Natural flood management (NFM) knowledge system: Part 1 - Sustainable urban drainage systems (SUDS) and flood management in urban areas

Final Report

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Contents

Executive Summary

This report, one of three reports produced for CREW to verify the current state of knowledge on NFM, focuses on establishing the effectiveness of SUDS measures for flood management in urban areas, particularly in relation to performance under saturation conditions and long term efficiency as a device becomes established.

Although it is explicitly recognised that SUDS can also deliver water quality and amenity benefits, this report focuses only on runoff detention and retention. Specifically, this report examines the performance of devices with high or moderate potential for runoff volume reduction in detail (green roofs, rainwater harvesting, pervious paving, infiltration devices and swales), reviewing the available evidence relating to the impact that these different SUDS measures have on managing flood scenarios.

The review focused on SUDS performance with respect to the following key hydrological processes:

1. Retention - where flow is not passed forward (including infiltration)
2. Detention/attenuation – temporarily slowing or storing runoff.
3. Conveyance - the transportation of surface runoff away from the original source
4. Water harvesting - the direct capture and use of water from its source.

A key outcome of the review has been to highlighted the uncertainty associated with the performance of SUDS devices. In some case this is due to the contrasting research methodologies and metrics. However, equally significant is the design, maintenance and catchment characteristics associated with the devices considered.

The research review also found that, regardless of the SUDS device considered, a number of environmental factors influence the performance of the device in managing runoff:

- The length of any preceding dry period: saturated systems are less efficient.
- The prevailing climate: devices perform differently in hot and cold climates depending on air temperature, wind conditions, humidity etc.
- Seasonal variation: performance varies throughout the year.
- The characteristics of a rain event: intensity and duration, temporal spacing of multiple events and intensities during an individual event.

With the exception green roofs, it was found that the devices considered could operate well during and/or soon after extended periods of rainfall. Although green roofs can retain significant volumes of rainfall, the research reviewed suggested that lightweight “extensive” roofs readily become saturated and then offer only modest detention. As highlighted in Table 1, one stratagem to mitigate against these problems on other types of device has been to update design methods to allow for a loss of efficiency over time or due to saturation. This approach, although it comes at a cost, underlies the design of permeable paving systems and its success is evidenced by their widespread use and relatively low maintenance requirements. An alternative to this may be to provide additional retention / detention downstream.

Table 1: SUDS device potential for hydraulic control of runoff when saturated and in the long-term.

SUDS Group	Device	Potential for Runoff Volume Reduction	Potential for Runoff Rate Control[1]			Performance when saturated.	Long-term performance.
			1: 2 year event	1:10 to 1:30 year event	1:100 year event		
Source Control	Green roof	High	High	Low	Low	Extensive system performance significantly degraded after 20mm-30mm of rainfall.	Good, with only limited degradation over time. Very little maintenance required to ensure drainage function.
	Rainwater harvesting	Medium	Medium	High	Low	Significantly degraded. Where collected water is for garden use only, the system may remain full throughout the winter.	Excellent.
	Pervious paving	High	High	High	Low	Significantly degraded. However, systems are designed to recover 50% of storage within 24 hours.	Significant degradation over time. New systems are designed to account for this.
Infiltration	Trench	High	High	High	Low	Significantly degraded. However, systems are designed to recover 50% of storage within 24 hours.	Reported performance is good, but pre-treatment is required.
	Basin	High	High	High	High		
	Soakaway	High	High	High	Low		
Open Channel	Conveyance swale	Medium	High	High	High	Significantly degraded. However, systems are designed to recover 50% of storage with 24 hours.	Reported performance is good.
	Dry swale	Medium	High	High	High		
	Wet swale	Low	High	High	High		

[1] Adapted from Woods-Ballard *et al.*, 2007. The value for green roofs has been updated to “low” to reflect the conclusions drawn as part of this project.

1.0 Introduction

Over time the approach to flood management has changed: an initial focus on land drainage and flood defence throughout the 1950s, 60s and 70s moved towards a flood control approach and then to flood management in the 1980s and 90s. Whilst these approaches had a strong focus on engineering measures, a more integrated and sustainable flood management (SFM) approach is currently being adopted. In Scotland, SFM was established in legislation as part of the Water Environment and Water Services (Scotland) Act in 2003. Natural flood management (NFM) is one aspect of SFM currently being promoted as a cost-effective catchment scale approach to managing flood risk. The Scottish Government has made it clear that NFM measures are an important part of their sustainable flood management policy as evidenced by the aims of The Flood Risk Management (Scotland) Act 2009 which transposes the European Floods Directive (2007/60/EC) into Scots law. The Act places an emphasis on all statutory bodies to consider the use of NFM approaches where possible. The review of the 2007 summer floods in the UK (Pitt, 2008) highlighted the potential of NFM by recommending “greater working with natural processes”. However, as recent reports have highlighted (ICE, 2011), there is a clear need to improve the evidence base of NFM performance, design and implementation.

This report, one of three reports produced for CREW to verify the current state of knowledge on NFM, focuses on establishing the effectiveness of SUDS measures for flood management in urban areas, particularly in relation to performance under saturation conditions and long term efficiency as a device becomes established. Although it is explicitly recognised that SUDS can also deliver water quality and amenity benefits, this report focuses only on runoff detention and retention. In particular this report examines the performance of devices with high or moderate potential for runoff volume reduction in detail (green roofs, rainwater harvesting, pervious paving, infiltration devices and swales), reviewing the available evidence relating to the impact that these different SUDS measures have on managing flood scenarios.

The range of SUDS types and sub-types used in Scotland is considerable. For example, terms such as “swale” “wetland”, “pond” and “basin” can be used to describe devices which have superficially similar appearances (particularly when wet) and function. To avoid any such confusion, the terminology used in this report is as defined in the “SUDS Manual” (Woods-Ballard *et al.*, 2007) which is commonly used and freely available[2].

2.0 SUDS – Policy and guidelines

SUDS are a legal requirement within Scotland. As detailed in the current planning policy for Scotland (Scottish Government, 2010), the Water Environment (Controlled Activities) (Scotland) Regulations 2005 require the use of SUDS for all new developments in Scotland other than single dwellings or discharges direct to coastal waters. A number of key documents have been developed to offer guidance and define requirements for the implementation of SUDS in Scotland. These include “The

[2] The SUDS manual (C697) - www.ciria.org.uk/suds/publications.htm

SUDS Manual" (Woods-Ballard et al., 2007), "Sewers for Scotland 2nd Edition" (WaterUK/WRc, 2007) and "Drainage Assessment – A guide for Scotland" (SEPA/SUDSWP, 2005). Specific requirements for SUDS associated with roads are detailed in "SUDS for Roads" (Pittner & Allerton, 2009). At a national level, in Scotland their importance is underlined in the Flood Risk Management (Scotland) Act 2009 which requires that they be mapped.

