A Review of Current Knowledge

Hard Sustainable Drainage Infrastructure in the Urban Environment

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This review is one of a series of Reviews Of Current Knowledge (ROCKs) produced by FWR. They focus on topics related to water supply, wastewater disposal and water environments, which may be the subject of debate and inquiry. The objective of each review is to produce concise, independent scientific and technical information on the subject to facilitate a wider understanding of the issues involved and to promote informed opinion about them.

Review of Current Knowledge

Hard Sustainable Drainage Infrastructure in the Urban Environment

Permeable car park, Barcelona, Spain

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ABBREVIATIONS

Acronym	**Meaning**	**Section:**
BRE	Building Research Establishment	5.3
CSS	Carbon sequestration and storage	5.2
ECB	Engineering and Computing Building, Coventry University	6
EPS	Extracellular polymeric substance	3
GCH	Glyphosate Containing Herbicide	7
PPS	Pervious Paving System	1
RA	Recycled aggregate	8
RC	Runoff Coefficient	2
RCB	Richard Crossman Building, Coventry University	6
RWH(S)	Rainwater Harvesting (System)	1
SuDS	Sustainable Drainage Systems	1
UHIE	Urban Heat Island Effect	5.1
VA	Virgin Aggregate	8
WSUD	Water Sensitive Urban Design	9

Review of Current Knowledge

1 Introduction

There are two sister publications to the present Review of Current Knowledge in the FWR's library: in 2011 Ashley *et al*. produced "Surface water management and urban green infrastructure: A review of potential benefits and UK and international benefits" (FR/R0014) taking account of the wider benefits of this approach to, for example, mitigate and adapt to climate change, and in 2013 Evans and Orman updated "Urban drainage and the water environment: A sustainable future?" in FR/R0011. The latter detailed the problems associated with combined sewer systems, particularly in times of excess surface water leading to flooding. Whilst it might seem to be an oxymoron to be covering essentially "hard" infrastructure in a publication about Sustainable Drainage Systems (SuDS), usually perceived as being "soft", nonetheless, hard SuDS devices (or variously Best Management Practices (BMPs) in the USA, installations, or interventions elsewhere) such as those shown in Table 1 have been designed to address the three main properties associated with SuDS infrastructure – that of allowing water to infiltrate into the ground, detaining it and also conveying it slowly through a management train (Woods Ballard *et al*., 2007). Also shown in Table 1 are the specific applications of these measures in terms of the SuDS Management Train – a fully designed mix of suitable individual devices that efficiently act together hydraulically, chemically and aesthetically (see: Charlesworth, 2010). The last of these illustrates one of the main differences between traditional hard drainage and that of SuDS in that the management of stormwater is carried out mostly in full view of the public (see Fig 1). It is not hidden "out of sight, out of mind" but rather is used as a feature to enhance living spaces and quality of life (this is discussed in more detail in section 4).

Table 1 Hard SuDS devices as included in Woods Ballard *et al*., 2007.

Device	Description	Use
Pervious pavements	Infiltration of rainwater into underlying layers.	Source control
Filter drain	Trenches and drains filled with permeable material with a perforated pipe in the base of the trench.	Conveyance, pre-treatment, source control
Soakaways	Sub-surface structures for storing and disposal of water through infiltration.	Source control
Infiltration trenches	As filter drains but permits the infiltration of water through the base of the trench as well as the sides.	Source control, site control
Sand filters	Devices for treating water using sand beds as filter media	Pre-treatment, site control
Silt removal devices	Structures for trapping silt.	Pre-treatment
Pipes, sub-surface storage	Used as storage devices and for conveyance. Water quality can be improved via sedimentation and filtering.	Conveyance, site control
Rainwater harvesting	Can be used to store water at the building or site scale. Provides uses for harvested rainwater such as toilet flushing and garden watering.	Site control

Going back to the Management Train, Fig 2 shows how this is designed with source control at the building scale, and at the larger scale, site and regional control as well as conveyance of excess surface water through the train. Sometimes this is called a "Treatment Train" due to its ability to improve water quality; this aspect is covered in section 3. As it passes through the train, water is lost through infiltration into the ground, passage to groundwater or the receiving watercourse, and evaporation of water either naturally from the surface of the device, within its structure, or deliberately through, for example, the use of so-called "wet" pavements, covered in more detail in section 5.1. It is therefore a very different way of thinking of water in a city, rather than as an embarrassment, hidden out of sight and its existence forgotten by the urban inhabitants; instead Semadeni-Davies *et al*. (2008) suggest it should be treated as a "liquid asset" whereby the behaviour of water is taken account of first, rather than being forced to change its behaviour to accommodate that of society.

Figure 1 Examples of hard SuDS infrastructure designed into a Management Train in North Hamilton, Leicestershire

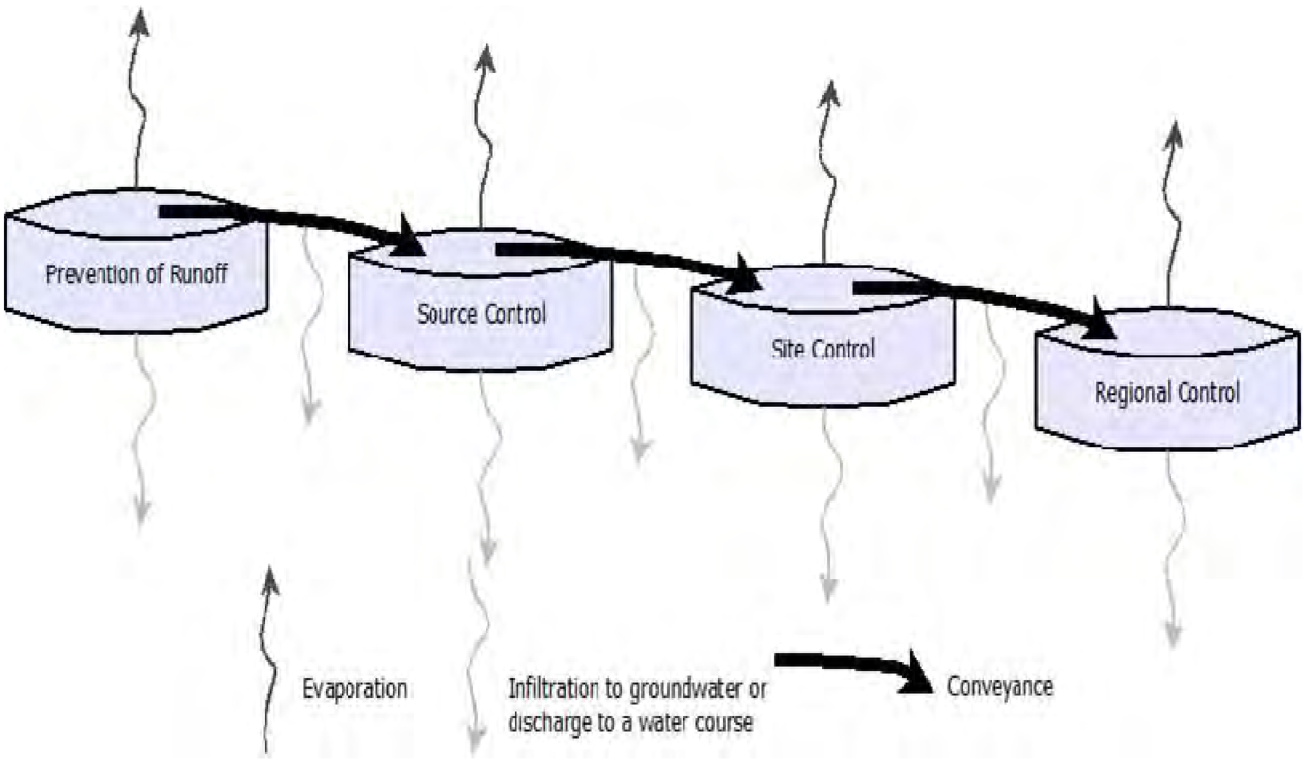
A. Bioretention area set into hard landscaping

B. Stepped flow down into retention pond

C. Weir used to throttle flow down a swale

D. Lined swale with aggregate bed

Figure 2 SuDS Management Train (after Lashford *et al*., 2014 and Charlesworth, 2010)



In order for any SuDS device to function effectively, it needs to be designed into the landscape. This is fairly easy in new build developments; however, arguably 70% of the dwellings needed by 2050 already exist, and there should therefore be a focus on retrofitting solutions to existing buildings. The main problem with retrofit is that it is perceived as difficult and expensive with such issues as land-take and up-front expense hindering their uptake. However, hard infrastructure such as pervious paving systems or PPS can simply replace the impermeable surfaces already in existence, therefore does not need extra land to install them, and there is evidence from Cost Benefit Analysis and Whole Life Costing that in the long term, PPS is no more expensive and in some cases cheaper, than traditional running and pedestrian surfaces. Gordon-Walker *et al*. (2007) state: *"Permeable paving costs less on a lifecycle basis than traditional surfaces, with reduced maintenance costs outweighing increased capital costs"*. It therefore represents a very viable and cost effective alternative to impermeable paving.

Whilst the SuDS triangle is familiar to most, with its equal treatment of water quantity, water quality, biodiversity and amenity (see Charlesworth *et al*., 2003), SuDS are far more flexible and multiple benefit that just these three (important) elements. Its multiple benefits were shown by Charlesworth (2010), with the SuDS "Rocket" which addressed several issues associated with adapting to, and mitigating, the effects of climate change. These included reduction of the Urban Heat Island Effect (UHIE) (see section 5.1) and carbon sequestration and storage (CSS) (see section 5.2). Whilst the former is not caused by climate change, it is in addition to, and exacerbated by it, and thus can be included as a benefit of hard SuDS infrastructure. The flexibility of SuDS include an enclosed or "tanked" PPS which can contain GSH or rainwater harvesting (RWH) systems with an overflow to a swale or bioretention and RWH coupled with a green wall growing green leafy vegetables (section 5.3) for local food provision.

