander, M. (1994) Melting of urban snow deposits. A water quality study. Licentiate Thesis, 1994:19L, Division of Sanitary Engineering, Luleå University of Technology, Luleå, Sweden.

Viklander, M. (1996) Urban Snow Deposits - pathways of pollutants, The Science of the Total Environment, 189/190: 379-384.

Viklander, M. (1997). Snow quality in urban areas. Doctoral thesis 1997:21. Division of Sanitary Engineering, Luleå University of Technology, Luleå, Sweden.

Viklander, M. (1997) Particle Size Distribution and Metal Content in Street Sediments in the City of Luleå Sweden, Doctoral thesis 2002:06, Division of Sanitary Engineering, Luleå University of Technology, Luleå, Sweden.

Viklander, M., Bäckström, M. and Malmqvist, P-A. (1998) Ecological storm water handling in cold climate. Unpubl., report. Luleå University of Technology.

Viklander, M. (1999) Dissolved and particle-bound substances in urban snow. Water Science and Technology 39(12): 27-32.

Walker, N. (2000) Retrofitting SUDS to sure CSO and flooding problems. Hydro International Ltd Conference, 19 October 2002, Bradford.

Walsh, P.M., Barrett, M.E., Malina, J.F. and Charbeneau, R.J. (1997). Use of vegetative controls for treatment of highway runoff. Online report 97-5. Center for Research in Water Resources, The University of Texas at Austin, USA

Wang, T., Spyridiakis, D.E., Mar, B.W., and Horner, R.R. (1981). Transport, deposition and control of heavy metals in highway runoff. Washington State Dept. of Transportation, Seattle, WA.

Watt, W.E., Marsalek, J. and Anderson, B.C. (1997) Stormwater pond perceptions vs. realities: a case study. Proc. Eng. Foundation Conference Sustaining urban water resources in the 21st century, September 7-12, 1997, Malmö, Sweden.

WEF and ASCE, (1998) Urban runoff quality management. WEF manual of practice No. 23. ASCE manual and report on engineering practice No. 87. WEF, Water environment Federation and ASCE, American Society of Civil Engineers. USA.

Welsh Harp Conservation Group (1992) Annual Report. London Borough of Barnet, Herts.

Westerström, G. (1995) Chemistry of snow melt from an urban lysimeter, Water Quality Research Journal Canada, 30(2): 231-242.

Wild, T C., Jefferies, C and D'Arcy, B J. (2002) SUS in Scotland; The Scottish SUDS database. Final report SR (02)09. SNIFFER, 11/13 Cumberland Street, Edinburgh.

Wild, T C, McKissock, G., D'Arcy, BJ, Shaffer, D and Elliott, C. (2003) An evaluation of SUDS guidance in Scoitland. 1 – 12 in C J Pratt., J W Davies., A P Newman and J L Perry (Edits): Proc 2nd Nat. Conf. on Sustainable Drainage. Coventry University, Coventry.

Woods Ballard, B and Malcolm, M. (2003) Whole life costing for sustainable drainage schemes. 181 – 192 in C J Pratt., J W Davies., A P Newman and J L Perry (Edits): Proc 2nd Nat. Conf. on Sustainable Drainage. Coventry University, Coventry.

WRc (1996) Reed Beds and Constructed Wetlands for Wastewater Treatment

Yu, S. L. and Benelmouffok, D. (1990) Field tests of urban best management practices for controlling stormwater pollution. 805 – 808 in Y Iwasa and T Sueishi (Edits): Proc 5th Int. Conf. On Urban Storm Drainage. Oasaka, Japan.

Yu, S. L., Norris, W. K. and Wyant, D. C. (1987) Urban BMP demonstration project in the Albemarle/Charlottesville area. Final Report to Virginia Department of Conservation and Historic Resources, University of Virginia, Charlottesville, Virginia.

Yu, S. L., Kuo, J.T., Fassman EA, (2001) Field test of a grassed-swale performance in removing runoff pollution. Journal of Water Research PL-ASCE127 (3): 168-171.