In Scotland SUDS systems are normally expected to convey flows up to a given design flow, generally a 1 in 30 year event flow, without causing any flooding on any part of the site. There is also a requirement for a further check for more extreme events (1 in 100 year and 1 in 200 years) to ensure no property is at risk of flooding. The guidance recommends that SUDS should be designed to last for 1 – 5 years before significant maintenance is required and 20 -50 years before requiring significant modification or replacement (CIRIA, 2005).

3.0 SUDS and Hydraulic Control– An Overview

Urbanisation has a significant effect on the hydrological cycle and, in particular, on the physical structure of watercourses and rainfall-runoff processes. Increases in impervious surfaces associated with urbanisation result in an increase in both peak flow and total volume of surface runoff. Urban stormwater is also recognised as significantly contributing to pollution of water courses. Where properly designed, SUDS have the potential to reduce flood risk, treat diffuse pollution and provide amenity in urban areas (Bastien et al., 2011). Fundamentally, SUDS and NFM measures are designed on the same basis: both aim to replicate natural processes by allowing a developed catchment to perform hydrologically as it would if it had remained undeveloped. With SUDS, this is achieved through attenuating and infiltrating flows using a 'Management Train' of devices (Figure 1). The management train starts with using good design to reduce runoff from individual premises, and then progresses through local source controls to larger downstream site and regional controls (CIRIA, 2005 and Bastien et al., 2005).

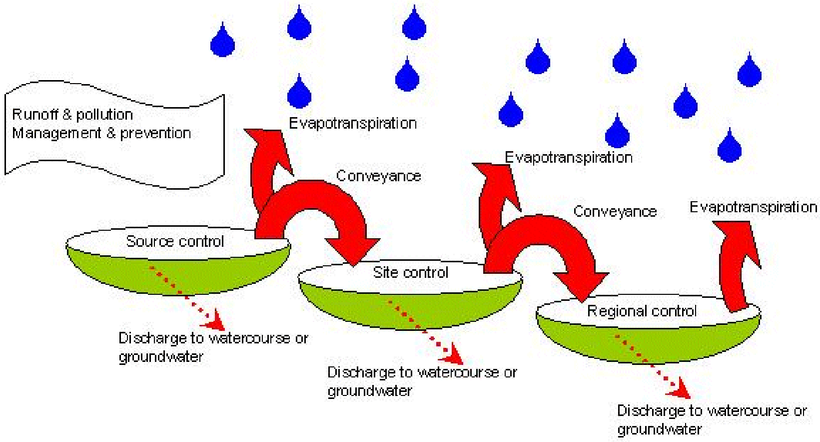

Figure 1 SUDS Management Train (CIRIA, 2005)

There are four main approaches to managing and controlling runoff:

1. Retention is where flow is not passed forward into the treatment train. For example, this could include infiltration, where water is allowed to soak into the ground. If there is no risk of contamination this water can be used to recharge ground water sources or supplement natural watercourses. This approach will reduce the total volume of runoff to varying

degrees as infiltration rates will vary with soil types and conditions, antecedent conditions and weather conditions.

2. Detention/attenuation which involves the use of a storage area associated with a restricted outlet. This approach slows down the rate of surface flow and may also reduce volume to some degree through infiltration or evaporation of the temporarily stored volume.
3. Conveyance, the transportation of surface runoff away from the original source. Controlled conveyance can be used to transfer water from one SUDS device to another and can also contribute, via infiltration, to volume reduction during transport.
4. Water harvesting, the direct capture and use of water from its source.

Individual SUDS devices may adopt more than one of these approaches for example, a swale used between stages in the management train will involve both conveyance, infiltration and attenuation.

Guidelines for the use of SUDS (The SUDS Manual) have been produced by the Construction Industry Research and Information Association (Woods-Ballard *et al.*, 2007). Within these guidelines, SUDS devices are classified as a number of different groups: Retention, Wetlands, Infiltration, Filtration, Detention, Open channel and Source control. Table 2 lists the main devices within each of these groups considered to be most suitable for hydraulic control of runoff.

Table 2: SUDS device potential for hydraulic control of runoff (adapted from Woods-Ballard *et al.*, 2007, Table 5.7)

SUDS Group	Device	Potential for Runoff Volume Reduction	Potential for Runoff Rate Control		
			1 in 2 year event	1 in 10 to 30 year event	1 in 100 year event
Source Control	Green roof	High	High	High	Low
	Rainwater harvesting	Medium	Medium	High	Low
	Pervious paving	High	High	High	Low
Retention	Ponds	Low	High	High	High
	Subsurface Storage	Low	High	High	High
Wetland	Shallow	Low	High	Medium	Low
	Extended detention	Low	High	Medium	Low
	Pond/wetland	Low	High	Medium	Low
	Pocket	Low	High	Medium	Low
	Submerged gravel	Low	High	Medium	Low
	Wetland channel	Low	High	Medium	Low
Infiltration	Trench	High	High	High	Low
	Basin	High	High	High	High
	Soakaway	High	High	High	Low
Filtration	Surface sand	Low	High	Medium	Low
	Subsurface sand	Low	High	Medium	Low
	Perimeter sand	Low	High	Medium	Low
	Bioretention/Filterstrip	Low	High	Medium	Low
	Trench	Low	High	High	Low
Detention	Basin	Low	High	High	High
Open Channel	Conveyance swale	Medium	High	High	High
	Dry swale	Medium	High	High	High
	Wet swale	Low	High	High	High

Historically the main use of SUDS in terms of managing water quantity was to reduce peak rate of runoff. However, the latest guidance emphasises that the need to reduce total runoff volume is as important (Woods-Ballard *et al.*, 2007). A number of SUDS devices are considered to have a high or moderate potential for runoff volume reduction: green roofs, water harvesting, pervious paving, conveyance and dry swales, and infiltration devices including trenches, basins and soakaways (Table 2). Although there is widespread acknowledgement in academic literature and industry guidelines that these devices can contribute to hydraulic control, there are still uncertainties regarding their efficiency. This particularly relates to how the devices perform once saturated and how performance is influenced by the increased vegetation and pollution storage of established devices. This report examines the performance of each of those devices with high or moderate potential for runoff volume reduction in detail, reviewing the available evidence relating to the impact that these different SUDS measures have on managing flood scenarios.