The “hard” SuDS infrastructure in this ROCK concentrates on PPS, but will also include some of those devices listed in Table 1, such as RWH and infiltration trenches where details are available. There is some argument as to whether RWH is a SuDS device, but it is included here as it can be used in storm attenuation, reducing both volume and flow, as well as its usual function of reducing potable water use by providing an alternative source of water for toilet flushing, garden watering, car washing etc.

2 . Water quantity

Table 2 shows individual hard SuDS devices and their abilities to convey water from one device to the next, or to the receiving watercourse, detain water in their structure or infiltrate it into the ground and also their potential to attenuate the storm peak and reduce the total volume of excess stormwater. Sand filters perhaps have the least potential, whilst RWH has “high” peak flow and total stormwater volume reduction potential. As Table 2 shows, PPS does not convey water, but rather detains and allows infiltration. This is mainly due to its structure, detailed in the next section, which concentrates on its pollutant remediation role.

Table 2: Water quantity benefits of some hard SuDS devices

Device	Conveyance	Detention	Infiltration	Water Harvesting	Peak Flow Reduction	Volume Reduction
PPS		Good	Good	Some potential, subject to design	Good	Good
Soakaway			Good		Good	Good
Infiltration Trench	Some potential, subject to design	Good	Good		Medium	High
Sand filter		Good	Some potential, subject to design		Poor	Poor
RWH		Some potential, subject to design		Good	High	Poor/ Good

2.1 Pervious paving systems

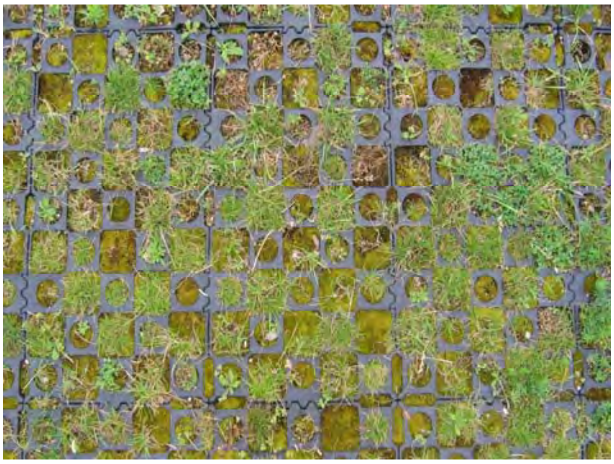
Key to the reduction of excess stormwater and the attenuation of the storm peak is in slowing down the flow of water through the drainage system. Hence, unlike impervious surfaces with which most city dwellers are very familiar, PPS allow water to infiltrate through the surface course into layers beneath. This can either be because the surface as a whole is porous (i.e. *porous paving*), for example porous asphalt and porous concrete or because the top layer comprises block pavers which are themselves impermeable, but which have slots incorporated into their design to allow water ingress beneath the blocks, in which case this would be termed a *permeable pavement* (see Fig 3a). *Pervious paving* is therefore a catch-all term for any hard running or pedestrian surface allowing water to percolate or infiltrate into the structure.

Vegetated PPS combines hard and soft infrastructure by utilising a surface course of plants, with the structural strength supplied by precast concrete containers or plastic grids (as shown in Fig 3b and c) further details of which can be found in Ashley *et al*. (2011).

Figure 3: Examples of different types of PPS

A. Examples of types of block pavers used in permeable paving systems

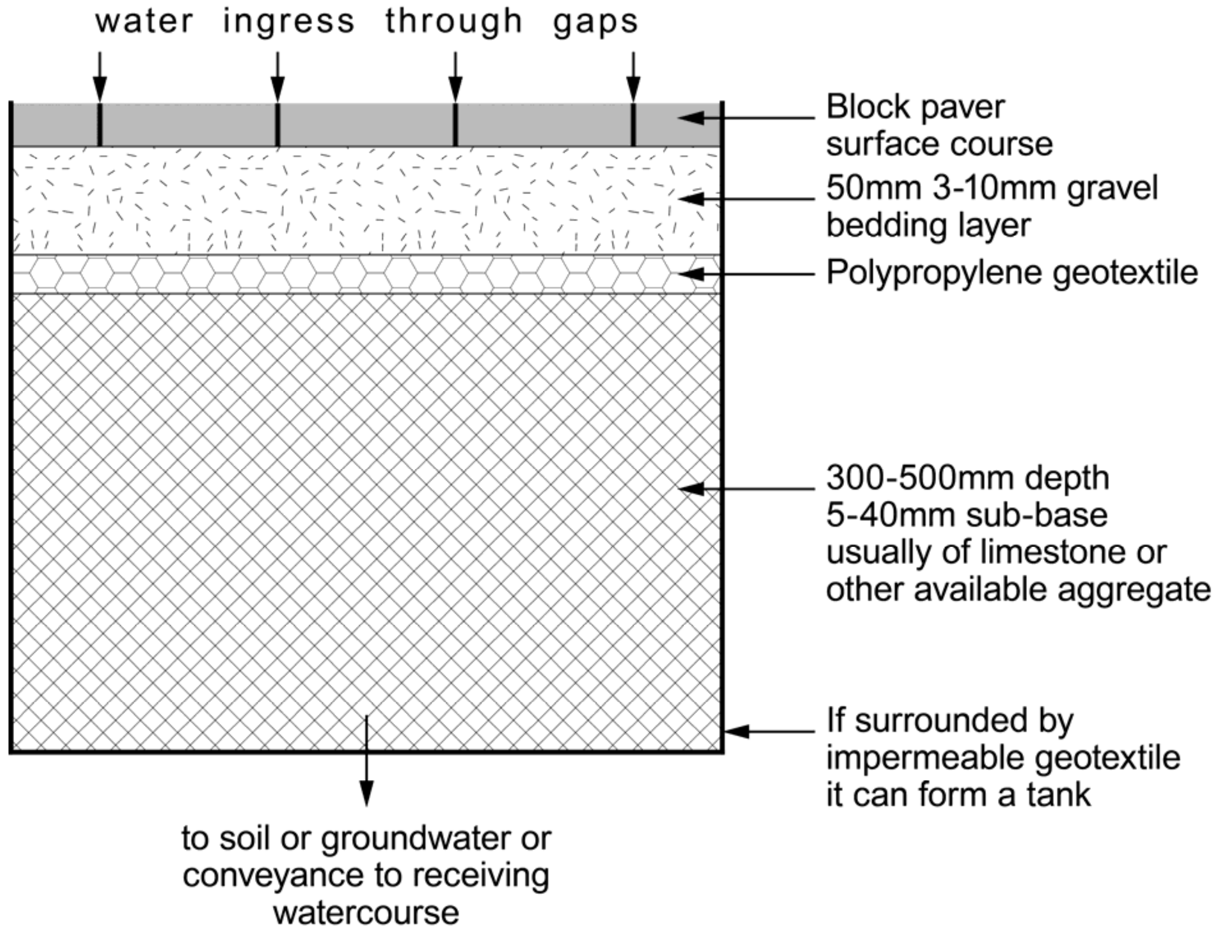
B. Concrete-supported vegetated PPS



C. Vegetated PPS supported by plastic grids

In general, the sub-structure of these different PPS are similar with the standard four-layered design used as shown in Fig 4.

Figure 4: Standard four-layered design of a PPS



The specific choice of construction largely depends on the properties of the ground underlying the PPS, such as soil and rock type. Mainly this concerns the ability of the soil to infiltrate water, whether it constitutes "brownfield" or not, ie whether it could be considered polluted, and the state, or presence of any aquifers beneath the proposed PPS. Designs of PPS therefore have to take account of the potential for pollutants to be carried through the structure with the infiltrating water and also of increasing flow in areas where flooding is an issue. There are three types of PPS according to Woods Ballard *et al*. (2007):

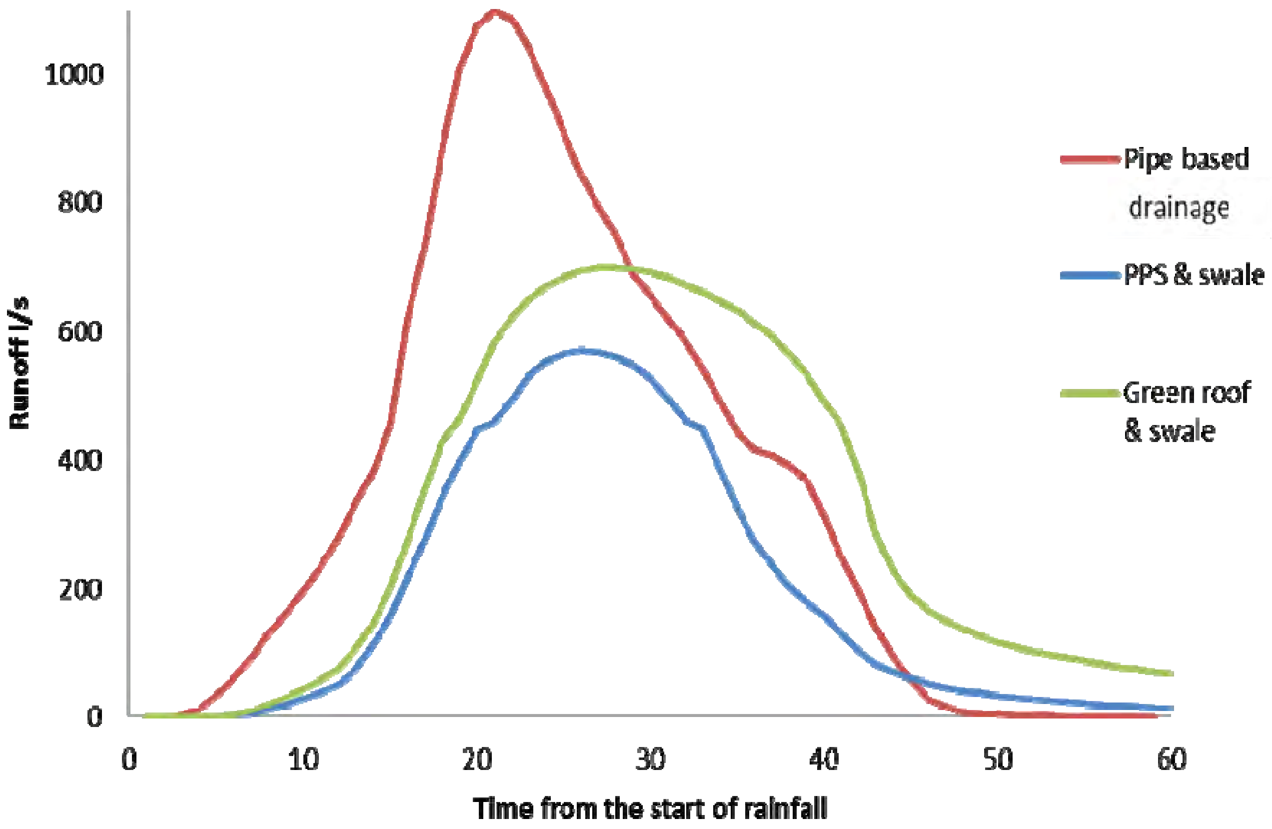
a. Unrestricted infiltration, whereby all runoff infiltrates into the underlying soil.
b. Infiltration is slowed, requiring additional storage in the structure of the PPS.
c. No infiltration of the water into the soil.