4.0 Source Controls

Green Roofs

Drainage Function	**Treatment Train**	**Performance when saturated.**	**Long-term performance.**
Planted roof surface allows infiltration and attenuation of rainfall.	Source Control.	Extensive system performance significantly degraded after 20mm-30mm of rainfall.	Good, with only limited degradation over time. Very little maintenance required to ensure drainage function.

Green roofs are multi-layered vegetative systems that cover the roof of a building or structure in a manner which, to a certain extent, replicates a natural surface. Below the vegetated layer the roof can contain various soils or substrates, drainage, insulation and waterproofing layers. A variation of the green roof, sometimes referred to as a brown (or biodiversity) roof, is composed of the substrate and drainage layers: the substrate is normally locally sourced and is allowed be colonised with vegetation naturally (Grant *et al*., 2003; Molineux *et al*., 2009).

There are two main types of green roof: Intensive and Extensive. Although specific definitions vary, they basically adhere to the following designs:

1. Intensive - used for public access with substrate depths of 300 to 350mm in depth. These can include grass and even trees. These may also include water features and rainfall storage devices. Intensive roofs add a significant additional load to the roof structure and require significant maintenance (Wilson et al., 2004; Mentens *et al.*, 2006; Berndtsson, 2010).
2. Extensive – primarily used for environmental or planning benefits and normally have no public access. They use a range of growing mediums, 25mm to 125mm deep, planted with hardy, drought tolerant, slow growing and low maintenance vegetation (e.g. sedums). Extensive roofs subject the roof structure to only modest loads and, as a result, are often suitable for retrofit (Woods-Ballard *et al*., 2007). Due to their popularity, most research focuses on the performance of extensive green roofs.

In terms of hydraulic performance, both intensive and extensive green roofs influence the runoff hydrograph by interception and retention during the storm. This occurs through:

- Retention of rainwater by the vegetation, substrate and drainage layers.
- Uptake and evapotranspiration of water by plants.
- Storage of water as plant material through photosynthesis driven biochemical incorporation.
- Evaporation from substrate.

A number of design aspects of the green roof will influence its efficiency at controlling runoff including: number of layers and materials used; substrate thickness, type, and antecedent conditions; vegetation type and cover; roof geometry, position and age.

The use of green roofs as SUDS devices is well established and a number of studies have been undertaken to assess the performance of green roofs in reducing runoff volume and rate. All the reviewed studies show that green roofs have an effect on stormwater, reducing surface runoff volume as well as lowering and delaying stormwater runoff peaks. However, only a limited number of studies have been undertaken to assess their performance whilst saturated or during extreme events (Johnston *et al*., 2003; Macmillan, 2003; Bengtsson *et al., 2*005; Carter & Rasmussen, 2005; Van Woert *et al*., 2005; Villarreal & Bengtsson, 2005; Carter & Rasmussen, 2006; Berghage *et al*., 2007; Getter *et al*., 2007; Teemusk & Mander, 2007; Simmons *et al*., 2008; Hilten, 2008; Buccola & Spolek, 2010; Fioretti *et al*., 2010; Stovin, 2010; Voyde *et al*., 2010; Beck *et al*., 2011; Carpenter & Kaluvakolanu, 2011). Table 3 summarises key research in this field.

Published research reports significant variation in the extent to which runoff volume is reduced. However, this is partly explained by the different conditions which were assessed in the studies and the varying methodologies used for analysis and reporting. The studies covered both field conditions and the results of experimental testing or modelling.

Two methods of quantifying the performance of the green roof were used:

1. A number of studies reported the reduction in runoff volume compared to that of a control hard surface roof
2. Others reported on the percentage of rainfall retained.

These differences result in difficulties in making direct comparisons and general assessments.

Values for runoff reduction compared to a control roof ranged from 5% (Johnston *et al.*, 2003) to 95% (Carpenter & Kaluvakolanu, 2011), often with each study reporting a significant variation depending on a number of factors such as substrate type and depth, antecedent conditions and rainfall intensity and volume. For example, Alfredo *et al.* (2010) report reductions of between 21% and 68% depending on substrate depth and Carpenter & Kaluvakolanu (2011) note volume reductions of 36%-95% depending on total volume of rainfall. Carpenter & Kaluvakolanu also report peak flow reductions of between 52.7% and 98.6%, while other studies suggest peak flow reductions compared to control roofs of 2%-94% (Johnston *et al.*, 2003), 46%-85% (Macmillan, 2003), 10%-60% (Lui & Minor, 2005), 5%-70% (Bliss *et al.*, 2007) and 22%-70% (Alfredo *et al.*, 2010). Studies reporting on rainfall retention show peak reductions varying between 0.4% and 100%, while total rainfall retention by green roof are reported between 0 and 100% with values depending on a number of factors including whether the study was reporting on annual retention or the retention of individual events.

Although few studies specifically investigated changes in performance once a green roof has become saturated, a number of them report on the consequences of saturation either before the onset of a rain event or during it. Villarreal & Bengtsson (2005) note that “Under dry initial conditions water can be both retained and detained, whereas with initial wet conditions only detention is possible”, similarly Berghage *et al.*(2007), Getter *et al.*, (2007), Spolek (2008), Fioretti *et al.* (2010), Stovin (2010), Voyde *et al.* (2010) and Beck *et al.* (2011) report that retention is dependent upon antecedent moisture conditions with more water being retained if rainfall events happen to a dry roof. In addition, the results from Voyde *et al*., (2010) show that there is a progressive decrease in retention performance during a storm event time-series and similar findings were also reported by Teemusk & Mander (2007) who note that “A green roof can effectively retain light rain events, but in the case of a heavy rainstorm, rainwater runs off relatively rapidly”. Furthermore, Fioretti *et al*. (2010) state that “If the initial water content is greater than the field capacity value (wet soil conditions) the substrates of the green roof are not able to store permanently or reduce the stormwater volume”. Reductions in retention capability were also noted by Johnston *et al.* (2003), Carter & Rasmussen (2005), Van Woert *et al.*(2005), Carter & Rasmussen (2006), Hilten *et al.*, (2008), Simmons *et al.* (2008) and Carpenter & Kaluvakolanu (2011). However, Fioretti *et al*. (2010) found that even when saturated a green roof was able to temporarily detain some volume, leading to peak flow reductions; similar findings were also reported by Schroll *et al*. (2011).

Only two of the available studies detailed how performance varied over time. Getter *et al*. (2007) report an increase in water retention as a green roof becomes established due to an increase in organic matter content and pore space, whilst Mentens *et al.* (2006) suggest that age of the roof is not correlated to runoff retention capability. However, this latter study compared different roof build-up configurations built over a number of years rather than the ageing of any single roof, so may not reflect the performance of an individual roof as it ages.

Rainwater Harvesting

Drainage Function	**Treatment Train**	**Performance when full.**	**Long-term performance.**
Local collection of rainwater for domestic use.	Source Control.	Significantly degraded. Where collected water is for garden use only, the system may remain full throughout the winter.	Excellent.

Rain water harvesting is the collection, storage and use of rainwater from roofs and hard surfaces. The collected water can be used for a number of purposes including toilet (WC) and urinal flushing, laundry (washing machines), hot water systems, vehicle washing and irrigation (gardens or other) (Ward, 2010).

The ‘SUDS Manual’ defines three general concepts for rain water harvesting (Woods-Ballard *et al*., 2007):

1. Direct system: water runs off the surface through a filter into a storage tank from where it is pumped directly to where it is required. Can be backed up by mains water.

2. Gravity system: water runs off the surface through a filter into a storage tank from where it is pumped to a header tank and then gravity fed to where it is required. Can be backed up by mains water direct into the header tank.
3. Centralised system: water runs off the surface through a filter into a storage tank. Water taken into the system from the tank if it is required.

The operation of a rainwater harvesting system under storm conditions will depend on the volume of storage provided and the design of the collection system.

To date, research has tended to focus on the potential to reduce the reliance on potable mains supply at the single-building scale or on financial aspects of rainwater harvesting systems and there have been few studies concerning how these devices perform in terms of stormwater management, although there is growing recognition that they can contribute to runoff control (e.g. Vaes & Berlamot, 2001; Memon *et al*., 2009). Table 4 summarises key publications in this area.

Based on studies of rainwater utilisation systems in Germany, Herrmann & Schmida (1999) report that "Even extreme events of a recurrence time of 10 years are significantly reduced in volume when operating rainwater usage systems". However, the ability to reduce runoff is dependent on the designed storage capacity and to a lesser extent on the level of water usage. For example, Forasté & Hirschman (2010), note that if designed appropriately rainwater harvesting can significantly reduce runoff volumes from impermeable surfaces and report reduction in runoff from 37%-77% depending on the cistern size used. It is also evident that devices used for irrigation may remain full (and unable to accept any inflow) over the winter months in Scotland.

Pervious Paving

Drainage Function	**Treatment Train**	**Performance when saturated.**	**Long-term performance.**
Road/car park / footpath surface allows infiltration and attenuation of rainfall.	Source Control	Significantly degraded. However, systems are designed to recover 50% of storage within 24 hours.	Significant degradation over time. New systems are designed to account for this.

Pervious surfaces are constructions that allow rainwater to infiltrate into the underlying construction layers, where water is stored prior to infiltration to the ground, reuse or being released to a surface watercourse or other drainage system.

There are two main types of pervious paving:

1. Porous surfacing: infiltrates water across the full surface of the material forming the surface.
2. Pervious surfacing: consists of material that is itself impervious but allows infiltration through gaps in the surface (e.g. between pavers).

A number of design aspects will influence the efficiency of the permeable paving at controlling runoff, including: the proportion of permeable surface, infiltration rate, drainage system, underlying soil type/thickness/condition, surrounding area – landscaping etc.

Pervious paving has become an integral component of SUDS treatment trains and as noted by Roseen *et al*. (2012), the hydrologic benefits have been well-documented for volume and peak flow reduction. All the available studies report that pervious paving has an effect on stormwater, reducing surface runoff volume as well as lowering and delaying total stormwater runoff peaks as compared to conventional impermeable surfaces. In addition a number of studies noted a reduction in the total volume of runoff which included both surface and subsurface flows. Table 5 summarises published results in this field.

Values for runoff reduction varied from 10% (Rushton, 2001) to 100% (Dempsey & Swisher, 2003; Haselbach *et al*., 2006; Collins, 2008) while peak flow reductions were reported from 12% (Pagotto *et al*., 2000) to 90% (Roseen *et al.*, 2012). Direct comparison of the results is difficult as some studies report the reduction in runoff compared to conventional hard surfaces while others consider the percentage of rainfall that results in runoff. In addition, each site assessed in the studies had different build-ups and environments. However, the general pattern of results suggests that the major factor controlling performance was the infiltration rate through the various layers of the pavement system. The infiltration rate varied from site to site depending on design of the drainage layers and the underlying soils. Ball & Rankin (2010) concluded that "The pavement is capable of infiltrating 100% of the runoff only when the rainfall is below a given intensity. After this rate, the infiltration capacity of the permeable pavement is reached and water which is unable to be infiltrated will run over the pavement surface".

There were contradictory reports of the influence of saturated conditions prior to storm events. For example Anderson *et al*. (1999) noted a change in storage of a 1 hour 15mm storm from 55% if initially dry to 30% if initially wet. Conversely, Fassman & Blackbourn (2010) noted that drainage from the permeable pavement demonstrated peak flow comparable to or below modelled predevelopment conditions for most storms, regardless of antecedent conditions. The variations in results are likely to be due to specific site conditions and build-up.

Few of the available studies reported on long term performance, although most designs allowed for a significant reduction in infiltration capability over time with recommendations for considering an infiltration rate of 10% of the initial rate when designing the system. The reduction in infiltration rate is the result of clogging of the pore spaces in the paving and the lower filtration layers. An example of the impact of clogging on performance was reported by Illgen *et al*. (2007) who noted that new pervious paving generated a maximum of only 2% runoff, whilst the value was 52%-71% for clogged systems.

5.0 Infiltration Devices

Drainage Function	**Treatment Train**	**Performance when saturated.**	**Long-term performance.**
Devices which allow storage and infiltration of runoff.	Site control / secondary treatment / retention.	Significantly degraded. However, systems are designed to recover 50% of storage within 24 hours.	Reported performance is good, but pre-treatment is required.