Water therefore enters the surface of the PPS through the pores in whatever the surface course is made of; the bedding layer beneath gives structural stability and strength and is generally a layer of gravel. Underlying this layer is the sub-base, a coarse aggregate, which supports the entire structure, also acting as storage for the water due to its large void space. In order to separate the gravel from the coarse aggregate underneath and to stop blocking of the aggregate layer by the finer gravel, many PPS manufacturers recommend using a geotextile. This is a layer of porous or non-porous polypropylene or polyester fabric (see Fig 5). Porous geotextile allows water to pass through from the bedding layer into the sub-base, whereas non-porous geotextiles can act as a seal, and if surrounding the whole PPS, can therefore turn it into a "tank" should the water need to be retained for a reason, such as using a tanked PPS for RWH, or as a combined device with GSH both of which are explained further in section 5.3. It was also found by Coupe *et al*., (2003) that the geotextile retained and degraded pollutants by filtering out particulates, and their associated contaminants as well and reducing dissolved pollutants, microorganisms and hydrocarbons. This property of the geotextile is further explored in section 3 where the development and role of the biofilm is considered.

Figure 5: Inbitex geotextile, commonly used in PPS

Lashford *et al*. (2014) compared the storm attenuation abilities of PPS with both a conventional piped drainage system and a green roof for a 1 in 100 year 30 minute winter storm using the modelling software *WinDes*. In the model, PPS was combined with a swale used to transport runoff away. Fig 6 is of the results using a hydrograph, the velocity of water against time, which shows that flow through the PPS is reduced by least 19% and that in this example, PPS is more effective at reducing peak flow than green roofs.

Figure 6: Modelled flow comparing runoff between a conventional pipe based system, and two management trains consisting of either PPS and swale or green roof and swale (adapted from Lashford *et al*., 2014). Flow is measured at the outlet of the system.



As is shown in Table 2, PPS has "good" peak flow and volume reduction potential which supports these results, and in other studies from Virginia, USA, it was suggested that PPS could reduce up to 75% of annual rainfall.

The rate at which water can pass through a porous concrete surface can be in excess of 1850 l/s/ha, however, this can reduce over time due to clogging. The extent of clogging is dependent on design, and some porous concrete pavements showed no signs of clogging after the equivalent of 26 years of service in laboratory trials (Yong *et al*., 2013). Regular cleaning of the system, removing any clogging materials, can increase the infiltration once more, thus, the success of PPS depends on it being maintained, although this need only be infrequent.

2.2 Storm attenuation using infiltration trenches and rainwater harvesting

Neither of these devices are necessarily the first choice when considering stormwater attenuation, however Table 2 does show potential for both of these to reduce the volume and flow of excess surface water. In fact, there is increasing interest in utilising RWH, particularly at the household scale for this purpose (EA, 2010).

2.2.1 Rainwater harvesting (RWH) system

The captured rain in a RWH system reduces the overall volume of stormwater by storing it and using it for toilet flushing, gardening, car washing and cooling air conditioning units rather than it being conveyed to conventional piped drainage, which would increase the volume of water in the sewer system (EA, 2011). However, the ability of a RWH system to reduce peak flows is dependent on the size of the tank, the type of roof and also how full the tank was before the onset of rain. The ease which rain runs off a roof is defined as its runoff coefficient (RC); the higher the RC, the greater the potential for RWH, as more runoff is generated. The smoother the roof, the higher the RC, so for example, sloping “metal” roofs have an RC of 0.95, but bituminous flat roofs have a lower RC at 0.7 - a smooth sloping roof has the potential to provide 50% more harvestable runoff than a rough flat one; flat roofs also lose potentially harvestable water due to evaporation.

In terms of flood prevention, Table 2 indicates that RWH has ‘Poor/ Good’ potential for both runoff and peak flow volume reduction; the impact of RWH does reduce over longer duration rainfall events as the tank fills. For example, Petrucci *et al*. (2012) monitored a village near Paris where 157 out of the 450 houses had taken up the offer by the local council to retrofit RWH, and found that the effectiveness of the RWH systems reduced with time as it continued to rain. An answer could be to increase tank size, and an increase of between 1.5 and 2.5 the times normal domestic tank size could result in the reduction in stormwater flows and volumes by up to 50% depending on the storm.

It is possible to compute harvestable volumes of rainwater related to roof area and rainfall amounts, and Charlesworth *et al*. (2014a) summarise this as well as the data and calculations needed to size subsequent RWH tanks and design the system, details of which are beyond the remit of this paper.

2.2.2 Infiltration trench

Infiltration trenches are generally gravel-filled ditches (see Figs 7 and 8a), possibly including a geotextile, which attenuate stormwater flows by providing local storage and infiltration, as identified in Table 2. As a device depending on infiltration for their role in SuDS, they must obviously be installed at sites with permeable ground underneath. They tend to receive runoff from impermeable surfaces, since they are very often located alongside highways (Fig 8b), and alleviate the resulting stress on sewer systems, therefore reducing flooding and providing groundwater recharge. However, for an infiltration trench to be successful, it must ‘manage’ or infiltrate all captured runoff within 72 hours in order to be ready to accept water from the next storm.

Figure 7: Diagrammatic representation of an infiltration trench

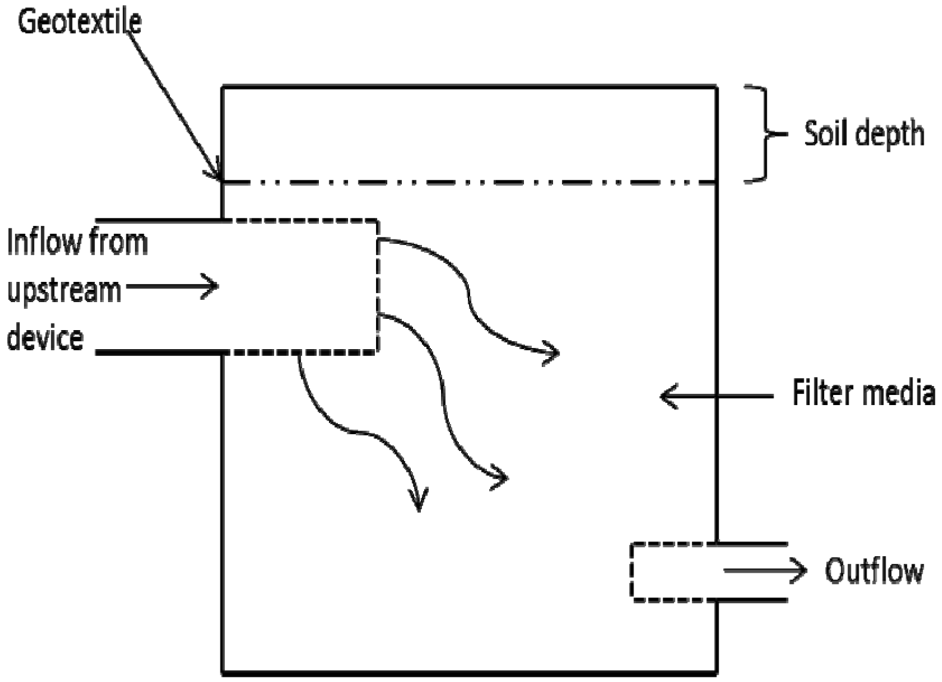


Figure 8: Infiltration trenches in Scotland (with kind permission of University of Abertay, SuDSnet)

A. Infiltration trench to the right of porus paving

B. Construction of an infiltration trench alongside a motorway

Whilst infiltration trenches do have the potential to reduce runoff rates, their ability to do so is limited; they are actually more effective at improving water quality. However, Barber *et al.* (2003) found that an infiltration trench could reduce up to 50% of a 24-hour 6.4cm rainfall event, which decreased to 10% as rainfall intensity decreased. In a study of infiltration trenches located in residential areas, Schluter and Jefferies (2004), recorded reductions in mean peak flow of between 45% and 75% and a reduction in average inflow volume of 25-90%. Table 2 indicates that infiltration devices had 'Medium' ability to reduce peak flow but a 'High' capacity to reduce runoff volume, but this performance depends on the infiltration rate of the site, and also the size of the device. However, infiltration trenches have large below-ground capacities, enabling them to detain large volumes of water prior to infiltration into the ground, which also helps to reduce the storm peak.

In common with PPS (see section 2.1) the long term effectiveness of an infiltration trench depends on proper maintenance and the removal of any clogging sediment. It is probably best, therefore, to trap fine sediment in detention basins or sediment filters before allowing runoff into the infiltration trench. In an evaluation of two infiltration trenches in Copenhagen over the first 15 years of service, Bergman *et al*. (2011) found that clogging reduced the overall efficiency of the system such that, without effective maintenance, flooding would increase, and after 100 years, 60% of runoff would not be retained by the trench.