Infiltration Devices (excluding permeable paving) take runoff and temporarily store it while it is allowed to percolate into the ground. There are three commonly used devices which make use of infiltration, namely:

1. Infiltration trenches: shallow excavations filled with crushed stone allowing temporary storage. Water can percolate into the ground from the sides and bottom of the trench. They work best when incorporated into a management train with other devices. They can also be used as a conveyance device and may include sections of perforated pipe. Infiltration trenches are commonly confused with infiltration trenches – the latter is a conveyance device which does not allow infiltration.
2. Infiltration basins: vegetated depressions designed to temporarily store runoff and allow gradual infiltration.
3. Soakaways: Circular or square excavations which may be filled or lined. They can be grouped to drain large areas. They provide stormwater attenuation, treatment and groundwater recharge. They are the most common type of infiltration device used within the UK (Wilson *et al*., 2004).

Current guidelines recommend that infiltration devices are designed to manage storms up to the standard of service required for the specific site, generally a 1 in 10 or 1 in 30 year storm. A number of design aspects of the device will influence its efficiency at controlling runoff including: type of device selected, type and condition of underlying soil, characteristics of the contributing catchment and adjacent landscaping and SUDS features.

Although the contribution of infiltration devices to reducing the impact of rainfall runoff and increasing ground recharge is acknowledged in current technical guidelines (Wilson *et al*., 2004), there are few studies reporting their performance and, as a result, there is uncertainty regarding their long term functionality as well as their capabilities under saturated conditions during large storm events. All the reviewed studies (Table 6) show that infiltration devices have an effect on stormwater, reducing surface runoff volume as well as lowering and delaying stormwater runoff peaks. Schuster *et al*. (2008) found that runoff volumes were strongly influenced by antecedent moisture conditions with a decreased time to runoff initiation and higher final runoff rate ratios when initial saturation levels were higher. Similar findings were also reported by Barber *et al*. (2003) and a number of other studies conclude that antecedent conditions may impact on infiltration ability though quantitative values are not always available (e.g. Braga *et al.*, 2007; Al-Houri *et al.*, 2009). Studies by Blake (2009) suggest that the position of the water table prior to the onset of rainfall exerts a significant control on infiltration and therefore runoff control.

Seasonal variations in infiltration ability are thought to be due to changes in the hydraulic conductivity resulting from temperature-induced viscosity changes of the pooled water (Braga *et al*., 2007; Emerson & Traver, 2008; Horst *et al*., 2011). In some areas seasonal growndwater level variation may also impact on performance.

Although there is strong anecdotal evidence which suggests infiltration trenches specifically require significant maintenance, a number of studies suggest that there is little deterioration in the performance of infiltration devices as they age (Abbott & Comino, 2001; Chen *et al*., 2008; Emerson & Traver, 2008). However the timescales involved were relatively short (less than 5 years). In one report of long term performance, significant deterioration was found in the rate at which an infiltration basin drained. Dechesne *et al.* (2004) report that 100% of events drained within 24 hours from infiltration basins aged 10, 12 and 15 years but only 91% of events drained within 24 hours once the basin reached 21 years and 62% once it reached 25 years. However, the decrease in drainage rate had no significant impact on flood risk as the total volumes held within the basin where still within design limits.

6.0 Swales

Drainage Function	Treatment Train	Performance when saturated.	Long-term performance.
Planted channels which allow storage, infiltration and / or conveyance runoff.	Site control / conveyance /retention.	Significantly degraded. However, systems are designed to recover 50% of storage within 24 hours.	Reported performance is good.

Swales are broad, shallow channels covered with grass or other vegetation that are designed to store and/or convey runoff and remove pollutants via filtration or sedimentation. They may be designed to act as conveyance conduits between stages in a management train or to infiltrate runoff directly into the ground. They can be used as either source or site controls within a management train. They reduce total runoff volume through infiltration and lower peak flows through attention (storage and lowering flow velocities as a result of channel roughness). Due to their linier nature, Swales are typically located next to roads, paths or car parks but can be used in many landscaped and open spaces.
There are three main swale types:

1. Standard conveyance swale: broad, shallow vegetated channels designed for filtration or detention.
2. Dry swale: vegetated channel designed to include a filter bed of soil overlaying an underdrain system which provides additional conveyance capacity.
3. Wet swale: similar to a standard swale but designed to encourage wet, marshy conditions to enhance water treatment processes.

Standard and dry swales are both potentially effective devices for runoff volume reduction while all three swale types offer good potential for peak flow reduction (Woods-Ballard *et al*., 2007).

A number of design aspects of the swale will influence its efficiency at controlling runoff including: type of swale selected, length and slope, type and condition of underlying soil, characteristics of the contributing catchment and adjacent landscaping features.

The use of swales as SUDS devices is well established and they are one of the simplest and most cost-effective forms of stormwater control (Delectic & Fletcher, 2006). Although, a number of studies have been undertaken to assess the performance of swales in improving water quality only a limited number of studies have been undertaken to assess their performance in relation to runoff control and long term efficiency. All the reviewed studies show that swales have an effect on stormwater, reducing surface runoff volume as well as lowering and delaying stormwater runoff peaks. Table 7 summarises the results found.

Mean volume reduction of runoff due to swales was reported as 45.7% (Delectic, 2001), 30% (Rushton, 2001), 84%-85% (MacDonald & Jeffries, 2003), 47% (Barrett, 2005), 62%-92% (Abida & Sabourin, 2006), 15%-87% (Delectic & Fletcher, 2006), 21%-77% (Ackerman & Stein, 2008), 73%-86% (Sabourin & Wilson, 2008), and 0%-34% without check dams and 27%-63% with check dams (Davis *et al*., 2011). Although a significant variation in runoff reduction is noted, direct comparisons between individual studies is again problematic as different conditions were assessed and varying methodologies were used for analysis and reporting. Some studies reported on field conditions, whilst others detailed the results of experimental testing or modelling. A number of studies used the reduction in runoff compared to runoff from equivalent storms on a conventional hard surface (e.g. Sabourin & Wilson, 2008, Davis *et al.*, 2011) while others considered reduction in total outflow compared to inflow (e.g. Delectic, 2001, Delectic & Fletcher, 2006).

Where peak discharge is concerned, a reduction of 52%-65% was reported by MacDonald & Jeffries (2003). Similarly, others reported peak reductions of 36% (Abida & Sabourin, 2006), 56%-60% (Jamil & Davis, 2008), 47-86% (Sabourin & Wilson, 2008), and 27-100% (Davis *et al.*, 2011). In common with the calculation of values for volume reductions, the peak flow reduction percentages were determined for different conditions using different assessment methodologies.

Very little published work details changes in performance once a swale has become saturated. Among them, Davis *et al*. (2011) state that “Due to soil saturation, volume attenuation during large or intense storms tends to be modest or even negligible” while Deletic & Fletcher (2006) show higher runoff reductions when the swale is dry before the onset of the storm.

Only one study detailed how performance varied over time; Sabourin & Wilson (2008) reported a reduction in infiltration rate of an order of magnitude after 10 years. However, it was uncertain whether this was the result of clogging of filtration layers due to the age of the swales or whether infiltration was reduced due to higher saturation levels of the underlying soil due to wetter antecedent conditions in the later testing.

7.0 Conclusion

Considerable research has been undertaken which assesses the hydraulic performance of individual SUDS devices and those installed as part of a treatment train. Whilst reviewing the research from individual studies, it can be observed that efficiency is generally gauged either by assessing performance of devices in situ, (within a site-specific setting), or through experimental testing of often very restricted environments and conditions. This can make it difficult to build a generalised understanding of the performance of any single device type. Additionally, differences in research methods and reporting strategies along with varying levels of detail of device design make general assessments problematic. These factors may have contributed significantly to the range of ‘effectiveness’ that have been reported. In addition, there is still a lack of long term monitoring data available which limits the knowledge available regarding lifetime performance of SUDS devices.

Notwithstanding the above, a general pattern is evident indicating that regardless of the SUDS device used, a number of environmental factors influence the performance of the device in managing runoff:

- The length of any preceding dry period: saturated systems are less efficient.
- The prevailing climate: devices perform differently in hot and cold climates depending on air temperature, wind conditions, humidity etc.
- Seasonal variation: performance varies throughout the year.
- The characteristics of a rain event: intensity and duration, temporal spacing of multiple events and intensities during an individual event.

With the exception green roofs, it was found that the devices considered could operate well during and/or soon after extended periods of rainfall. Although green roofs can retain significant volumes of rainfall, the research reviewed suggested that lightweight “extensive” roofs readily become saturated and then offer only modest detention. As highlighted in Table 1, one stratagem to mitigate against these problems on other types of device has been to update design methods to allow for a loss of efficiency over time or due to saturation. This approach, although it comes at a cost, underlies the design of permeable paving systems and its success is evidenced by their widespread use and relatively low maintenance requirements (Wright *et al*., 2011). An alternative to this may be to provide additional retention / detention downstream.

8.0 Tables 3 to 7

Table 3: Peak and volume reduction for green roofs.

	Peak Reduction	**Volume Reduction/Rainfall Retained**
Alfredo *et al.*(2010)	Peak rate reduced compared to hard roof depending on substrate depth Substrate Depth Reduction 25mm 25% 63mm 44.5% 101mm 70.5% The deeper the substrate the longer the tail of the discharge hydrograph.	Runoff reduced by 21% to 68% compared to hard roof depending on substrate depth
Beck *et al.* (2011)		Soil Retained Unsaturated 19.3 - 32.9% Saturated 6.9 - 8.2%
Bengtsson (2005)		Water storage capacity of the studied green roof is related to the rain intensity variations.
Bengtsson *et al.* (2005)	Peak flow reduced and runoff delayed until soil at field capacity	Seasonal variations Month Retained September–February 34% March–August 67%. February 19% June 88%
Berghage *et al.* (2007)		Plants increase water retention by up to 40% compared to non vegetated roofs Soil Condition Retained Unsaturated 19.3-32.9% Near saturated 23%
Bliss *et al.* (2007)	5 – 70% compared to ballasted roof	Compared to ballasted roof up to 70% runoff reduction
Buccola & Spolek (2011)		Rainfall Retained 30mm/h 36-64% 340mm/h 20 - 56 % Depends on soil depth Depth Retained 50mm 20 – 36% 140mm 56-64%

	Peak Reduction	**Volume Reduction/Rainfall Retained**
Carpenter & Kaluvakolanu (2011)	Average peak reduction Rainfall Reduction <127mm 98.6% 127–254mm 90.24% >254mm 52.7%	Average reduction in runoff compared to asphalt roof Rainfall Reduction <127mm 95% 127–254mm 85% >254mm 36%
Carter & Rasmussen (2005)		Rainfall Retained 13mm 90% 54mm 39%
Carter & Rasmussen (2006)	Peak discharge for small storms much lower but effect reduced for larger storms. 57% of peaks delayed up to 10 minutes.	Rainfall Retained <25.4mm 88% 25.4–76.2mm > 54% >76.2mm) 48%
DeNardo *et al.* (2005)	5.7 hour delay start of runoff 2 hour delay to peak run off	
Dunnett *et al.*(2008)		Retention varied due to vegetation type, more pronounced in periods with low water availability and higher temperatures.
Fioretti *et al.* (2010)		The antecedent dry weather period, is the variable that regulates the hydraulic response of the green roof system. Antecedent Dry Period Volume Reduction < 96 hours < 20% < 12 hours 0
Getter *et al.* (2007)	Minimal delay in runoff	Organic matter content and pore space doubled in 5 years (from 2% to 4% and from 41% to 82%, respectively). The water holding capacity increased from 17% to 67% Rainfall Retention >10mm 57% - 71% <2mm 93 - 95% Antecedent condition Slope Rainfall Retained Dry 2% 68% Dry 7% 64% Dry 15% 57% Dry 25% 58% Wet 2% 45% Wet 7% 30% Wet 15% 27% Wet 25% 29%
Gregoire & Clausen (2011)		41.6% of rainfall retained
Hardin (2005)	50% reduction for vegetated and non vegetated green roofs	
Hilten *et al.*(2008)	Average peak reduction Rainfall Retained 127mm event 100% 381mm event 55% 793mm event 0.4%	Rainfall Retained 127mm event 100% 381mm event 44% 793mm event 21.6%