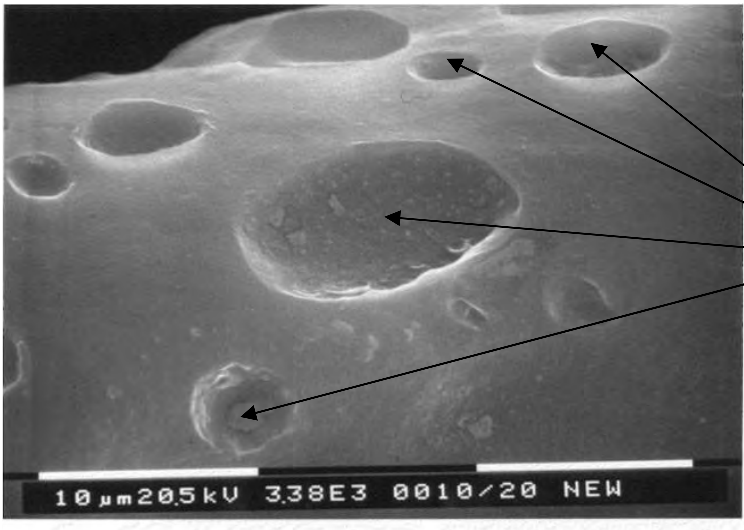
3. Water quality: Biofilm development, biodegradation and pollutant trapping

There has been a great deal of research on pollutant removal in PPS, but less so for infiltration trenches and even less for RWH. The following sections therefore concentrate on PPS, in particular on the growth of *biofilm* on the geotextile (see Fig 5) and its ability to improve water quality by physically trapping sediment, pollutants such as metals (e.g. lead, zinc, cadmium), and also its ability to use hydrocarbons in oil as a source of food.

3.1 Pervious paving systems

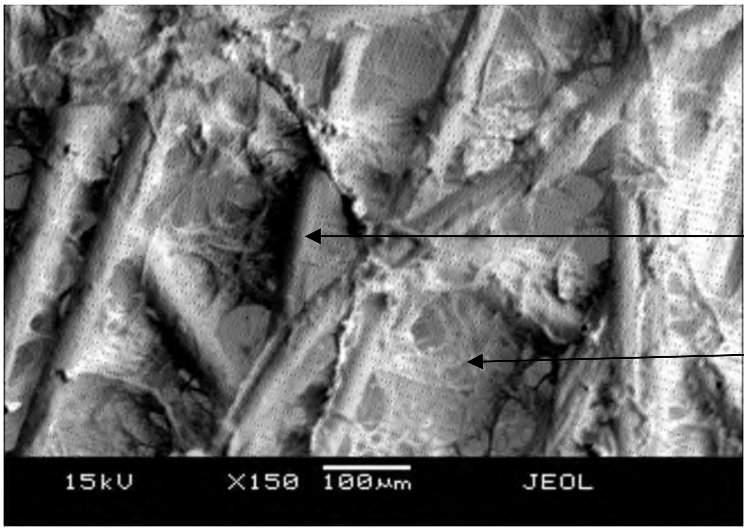
As was explained in section 2.1, many PPS contain a geotextile whose primary purpose is to separate the gravel from the aggregate beneath. However, researchers have found that a dense organic growth, known as a *biofilm* grows on the surface of the geotextile (see Fig 9). These biofilms are well-organised micro-ecosystems surrounded by a slimy, gel-like material called an extracellular polymeric substance or EPS which is produced by the biofilm itself. Biofilm growth generally occurs whenever water is in contact with a solid surface, for example inside suitable rocks, the clogging of water pipes or the slimy coatings found on stones or pebbles in streambeds. The single-celled microorganisms forming biofilms are closely packed together and firmly attached to each other via the protective EPS. Biofilm microbes are similar to those found in soil, including bacteria and fungi (see Fig 9b-d) and in favourable conditions, may include higher organisms in the food chain such as rotifers, tardigrades, nematodes and gastrotrichs, examples of which are given in Fig 10.

Figure 9 Photomicrographs of the development of biofilm



A. Surface of new geotextile fibre showing pits = 3.12 µm

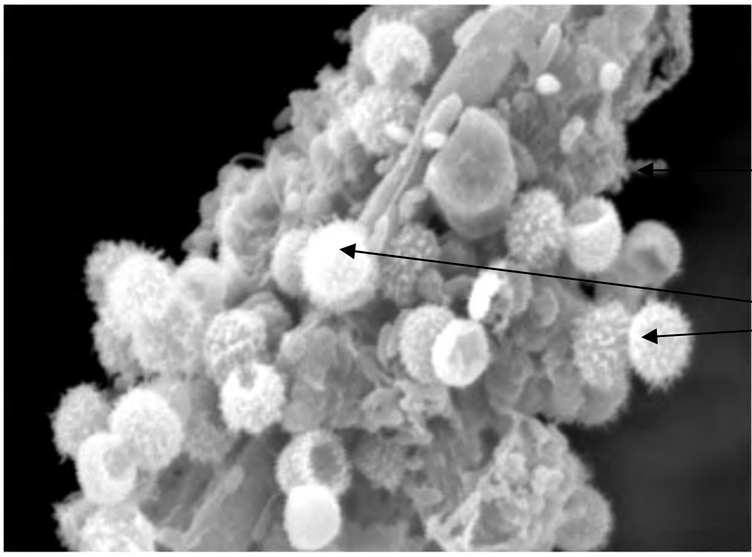
Pits



B. Geotextile after 6 months oil addition

Individual geotextile fibres

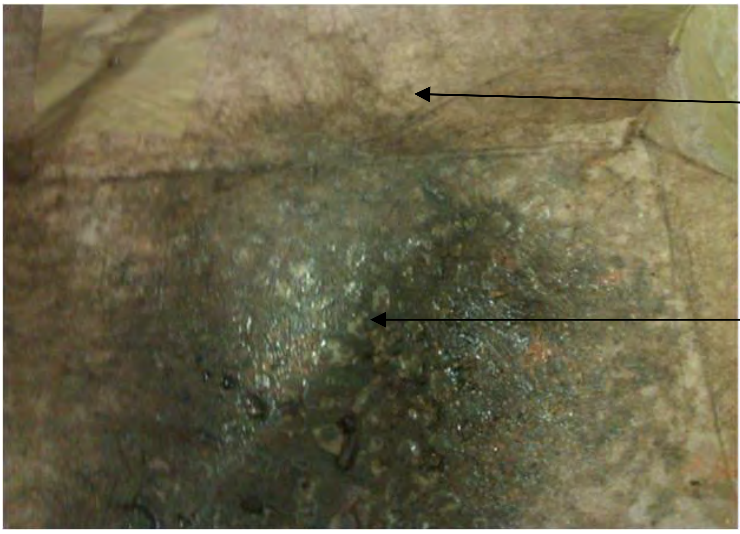
Biofilm



C. Fungal spores and bacteria on a geotextile fibre

Bacterium

Fungal spores



D. Biofilm growth on geotextile

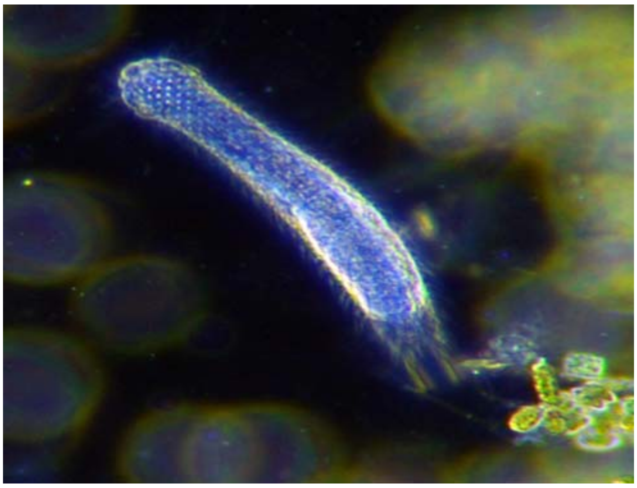
There is a successional structure in the biofilm, starting with the smaller, but more abundant species leading in time to the larger, but less abundant ones, with the predation of some species by others which controls their numbers. This leads to a diverse population which is essential to efficient biodegradation of contaminants; all trophic levels are needed for optimum biodegradation to take place.

Figure 10: Examples of higher animals which may be found in association with biofilms

A. Rotifer (source: S Coupe)

B. Tardigrade (source: Wikimedia Commons) Bob Goldstein & Vicky Madden, UNC Chapel Hill

C. Nematode (source: Wikimedia Commons) Alan R Walker



D. Gastrotrich (source:Wikimedia Commons) Jasper Nance

Due to the chemical compounds which make up the EPS, it carries a chemical charge which allows it to take toxic metals, minerals and nutrients out of the liquid which carries them and chemically bind them to itself; a small amount of EPS is capable of binding a relatively large amount of metals. Bacterial cell walls can also bind metals for example cadmium, nickel and zinc ions are generally found bound to their cell surfaces. Nevertheless, wherever the pollutants are bound within the biofilm, the fact that they are eventually dealt with there highlights the importance of the geotextile-associated biofilm in terms of the binding and retention of metals, and also the removal of hydrocarbons by degradation.

In common with metal pollutants, hydrocarbons, in the form of oil dripped onto the pavement surface, are treated in association with the geotextile-associated biofilm. However, rather than trapping, or binding these contaminants, they are used as a nutrient source by the microbes leading to up to 98.7% of the oil being removed and the outflow water being virtually oil-free (Newman *et al*., 2006). Phosphorus was identified as the limiting nutrient by Coupe (2004) and insufficient supply of this prevented adequate formation of the biofilm, and hence slowed biodegradation of hydrocarbons with time. In further research, fertiliser was added to the geotextile and Spicer (2006), found that microbial activity (measured by monitoring the carbon dioxide given off when hydrocarbons are broken down) was more than double that without fertiliser after nine weeks monitoring.

3.2 Water quality: infiltration trenches and RWH

According to the USEPA (n.d.) there is very little information about the potential for water quality improvements using infiltration trenches, however, some of the removal rates for quite a wide variety of pollutants are given in Table 3. Nilsson and Stigsson (2012) reported specific removal efficiencies for individual metals (zinc, lead, copper, chromium at 70-80% and cadmium, nickel at 50-60%). They also observed that the flow through infiltration trenches was efficient since the outflow was significantly lower than that of the inflow for all the storm events monitored.