	Peak Reduction	**Volume Reduction/Rainfall Retained**
Johnston *et al.*(2003)	Reduced peak flows during summer storms by > 80% In winter reduction decreased with size of storm event Season Reduction Summer 84-94% Winter 24-46% Severe storm 2-3% (> 2 year event)	Compared to control roof 48% Annual reduction in runoff 30% for smaller winter events < 5% larger severe events
Kirby *et al.*(2010)	Up to 95%	Up to 71% rainfall retained
Kohler *et al.* (2002)		Mean annual rainfall retained 76%
LaBerge *et al.* (2005)		Rainfall Retained < 8mm event 90% 8- 23mm events 63 - 79% >25mm 20-30% Individual event or consecutive events < 23mm 76-100% >23mm 5-95%
Lui & Minor (2005)	25 – 60% reduction 10-30% when saturated	Annual reduction 57% compared to hard roof 100% retention on summer events < 15mm
MacIvor & Lundholm (2011)		Plant species with extremely dense fibrous roots captured the least amount of water runoff because they reduced the porosity of the growing medium and the volume of space in which water could be retained. Plants more efficient at evapotranspiration will increase water storage capacity.
Macmillan (2003)	Rainfall Reduction 10-19mm event 85% 20-29mm event 82% 30-39mm event 68% >39mm event 46%	Annual reduction compared to hard roof 55%
Mentens *et al.* (2006)		Annual reduction compared to standard roofs 65-85% for intensive green roof, 27-81% for extensive green roofs Age of a green roof is not significantly correlated with annual runoff. Summer results in higher evapotranspiration and the green roof retention capacity regenerates faster
Metselaar (2012)		Green roofs are efficient in summer, but have less retention capacity in winter
Monterusso *et al.* (2004)		Depth and type of substrate are more significant than vegetation type and cover in determining runoff retention.
Moran *et al.* (2005)	90% of events delayed peak flow	
Nagase & Dunnett (2012)		Plant with more extensive root growth retained more water.
Nardini *et al.*(2011)		Retained 120mm substrate 63% 200mm substrate 83% Vegetated substrate 90%
Palla *et al.* (2008)	95% peak reduction	85% rainfall retained

	Peak Reduction	Volume Reduction/Rainfall Retained
Schroll *et al.*(2011)		Rainfall retained Wet season Non vegetated 26.4%, Vegetated 27.2% Dry season Non vegetated 51.9%, Vegetated 64.7
She & Pang (2010)	Rainfall Reduction 1 yr event 47% 2 yr event 54% 4 yr event 52%	
Simmons *et al.* (2008)		Rainfall Retained <10mm 100%. 12mm 26-88% 28mm 8 - 43% 49mm 13 - 44% Depended on substrate and drainage type
Spolek (2008)		Annual rainfall retention 12-25% Individual event 0-85% Season Retention Summer 7-85% Winter 0-52%
Steusloff (1998)		Volume of rainfall retained depended on type of vegetation.
Stovin (2010)	Average reduction 57%	Average rainfall retention 34% Antecedent Rainfall Rainfall condition Retained Dry 13mm 100% Moist 25mm 65% Saturated 74mm 5% After limited recovery from saturated 25mm 27% 37mm 0%
Stovin *et al.*(2012)		Annual rainfall retention 50.2% Single event 0 – 100% Mean for 'significant storms' 43% Max retention for >2 yr event 29% 16yr event 15%
Teemusk & Mander (2007)		Rainfall retained 85.7%
Uhl & Schiedt (2008)	66-88 %	Annual rainfall retained 62-76% Season Retention Summer 69-84% Winter 40 – 60%
USEPA (2000)	Up to 64% reduction, significant even when saturated	Annual retention 54% 38% predicted for 10yr 24hr event Negligible runoff for event < 15mm

	Peak Reduction	**Volume Reduction/Rainfall Retained**
VanWoert *et al.* (2005)	Reduced	Rainfall retained Vegetated Non Vegetated Annual 61% 50% Light 96 96 Medium 83 82 Heavy 52 38 Roof Slope Retained 2% 87% 6.5% 65.9%
Villarreal and Bengtsson (2005)	For dry conditions 6–12mm rain were required to initiate runoff; For wet conditions the response was almost immediate.	Dry initial conditions Under dry initial conditions Slope Retention % 2% 21-62 5 30-43 14 10-39 Wet initial conditions (saturated to field capacity) 17-51% depending on rainfall pattern – slope had no impact The lower the intensity the larger the retention. Under dry initial conditions Rainfall Retention 0.4mm/min 62% 0.8mm/min 54% 1.3mm/min 21% For substrate depths 50-150mm Season Retention Warm 70% In-between 49% Cold 33%
Voyde *et al.*(2010)	Median peak flow reduction 93%	66% Annual retention Events on consecutive days Rain (mm) % Retained Runoff Delay 4.3 100 - 15.2 82 25 mins 19.8 66 none 1.8 86 none 16 59 none
Wanielista *et al.*(2007)	50% peak flow reduction	46% Annual retention
Wolf & Lundholm(2008)		Role in water retention, pronounced in periods with low water availability and higher temperatures and negligible in winter.

Table 4: Peak and volume reduction for rainwater harvesting.

	Peak Reduction	**Runoff Volume**
Forasté & Hirschman (2010)		37-77% reduction depending on cistern volume
Guillon *et al*. (2008)		30% reduction for individual premises if stored for garden watering. 10% for catchment if 50% of houses have device
Herrmann & Schmida (1999)		Reductions 4 – 95% depending on usage rates and storage Rainwater usage is most effective when it is applied in multi-storey buildings and densely populated districts. There the specific roof surface per head is low, and therefore the total roof runoff can be consumed.
Huang & Shaaban (2000)	Devices located at houses 48-66% for individual house 21 – 24% for catchment Devices at houses, shops and park 67-70%	
Jones & Hunt (2010)		68% of storms over 10mm resulted in overflow from barrels however larger rainwater harvesting systems can have a substantial impact on runoff volume capture
Kim & Yoo (2009)		1% Reduction Depends on storage capacity and water use.
Petrucci *et al*. (2012)		The rainwater tanks installed, although they affect the catchment hydrology for usual rain events, are too small and too few to prevent sewer overflows in the case of heavy rain events
Vaes & Berlamont (1999)	Storage in tanks produced a reduced storage in CSOs, with peak discharges being reduced by 15-25%. Impacts significantly enhanced for higher consumption rates.	The occurrence of completely full tanks was lower in summer than in the winter.

Table 5: Peak and volume reduction for pervious paving.

	Peak Reduction	Runoff Volume
Anderson *et al*. (1999)		For 1 hour 15mm storm Initial Conditions Retention Dry 55% Wet 30%
Ball & Rankin (2010)		Surface runoff 0 – 7% of rainfall
Bean *et al*. (2007a)		Permeable pavement that was installed in sandy soil environments maintained relatively high surface infiltration rates, without regard to pavement age or type
Bean *et al*. (2007b)		Rainfall events <50mm depth can be totally infiltrated into the soil, significant reductions in total runoff volume can be achieved for more intense events
Booth (1999)	Peak reduction of 30%, all in subsurface flow for various percentages of Impermeability	
Brattebo(2003)		Max surface runoff 3% of rainfall for various percentages of impermeability.
Collins(2008)	60-77% compared to asphalt	Runoff reduction from rainfall Surface Total Porous concrete 99.9 43.3 PICP 99.4 51 Concrete grid 98.2 63.6 Asphalt 34.6 35.7
Dempsey & Swisher (2003)		100% volume reduction
Dreelin *et al*. (2006)	No peaked hydrograph	93% less total runoff than asphalt
Fassman & Blackbourn (2010)	Peak Flows mm/h Asphalt permeable paving 16 2.9 46 6.5 48.6 14.9	Total Runoff permeable paving 29-74% depending on percent impervious
Gilbert & Clausen (2006)		Runoff reduction compared to asphalt ICPP 72% (40% of rainfall) Crushed stone 98%
González-Angullo *et al.* (2008)		Runoff 19% of rainfall for 50mm/h event
Haselbach *et al*. (2006)		Negligible surface runoff with simulations of typical rainfall intensities of up to 100 year frequencies for the Columbia, SC region.
Illgen *et al*. (2007)		Surface Runoff 0-2% for new paving 52-71% for clogged paving
James & Thomson (1997)		Runoff from ICPP 38-61% of rainfall
Legret & Colandini (1999)		97% volume reduction

	Peak Reduction	**Runoff Volume**
Pagotto *et al*. (2000)	Conventional surface 6.2 l/s Permeable paving 5.5 l/s Flow duration of Permeable paving 1.15 times conventional surface	Higher total runoff from permeable paving (includes sub surface flow). Thought to be result of lack of evaporation
Pratt *et al*. (1995)		Run off from ICPP 37-47% of rainfall
Roseen *et al*. (2012)	90% reduction	Total Runoff 75% of rainfall All through subdrains No significant statistical seasonal difference in hydrologic performance
Rushton(2001)		Surface runoff reduced 10-15%
Scholz & Grabowiecki (2007)	Up to 42% reduction	
Stenmark (1995)		Annual runoff volume reductions of 50–81%

Table 6 Peak and volume reduction for infiltration devices.

	Peak Reduction	Runoff Volume
Abbott & Comino (2001)		% of rainfall entering the soakaway 46-85% No deterioration in performance over 4 years
Al-Houri *et al.*(2009)		Infiltration rate once frozen depends on drain down time before onset of freezing but is soil type dependent Infiltrability and hydraulic conductivity in frozen soils have been shown to be closely linked to soil water content at the time of freezing Drain Time — % of unfrozen infiltration 2 hrs — 5% 4hrs — 21% 24hrs — 30%
Barber *et al.*(2003)	Reduces as storm size increases Continues to reduce until a steady state of water infiltration is reached Dry Period — Storm Size — Peak Reduction 3hrs — S — 87% 24 hrs — S — 67% 72 hrs — S — 65% 3hrs — M — 60% 24 hrs — M — 50% 72 hrs — M — 50% 3hrs — L — 40% 24 hrs — L — 40% 72 hrs — L — 40%	
Blake (2009)		Antecedent water table position, possibly above a threshold depth, exerts a significant control on infiltration. Threshold depth may vary depending on soil type.

	Peak Reduction	Runoff Volume
Braga *et al.*(2007)		The governing factor affecting hydraulic conductivity and infiltration rate is temperature; with higher rates occurring during warmer periods, affecting the infiltration rate by as much as 56%. Factors other than temperature and intrinsic permeability also affect the hydraulic conductivity of flow through a soil. Possible factors include antecedent dry time between storms, and initial soil moisture content.
Chen *et al.*(2008)		Soakaway performance is maintained over a number of years.
Deschesne *et al.*(2004)		100% retention % of events after which basin drains in 24 hrs Age of basin % of events 10 100 12 100 15 100 21 91 25 62
Emerson & Traver (2008)		The seasonal changes are significant and result in event ponding times which vary over the course of 1 year between 50 and 80 hours and 80 and 120 h. Values for two devices. No noticeable reduction in performance over 4.25 (starting 1.5 years after installation)
Horst *et al.*(2011)		Surface volume reduction 84.9-99.7% Cyclic variation, highest in late summer, lowest in late winter. This variation is similar to that which is expected due to changes in the hydraulic conductivity resulting from temperature-induced viscosity changes of the ponded water.
Lindsey *et al.* 1992		67% of Infiltration devices operating as intended after 2 years 49% after 6 years
Schuster *et al.*(2008)		Runoff as % of rainfall Wet conditions 77-87% Dry conditions 65-77%

Table 7: Peak and volume reduction for swales.

	Peak Reduction	Runoff Volume
Abida & Sabourin (2006)	36%	50% retention of inflow – Experimental study Runoff 3-15% of rainfall compared to 40% for conventional drainage – Field study
Ackerman & Stein (2008)		21-77% reduction for 10 swales 52.5% mean reduction
Barrett (2005)		47% reduction
Davis *et al.*(2011)	Light event 100% Moderate event 67-87% Heavy event 27-80%	Compared to highway runoff 0-34% reduction 27-63% reduction if check dams in place Complete capture of the smallest 40% of monitored storm events, Reduced runoff volume for an additional 40% of events, Negligible volume attenuation for the largest 20% of events
Deletic (2001)		0-78.3% reduction compared to inflow for 52 events 45.7% reduction to total inflow for all events
Deletic & Fletcher (2006)		Reduction in flow compared to inflow Inflow(l/sm) Wet Dry 0.33 33 87,62 0.67 55,23 45 1.00 25 17,15 Wet when grass had received water in previous 24 hours Lower second values for repeated experiments were due to clogging of the filtering layer
Jamil & Davis (2008)	56-60%	
Macdonald & Jeffries (2003)	52%-65%	84-85% reduction compared to runoff from road – 2 swales
Rushton (2001)		30% reduction
Sabourin & Wilson (2008)	Compared to conventional drainage 47-86%	Runoff volume reduction compared to conventional drainage 73-86%
Wu *et al.*(1998)	10-20%	

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