Table 3 Pollutant removal efficiencies of infiltration trenches from the literature (Schueler *et al*., 1992; Winer, 2000; Nilsson and Stigsson, 2012).

Pollutant	**% removal rate**
Sediment	80-90
Total Phosphorus	60-100
Total Nitrogen	42-60
Metals	50-90
Bacteria	90
Organics	90
Biochemical Oxygen Demand	70-80
NO_x	82

There is even less on the potential for RWH systems to address water quality issues. In fact, the quality of the harvested water itself has been an issue for use inside buildings, e.g. for toilet flushing. Thus, much work has concentrated on sources of pollutants, particularly those from the roof and methods of water treatment so that the water is of suitable quality for its intended use (see Charlesworth *et al*., 2014a). These concerns include potential microbiological contaminants e.g. total and faecal coliforms (EA, 2010) as well as metals from the roof material such as copper and zinc, and pH changes due to dissolution of cement in the roof materials and the release of certain contaminants bound to the cement (Charlesworth *et al*., 2014a).

4. Amenity and Biodiversity

Biodiversity is mainly provided by the “soft” vegetated SuDS devices such as green roofs and ponds. As such, therefore, it is beyond the scope of the present ROCK which will concentrate in this section on amenity provision. The amenity benefits provided by SuDS devices are typically overlooked, often treated as the least important aspect of the SuDS triangle, with developers primarily focusing on water quantity and quality impacts (Apostolaki *et al*., 2006). Table 4 shows the general lack of amenity and biodiversity benefits offered by some hard SuDS infrastructure, however it does indicate that there is some potential, depending on the way in which the device is designed. Often, this potential can only be realised by its design into a management train, with other, more amenity- and biodiversity-rich devices such as those which are vegetated. As the rest of this section shows, whilst research in this area is sparse, even for vegetated SuDS, nonetheless there are opportunities to provide amenity in association with hard SuDS infrastructure.

Table 4: Amenity and biodiversity benefits of hard SuDS infrastructure (adapted from Woods Ballard *et al*., 2007).

Device	Aesthetics	Amenity	Ecology	Amenity Potential	Ecology Potential
PPS	Some potential, subject to design	Some potential, subject to design	Some potential, subject to design	Poor	Poor
Soakaway				Poor	Poor
Infiltration trench				Low	Low
Sand filter				Poor	Poor
RWH	Some potential, subject to design	Some potential, subject to design	Some potential, subject to design	Poor	Poor

It is difficult to define what exactly is meant by amenity, particularly when it is in relation to what is, essentially, a drain. Dictionaries define it variously as: “a useful or pleasant facility” (Collins Dictionary, 2012) or as having “the quality of being pleasant” (Oxford English Dictionary, 2012). However, the definition of amenity in relation to SuDS varies according to the author: Bray (2009) focuses on the added value they provide to a site, and the fact that they are visible to the urban population, whereas others consider the presence of storm water in the urban environment to be a benefit overall. Health and safety issues constitute particular concerns for both developers and residents when considering SuDS for a site, and are arguably one of the main reasons for the lack of interest in SuDS in England and Wales. However, SNIFFER, 2005, acknowledges that positive public perception and participation with SuDS systems is crucial for their long term success. Amenity provision is difficult to provide a *measure* of; it is possible to quantify its *use*, but pleasure is *experienced* by the individual, hence the difficulty in quantifying it since its value is subjective (Cho *et al*., 2006). In order to provide amenity and hence pleasurable spaces, SuDS must control flows and volumes to provide conditions that are predictable, with identifiably clean water for people to enjoy, but which will also support wildlife and the wider environment. SuDS are not at all like traditional piped drainage which is hidden from view, but are in full view of the public.

4.1 *Pervious Paving Systems*

There is very little difference, visually, between PPS and conventional impermeable paving and they present few health and safety issues. Since less water is ponded or pooled on the pavement surface, pedestrians can walk in more comfort. One of the largest vegetated car parks in Western Europe is found in Gijon, in the north of Spain, and provides parking for a local sports centre. It has more than 70 car parking bays and also includes some experimental hard PPS (Sanudo-Fontaneda *et al*., 2014). As can be seen in Fig 11, groups from the sports centre make use of it for walking and jogging, and local people also walk their dogs around the perimeter; these are not the sort of activities usually associated with large car parking facilities and indicate how amenity can be adopted, and valued, in time by the local community. The community benefits of PPS can be improved by the addition of an underground tank for water harvesting, for such uses as flushing toilets, irrigation and other non-potable uses at the household scale, possibly leading to long-term water savings. PPS, however, does offer the opportunity to improve the otherwise bland appearance of car parks by utilising different colours and shapes and thus adding to the aesthetic value of the area (see Fig 12).

Figure 11: Vegetated and hard infrastructure, Gijon Sports Centre car park, Northern Spain

Figure 12: Enhancing the aesthetics of PPS in public parking areas

A. Different coloured pavers delineating parking spaces and pedestrian areas at a plant nursery

B. Disabled spaces delineated using different coloured pavers, ACT-UK Building, Coventry University Technology Park, Coventry, UK

4.2 Rainwater harvesting

Table 4 shows that, in common with PPS, RWH has only limited potential for amenity, ecology and aesthetics. However, research by Gabe *et al*., (2012) in New Zealand indicated that by ensuring communities engage with RWH, there is likely to be an increase in both understanding of the system, and wider social benefits by integrating water into urban design. Furthermore, as RWH is typically seen as the most consumer friendly, "cheap" approach to integrating retrofit SuDS, it tends to be more readily adopted, therefore enhancing public awareness of the benefits of SuDS (White, 2010). The key amenity benefit of RWH is its integration into the household water system reducing reliance on potable water and Ward *et al*., (2009), found that UK households were open to the use of runoff from roofs as a source of water, however remain cautious of runoff from other sources. The recent increase in adoption of RWH in Australia was driven by the simplicity of retrofitting it (White, 2010) which is a typical justification in areas that suffer water stress. Water scarcity will further drive uptake of RWH and its use for agricultural and household purposes.

Health and safety is a key concern regarding RWH uptake (Gabe *et al*., 2012) since runoff can present a series of water quality issues which need to be filtered out before it can be used in the building. However, if designed effectively, RWH can provide a sustainable source of non-potable water at the small scale for individual households as well as at the larger scale for industrial and various institutional buildings (Charlesworth *et al*., 2014a).

4.3 Infiltration trench

Table 4 suggests that infiltration trenches provide limited site amenity benefits, along with a "Poor" potential for ecology. However, infiltration trenches can be "greened" which can enhance both site biodiversity and aesthetics. The ultimate in "greened" infiltration trenches are BioEcods (Zakaria *et al*., 2007) which have been designed for use in tropical areas where disease vectors, such as mosquitoes may be a problem, and thus the water has to be isolated from the land surface. If designed correctly, they can form part of a management train in many different climate types, integrated prior to a PPS, installed alongside roads, providing additional “green space” and managing runoff. Stakeholders rarely consider infiltration trenches in their top three priority SuDS devices to address community or environmental issues, ecosystem services or to integrate into a management train (Uzomah *et al*., 2014).

5. Beyond the SuDS triangle

Charlesworth (2010) proposed an extension to the traditional SuDS triangle which reflects the multiple benefits SuDS can provide, but also its flexibility as an approach. By adding the ways in which SuDS can offer mitigation of climate change, and adaptation to the changes already brought about by it to the SuDS triangle, the resulting SuDS “Rocket” addresses the UHIE, energy usage, carbon sequestration and storage (CSS) and human health and wellbeing. Some of these benefits are associated with green infrastructure and their ecosystem services, but hard infrastructure can also play a part as discussed in the following sections.

5.1 UHIE mitigation, wet pavements and brown roofs

Nearly 2 centuries ago in 1819, the UHIE was reported from London (GLA, 2006). This phenomenon is peculiar to cities where, even in winter, the urban area can be several degrees warmer than the countryside surrounding it; for example, night-time temperatures in London can be up to 9^{o} C higher than those in rural areas. The UHIE certainly has adverse impacts on human comfort, but also has the potential to cause human health issues, even death, particularly during extreme events. The causes of the UHIE include the removal of vegetation from urban areas and its replacement by concrete and asphalt which absorb and then release heat. Evidence of this from Wilson *et al*. (2003), used remotely sensed images to show discrete heat islands associated with the spatial distribution of roads, pavements and buildings; temperatures in parks and greenspace were similar to those of surrounding rural areas, showing the potential for vegetation to cool cities. Other factors related to this excess heat in cities include energy use to both heat and cool buildings to comfortable levels, resulting in the release of excess energy which in turn adds to the UHIE.

Robitu *et al*. (2006) argue that cooling by evaporation or *evaporative cooling* is one of the most promising means of addressing the UHIE. Moisture is evaporated from pavement surfaces or inside the layers of a PPS to cool the overlying atmosphere. PPS have therefore been designed with materials such as slag, bentonite and diatomite that can retain water and have maximum evaporative properties (Okada *et al*., 2008). When it was found that water was released from these structures too quickly, reducing their cooling ability, “wet pavements” were developed (e.g. Yamagata *et al*., 2008), whereby reclaimed wastewater was applied to the pavement surface during the day. Used in Tokyo, they reduced day time temperatures by 8^{o}C and temperatures at night time by up to 3^{o}C. This wet paving can be used in combination with so-called “cool pavements” (US EPA, 2009). These have a higher albedo, or solar reflectivity, than conventional paving, and thus combining them in PPS for cooling the urban environment looks promising. In a study in a public park in Athens, Greece, results of the monitoring of a 4500 m^2 cool pavement by Santamouris *et al.* (2013) estimated that the peak ambient temperature of a typical summer’s day across the city could be reduced by up to 1.9 ^{o}C and that across the park itself by 12 ^{o}C.

Evaporative cooling is generally associated with vegetated devices, such as green walls and roofs, however there has been progress in the investigation of a variety of porous and non-porous materials for use on roofs which do not include plants, so-called “brown” roofs. An example of one of these materials is siliceous shale which could reduce daily average surface temperatures by as much as 8 ºC (Wanphen and Nagano, 2009). The overall advantage of this simple design is that it does not require maintenance of vegetation, and thus the USEPA, (n.d.) consider it a positive addition to the SuDS options available.

Charlesworth (2010) lists some Participating Cities in the C40 Clinton Climate Initiative which include SuDS devices in their climate change strategies. Examples include Chicago which incorporate PPS in their “green alley” initiative, New York quoting PPS and RWH, Philadelphia, Tokyo and Toronto making use of PPS with Tokyo specifying “water retaining” pavements, and Sidney and Chicago utilising RWH. Other climate change strategies include the storage and sequestration of carbon which can also be undertaken in hard SuDS infrastructure are discussed in the following section.

5.2 *Climate change adaptation and mitigation: C-neutral materials, carbon sequestration and storage*

SuDS are well placed to offer adaptation to the changing climate and also mitigation of changes that have already taken place (Charlesworth, 2010). As discussed in the previous section, SuDS can offer cooling of the UHIE and also carbon sequestration and storage or CSS. CSS is more often associated with green infrastructure, and there has been much research, for example on the potential for urban trees to absorb and store excess atmospheric carbon (Charlesworth, 2010). Utilising C-neutral materials, or even those that absorb carbon, in hard SuDS infrastructure is still in its infancy, although section 8 does cover the use of Recycled Aggregate (RA) in PPS which can lower the C-footprint of such devices. There is no reason why C-neutral or C–absorbing materials should not be made into e.g. block pavers, and indeed some manufacturers are now using, for example recycled glass to make them.

Claisse (2013) estimates that using C-absorbing materials as block pavers could result in CO_2 savings of roughly 150,000 tonnes per annum (±50%) in the UK. There has been much research on the CSS potential of the near-surface of pavement samples, where it has been found there is the potential to sequester 75% of near surface carbon (Haselbach and Thomas, 2014). However, Claisse (2013) highlights the sequestration potential of *crushed* demolition waste offering a high surface area for CSS which may be increased when wetted, giving its use in PPS added benefits (see also section 8).

The manufacturing of typical Portland Cement accounts for 5% of all human-created greenhouse gas emissions (Amato, 2013). By replacing it with reactive magnesia, there is potential for the material to absorb carbon as it sets, and furthermore, it has been found that porous blocks containing reactive magnesia cement had better structural strength than standard Portland Cement. Reactive magnesia can also be combined with waste materials, such as ground granulated blast furnace slag which also increases hardness and strength in the final product. A further benefit of reactive magnesia is that it requires a lower temperature to form than Portland Cement which requires temperatures of up to 1450°C, as opposed to reactive magnesia’s 750°C; therefore there is a significant reduction in carbon dioxide outputs during the processing phase (Liska *et al*., 2012).

There would therefore appear to be potential for the production of C-neutral and CSS cement and concrete to make block pavers for PPS. However, PPS are relatively unusual environments, and it would have to be determined whether the ability to sequester and store carbon would compromise these abilities in PPS, or whether water infiltrating the pavement would compromise CSS.

5.3 *Multiple benefits of hard SuDS infrastructure*

SuDS are often described as being flexible and multiple benefit (Charlesworth, 2010), and this is illustrated by combining technologies to provide more than one function. Examples discussed in this section include the use of tanked PPS for RWH as well as with GSH and combining RWH with green infrastructure.

Harvested rainwater cannot be used for drinking in the UK, but in some African countries and Australia it can be drunk and used in cooking (Sazaklia *et al*., 2007). As has been detailed in earlier sections, water infiltrating through the PPS is essentially treated, and research in the laboratory has found that water harvested through various PPS designs can be successfully used to irrigate a variety of food plants, such as rye grass and tomatoes (Nnadi, 2009). The outflow water collected and used for irrigation in these experiments were within WHO drinking water guidelines, producing fruits that met international standards.

In a field study conducted at the Hanson Ecohouse (Fig 13a) on the Building Research Establishment's (BRE) Innovation Park, Watford, UK site, rainwater was harvested through a tanked PPS associated with a 3-bedroomed family home (Coupe *et al*., 2014). The rainwater was collected from the roof (downspouts were cut off as shown in Fig 13b) and surrounding pavement with a total collecting area of about 100 m^2 and a total tank capacity of 4 m^3. The harvested rainwater was used to flush two variable-flush WCs and was connected to an outside tap which was used for car washing and garden irrigation. At times, the tank overflowed, and this was conveyed to a swale at the centre of the Innovation Park (see Fig 13c) providing biodiversity and some amenity benefits.

Figure 13: Example of a combined tanked PPS and RWH conveyed to on-site swale, Hanson Ecohouse BRE Innovation Park, Watford, UK.

A. Hanson Ecohouse

B. Downspout from Ecohouse roof cut off to allow water to flow into PPS tank

C. Overflow swale

Also associated with the Hanson Ecohouse, but separate from it, the first use of a combined tanked PPS and GSH was installed in September 2007 (Coupe *et al*., 2009). A detailed explanation of heat capture from the ground is beyond the scope of this ROCK, so the reader is directed to other publications such as Singh *et al*. (2010) Curtis *et al*. (2005) or Lund *et al*. (2011) for further information. However, in summary, GSH operates at relatively low temperatures, extracting heat from the ground. When the outside air temperature is low, the ground temperature will be higher and thus this heat can be transferred into the building. It can also operate in reverse by acting as a heat sink by transferring excess heat in the building back into the ground. It has been established that this heat transfer is more efficient when the environment of the heat collectors is damp, or even wet, thus a tanked PPS collecting rainwater would appear to be ideal. Fig 14 a and b show the structure of the PPS and the location of the geotextile and GSH collectors. In this case study, the GSH collectors were horizontal "slinky coils" laid in the bottom of the PPS tank.

Faraj (2013) monitored the efficiency of the system for 3 years, which included two of the coldest winters for 30 years, to assess its ability to adequately heat the house. Key findings of the study were that the system was capable of providing sufficient heat for the house to be at defined "comfortable" temperatures (i.e. 19.5±0.5^{o}C in winter and 21±1^{o}C in summer, CIBSE, 2006) at times throughout the year. However, the overall Coefficient of Performance of the system was low, at 1.8, whereas to be considered under the EU Renewable Energy Directive, it needs to be at least 2.875. Lessons have been learnt from this study, one of which was to increase the depth of the tank, and Coupe *et al*. (2014) report on the successful utilisation of 6500 m^2 of PPS used to heat, cool and drain a 7000 m^2 office block.

Figure 14: (A) Installation of combined tank PPS and GSH at Henson Ecohouse, BRE, Watford, UK. (B) The tower used to collect temperature data from the combined system.

Concerns have been expressed over potential water quality problems in such a combined system, but Coupe *et al*. (2014) report that water quality in the combined PPS and GSH at the Ecohouse was good and laboratory experiments conducted by Tota–Maharaj *et al*. (2010) found no significant problems associated with either water chemistry or potentially pathogenic organisms in the water harvested and stored in the tank.

Also at the BRE site, and an illustration of combining so-called “hard” and “soft” SuDS infrastructure, was a green wall retrofitted in 2009, growing grass, but also green leafy vegetables (see Fig 15) which was irrigated using rainwater harvested from the building roof. The water was stored at ground level, and therefore had to be pumped back to the green wall, but there are now roof- and gutter-level tanks which could also be retrofitted and which would simply rely on gravity to feed the water to the green wall.

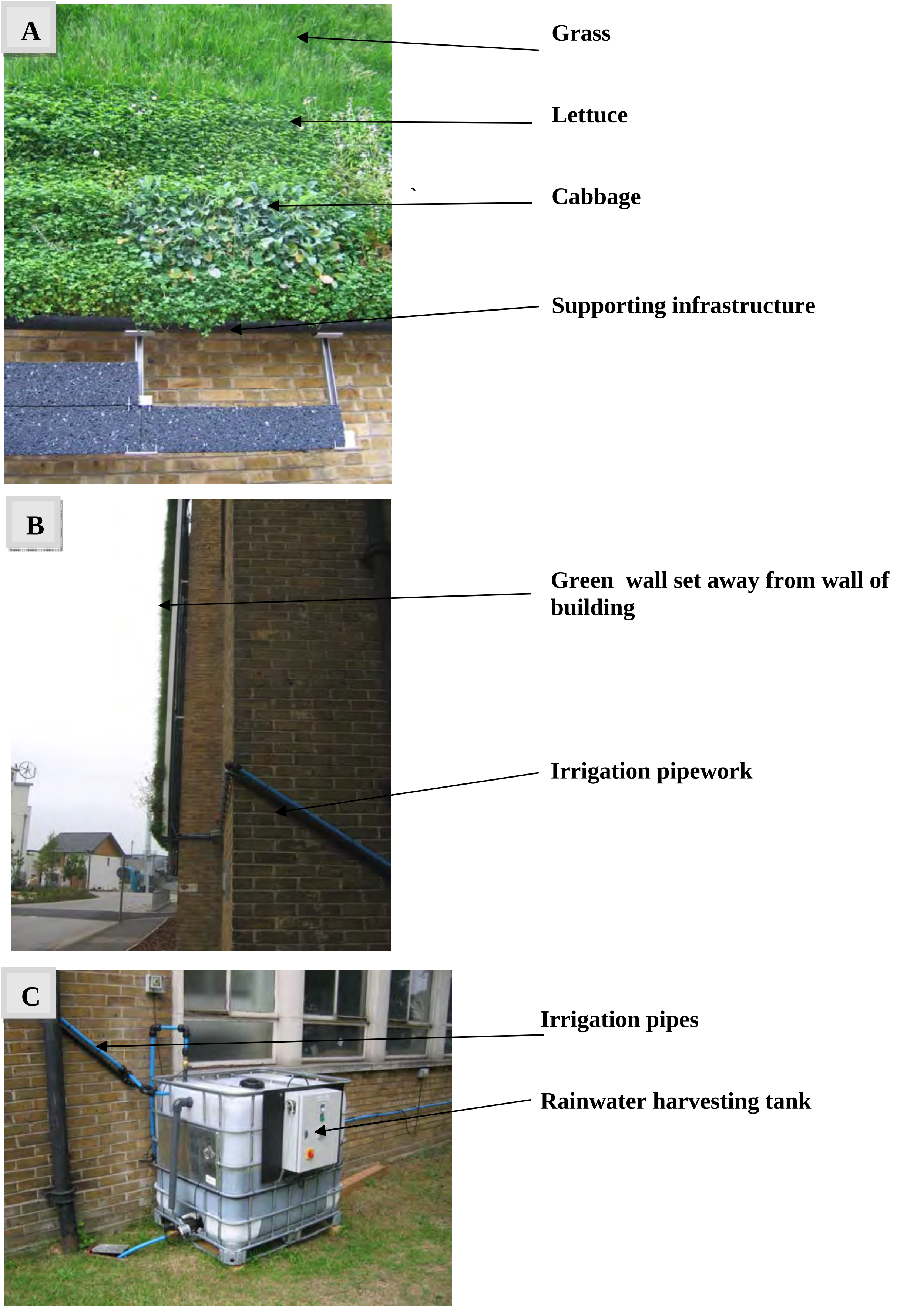
6. Designing sustainable drainage using hard infrastructure

Integrating SuDS into new build developments is relatively easy, although the drainage system still has to be designed properly, in the same way as conventional drainage must be (see Watkins and Charlesworth, 2014; Scholz *et al*., 2014). However, there are substantial differences in the two approaches, not least that SuDS, unlike conventional drainage, should be visible, integrating water as a designed feature in the urban environment and ensuring it has a role as a useful or pleasurable place for those living and working there (see section 4 for more about amenity aspects of SuDS). This is in direct contradiction to the role of traditional or conventional piped drainage whereby water is hidden away underground and removed from the urban area as quickly as possible. Whilst vegetated or “soft” SuDS are much more visible, hard SuDS tend to be more focussed on detaining water, which is often stored underground, subsequently allowing for its infiltration into the surrounding soil.

Detailed coverage of the hydraulic design and calculations required for individual SuDS devices, and their integration into management trains is beyond the scope of this publication, but further details for PPS can be found in Scholz and Grabowiecki (2007) for RWH, tank sizes, volumes and flows can be found in Charlesworth *et al*. (2014a) and for infiltration trenches Chahar *et al*. (2012) give useful guidance. Design of SuDS overall is covered in great detail in Woods Ballard *et al*. (2007).

By successfully integrating hard SuDS infrastructure into site design, there is a greater potential to satisfy all criteria of the SuDS triangle and beyond it (see Charlesworth, 2010). However, if hard SuDS are incorrectly designed, poorly integrated and inadequately maintained they are likely to deteriorate quickly (Wilson *et al*. 2004).

Figure 15: Retrofitted green wall (A and B) supplied with harvested rainfall from the building roof (C), BRE Innovation Park, Watford UK



6.1 Integrating hard SuDS infrastructure into urban design

Charlesworth (2010) represented SuDS design as a "Bulls Eye" in which small "patches" of, for example, PPS were installed in the centre of the city, along with RWH and concrete lined rain gardens. In the suburbs and urban periphery, larger individual devices such as ponds and wetlands could be used, as well as the design of a full Management Train as was shown in Fig 2. Devices normally associated with "soft" infrastructure can be modified to integrate into cities by lining with concrete, or channelising, as shown in Fig 16 and also earlier in Fig 1.

Figure 16: Examples of the use of hard landscaping in the design of SuDS devices

A. Berlin: downspout cut off and allowed to runoff into concrete lined raingarden

B. Berlin: concrete block lined channel in filter strip

C. Berlin; hard landscaped area in front of high rise blocks with "ponds" and "rivulets" at various levels slowing the water down

D. Formal pond, Springhill SuDS management train, Gloucestershire (source: Simon Watkins)

RWH is slowly becoming more acceptable across the UK, with an increasing number of residential buildings opting to capture and recycle water, although the figures for its uptake remain lower than the rest of Europe (Ward *et al*., 2012). The UK Environment Agency, 2007, suggested that up to 75% of existing industrial and commercial plots could integrate RWH systems, as well as up to 50% of all domestic buildings. Whilst RWH is considered "cheap" and relatively easy to retrofit, PPS and infiltration trenches are both expensive in terms of upfront costs but their cost benefit analysis and whole life costings (Gordon-Walker, 2007) show that they are cost effective when compared, for example to the £3.2 billion total economic costs of the 2007 floods (EA, 2010) or the £174 billion (2007-08 prices) that Ofwat (n.d.,) calculate as the cost to upsize the 309,000km of sewers in the UK that would potentially take centuries to deliver.

The UK Environment Agency (2007), conservatively estimates that more than 50% of off road hard surfaces could be made permeable, whereas just 4% in urban areas and 20% in rural areas could be utilised for infiltration trenches.

6.2 Case Studies

The use of SuDS across England and Wales is now becoming more frequent. Legislation in Scotland has promoted the use of SuDS for longer, however, as the following section shows, a number of sites across the UK have adopted hard SuDS to take a more sustainable approach to drainage. The SUSdrain website has a number of SuDS retrofit case studies (see: http://www.susdrain.org/case-studies/), and some successful sites will be discussed in the section following.

a. Wauchope Square, Edinburgh, Scotland.

The redevelopment of the 7ha Wauchope Square (Interpave, 2012; Pittner and Allerton, 2009) was completed in 2009 as part of the wider Edinburgh Craigmillar Regeneration Project. It was a key site for SuDS due to issues with water quality management due to diffuse pollution. As space was critical, PPS was used extensively, combining areas of both porous asphalt and permeable block paving. See:
http://www.skintwater.com/web/skint/NL/0,0,7,1180/Wauchope%20Square%20Redevelopm.
The purpose of the system was to promote both infiltration and evaporation of runoff, whilst also directing some runoff into the local sewer system after treatment.

b. Coventry University Campus

Coventry University has both retrofitted hard SuDS into its buildings on campus (the Richard Crossman Building, RCB), and also integrated hard and soft approaches into the design of two new buildings: the Engineering and Computing Building (ECB) and the Student Centre or Hub. At the RCB, a courtyard of combined block pavers, porous asphalt and porous resin paving surrounding existing trees has been installed to provide an outdoor teaching space with a small set of semi-circular benches providing seating and a focus for the area (Fig 17A). Before this was retrofitted, it suffered from frequent ponding with areas of mud which became trampled and in which plants would not grow. The ponding has now stopped and bioretention for any runoff is provided by surrounding borders which contain edible plants and flowers.

Both the Hub and ECB have green roofs which intercept rainwater and slow runoff (see Fig 17b and c). Any runoff from the roofs without greening is directed into harvesting tanks (see Fig 17d and e) where it is used for flushing all toilets in each building, resulting in an overall net reduction in potable water consumption. Furthermore, both buildings have achieved an 'Excellent' BREEAM rating (Coventry University, 2013).

Figure 17: Examples of hard landscaping used in buildings around Coventry University campus: new build and retrofit

A. Richard Crossman Building retrofit area

B. Green roof, ECB

C. Green roof, the Hub

D. The Hub, 20,000 litre RWH tank

E. ECB, 80,000 litre RWH tank

c. Bognor Regis Sports Centre

The Bognor Regis Sports Centre was built in 1999 (see: http://www.susdrain.org/case-studies/case_studies/bognor_regis_sports_centre_west_sussex.html). Since all runoff from the site required slowing down and attenuating, Southern Water, the local Water Company, limited discharge to 7l s^{-1}, therefore, the design of the 2ha site incorporated a series of SuDS devices, including both PPS and infiltration trenches. The infiltration trenches provide attenuation for runoff from the sports pitches, particular during high flow, whilst the PPS was installed in the access roads and some of the 136 space car park. Runoff from the Sports Centre roof and hard standing around the site was directed onto the PPS. Overall, the site has dealt sufficiently with all rainfall events since its inception, reducing the flood risk for the site and promoting groundwater recharge via the infiltration devices.

d. Nottingham Retrofit Rain Garden Demonstration Project

Completed in 2013, and initiated due to both flooding and water quality issues, the Nottingham Retrofit Rain Garden Demonstration Project was a result of collaboration between the Environment Agency, Nottingham City Council, Groundwork Greater Nottingham and Severn Trent Water and is an example of the combination of hard and soft SuDS infrastructure. 21 linear rain gardens were installed along a quiet residential street of 67 houses within the grass verge and taking account of the need for access via driveways to the properties as well as provision of underground services. Fig 18 shows the successful integration of the rain gardens into the street.

Figure 18: Nottingham Retrofit Rain Garden Demonstration Project (source John Brewington, EA MURCI Waters Coordinator)

A. Completed rain gardens

B. Rain gardens under construction

C. Inlet to completed rain garden

More information on the monitoring of these rain gardens can be found at: http://www.susdrain.org/case-studies/casestudies/nottingham_green_streets_retrofit_rain_gardenproject.html
The rain gardens were designed for the 1 in 30 year storm event, to capture runoff from 5500 m^2 of highway and to treat the polluted first flush, which is the first 10% of the storm, and carries the most polluted water. Monitoring is ongoing (J. Brewington, *pers. comm.*), however initial

storm hydrographs of 5 rainfall events indicate that the rain gardens intercepted up to 0.35 cm of rain; modelling the impacts of the rain gardens on water quantity indicated a potential reduction of 33% in the amount of water discharged to the sewer following a 1 in 1 year return period event.

7. Emerging pollutants and PPS: a case study of glyphosate-containing herbicide

Research focus on contaminants in general has changed over time as concerns over certain urban pollutants have largely been addressed, e.g. by the introduction of unleaded petrol. However, these have been replaced by other New and Emerging Pollutants (NEPs) which include Pharmaceutical and Personal Care Products (PPCPs) such as non-steroidal anti-inflammatory drugs e.g Ibuprofen, hormones eg from contraceptive pills, cosmetics, perfumes and pesticides (Ellis *et al*. 2013). Whilst there has been research into the impacts of these PPCP compounds on urban watercourses, little of this wider research has focussed on their impacts on SuDS devices. Recent work at the laboratory-scale has assessed the impacts of one these potential pollutants – glyphosate-containing herbicide or GCH – on the geotextile-associated biofilm whose structure and function is detailed in section 3.1.

With changes in legislation throughout the UK, it is likely that more SuDS devices, such as PPS, will be used as driveways for individual front gardens, or in larger amenity areas. In order to control weeds, householders and Local Authorities frequently use herbicides and those containing glyphosate are amongst the most widely used worldwide. The efficiency of GCH is enhanced by the addition of a soap-like substance, or surfactant, which may partially account for the compound’s relatively high aquatic toxicity (Tsui and Chu, 2004). Depending on the formulation, and the concentration of glyphosate the product contains, it requires at least a minimum classification of R53 ‘May cause long term adverse effects in the aquatic environment’. Whilst it is known that GCH is readily broken down in soils, there are few studies of the use of such dissolved chemicals on SuDS devices such as PPS, and their subsequent ability to carry out their pollution remediation role.

Coupe and Smith (2006), applied GCH to some biofilm growing on geotextile and found that it substantially increased the mortality of protozoans. Mbanaso *et al*. (2012) monitored the impacts of GCH on small laboratory-based test rig PPS, particularly hydrocarbon breakdown; outflow water quality (Charlesworth et al., 2014b) and the impacts of the GCH on non-target organisms (Mbanaso *et al*., 2014). The findings in general were that application of GCH compromised the PPS’s ability to manage pollutants and that the biofilm was affected negatively, particularly with respect to diversity of species.

With the half-life of GCH in soil at about 4 days and the flow of water through a PPS at the most a matter of hours, there is also the potential for GCH and its breakdown products to reach the aquatic environment through permeable surfaces, and with legislation encouraging the use of SuDS, recommended guidelines for herbicide application to PPS are urgently needed.

8. *Sustainable* drainage?

Taken broadly, sustainability aims to balance the environment, economy and society; as such, SuDS badges itself as being “sustainable” which does beg the question of the extent to which it fulfils the criteria to make it fully sustainable. Environmental considerations are covered in the water quality, water quantity and biodiversity benefits of SuDS. There has been much research on the first two, with some research undertaken around biodiversity. In terms of social aspects, covered by amenity in the SuDS triangle, there has been very little research carried out as detailed in section 4 of this document. Heal *et al*. (2004) highlight four main issues with regard to the sustainability of SuDS:

1. They require regular maintenance, inspections and interventions, as does traditional piped drainage;
2. Section 3 detailed the potential of PPS to improve water quality, by trapping and biodegradation of contaminants. However, ultimately, there is little is known of the ultimate fate of these pollutants, particularly non-degradable toxic metals;
3. Hard infrastructure would need to be designed in with soft, vegetated devices as a management train in order to fulfil the "biodiversity" side of the SuDS triangle and thus achieve sustainability; and
4. Unless designed and managed properly, SuDS devices will fail, in the same way as conventional piped drainage. Here, the primary factor impairing SuDS performance is clogging, particularly infiltration trenches and PPS. Effective design must therefore trap any sediment without reducing the overall functioning of the system (Woods Ballard *et al*., 2007). Additionally, an understanding of conditions suitable for devices must be taken account of, for example RWH is less effective on certain types of roof as described in section 2.

Social acceptability is also of fundamental importance if SuDS are to become common. If SuDS are unacceptable to those living close by, for example due to health and safety concerns of open water, householders and land owners will remove or replace them, thus rendering the approach unsustainable. There has been very little research into public perceptions or acceptability of SuDS devices, particularly hard infrastructure.

PPS and infiltration trenches both make use of gravel and aggregates in their structure. Sourcing of virgin aggregate (VA) carries with it environmental impacts, as well as energy and carbon use which can be addressed with recycled aggregates (RA). Construction and demolition waste can also be used in place of VA in hard SuDS infrastructure, examples of which include: recycled concrete, reclaimed asphalt pavement and spent railway ballast. There has been much research relating to the use of RA in impermeable road surfaces (e.g. Poon and Chan, 2006), but in the case of PPS, water infiltrates through the structure, raising concerns should the RA be contaminated since there is potential for groundwater pollution, in particular with hydrocarbons, heavy metals and salts (Rao *et al*. 2007). Akerejola (2010), conducted a series of laboratory experiments to investigate the potential for RA to leach contaminants compared with a VA control. It was found that very little contamination was washed through the RA tested with most of the levels either below the limits of detection, or below environmental guidelines. However, this is one of very few studies carried out to specifically apply RA in a PPS; more research is required to provide the data needed before RA can be confidently used in PPS, or indeed in infiltration trenches.

The fact remains that the current system of constraining water in pipes underground is unsustainable (Chocat *et al*., 2007), particularly in developing countries, and leads to environmental problems around flooding and contamination, as well as not making best use of what should be regarded as a resource. In fact, the Millenium Development Goals hail *water* as key to security in terms of the provision of food, factors around human health and also economic stability. Chocat *et al*. (2007), emphasise the importance of systems organised by relevant institutions, advances in technology and also the responsibility of stakeholders as crucial to addressing current water shortages as well as needs for the future.

9. The future for hard SuDS infrastructure.

Chocat *et al*. (2007), state that the concept of sustainability has been a “major driving force” in terms of guiding water policy, and that there is reason for what they call “hydro-optimism” for the sustainable management of water in urban areas due to factors driving the agenda such as water shortages, and the increasing global population. In the short term, however, and certainly in England and Wales, stronger legislation is needed to propel the SuDS agenda forward. At present, the piecemeal implementation of the Flood and Water Management Act, 2010, and to date, the lack of SuDS guidance has been unhelpful, with Local Authorities due to become responsible for ownership and maintenance of the SuDS devices. The unfortunate impacts of the 2013/2014 winter floods should have given some impetus to legislators. In the medium term, demonstrator sites are needed to show the benefits of SuDS in a temperate climate, as presently proof is required of the efficacy of SuDS before there is sufficient confidence in their reliability and performance. In the long term, climate change is a driver, with Defra, 2012, quoting a figure of 27% for the potential increase in sewer flooding due to such changes. All cities should therefore aspire to Water Sensitive Urban Design (WSUD) whereby they transition to become Water Sensitive Cities (Wong, 2007). Water becomes integral to the functioning and health of the city and its inhabitants under WSUD, with the city functioning as a water supply catchment, providing a variety of ecosystem services and also providing the social and institutional capital to enable sustainable water management. SuDS as an approach would therefore be part of WSUD, with the hard infrastructure discussed in this paper a part of SuDS design. Hard SuDS infrastructure allows what is currently a “wasted waste” (Charlesworth, 2010) to become “opportunity water” (Chocat *et al*., 2007) or Semadini-Davies *et al*.’s (2008), “liquid asset”. By removing excess surface water from the storm sewer system, either to simply replenish the natural water cycle, or by using it elsewhere, there is an opportunity to decrease the amount of water having to be treated and reduce the necessity for upgrading the storm sewer network.

Whilst much research has focused on the water quantity benefits of hard SuDS infrastructure, there has been less on water quality, with many studies specifically addressing biodegradation and the trapping of particulate-associated pollutants in the biofilm growing on geotextiles in PPS. Future research needs to be directed at the ultimate fate of these pollutants and the end-of-life consequences for the materials which contain them. New and emerging pollutants such as pharmaceuticals, herbicides and cosmetics are coming under the spotlight, and there have been few studies of the efficacy and efficiency of hard SuDS in dealing with these; the study of their fate in hard SuDS infrastructure would appear to be a promising area of research for the future.

Many of the arguments against SuDS in general focus on the fact that they take up space. Hard infrastructure such as PPS utilise the same space as impermeable surfacing, infiltration trenches are installed alongside roads and highways and RWH can be as simple as a barrel or tank outside a house. There are currently roof-level tanks available which rely on gravity feed and take up no space. Maintenance is also used as an argument against implementing SuDS, but impermeable surfaces also require regular maintenance in order to work efficiently, and by using PPS, there would no longer be any necessity for gully pots which need regular emptying, and the transport of the contents to landfill.

The key to all of these negative arguments is what Chocat *et al*., 2007, call "de-learning". Many of the objections to SuDS in general hinge on traditionalist thinking and the lack of any desire to engage with what is perceived as "new" technology. SuDS mimics nature by infiltrating, storing and conveying water, and thus it is not a new idea. Countries such as the USA, France, Sweden, New Zealand, Australia, have been using SuDS successfully for decades.

10 Summary

1. The influence of global climate change will inevitably have wide ranging consequences, not least of which will be on drainage systems and the increased influence of flooding as storm sewer systems are overwhelmed. There is no one solution to these problems, thus the answer has to be flexible and have multiple benefits.
2. This ROCK has illustrated the multiple benefits of hard SuDS infrastructure, showing how they can address individual aspects of climate change by reducing the UHIE, and in the future, by storing and sequestering carbon in materials used to construct hard SuDS, such as PPS.
3. This publication has shown how SuDS can be designed with both hard and soft options together, and used in concert with conventional, pipe-based systems. Hard SuDS devices can be designed into a management train with so-called "soft" or green infrastructure and can thus address all aspects of the SuDS triangle: water quantity reduction, water quality improvements, provision of amenity and biodiversity when partnered with vegetation.
4. Currently, therefore, there is a reasonably wide knowledge of the role and functioning of hard SuDS infrastructure, and this ROCK has reviewed current knowledge of the processes underlying their functions such as the development of a geotextile associated biofilm for pollutants trapping and biodegradation.
5. However, unless these systems are accepted both by stakeholders and the general public, it is unlikely they will be installed widely.
6. Future needs will focus on utilising hard SuDS to remediate new and emerging pollutants; provision of more demonstration sites to provide the information required on their efficiency and efficacy in improving urban storm drainage; and improved education and training.

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