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Shuttleworth, A. B., Nnadi, E., Mbanaso, F., Coupe, S., Voeten, J. G. W. F. & Newman, A. 1

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Chapter 6

Applications of SuDS Techniques in Harvesting Stormwater for Landscape Irrigation Purposes: Issues and Considerations

Andrew B. Shuttleworth, Ernest O. Nnadi,
Fredrick U. Mbanaso, Stephen J. Coupe,
Joris G.W.F. Voeten and Alan P. Newman

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Abstract

While urbanization and increasing population has put much pressure on natural drainage channels and resulted in increase in flooding, there is increased pressure on available water resources due to climate change, reduction in frequency of rainfall events and drought. The emergence of a sustainable drainage system (SuDS), also known as best management practice (BMP) and low impact development (LID), has changed the management strategy of drainage from conventional to sustainable. SuDS techniques seek to deliver the three cardinal paradigms of sustainable drainage: quantity, quality and amenity and as such, they can offer an additional benefit for applications such as landscape irrigation. Most SuDS techniques have the potential for water storage with minimal or no modifications required. This chapter, while covering the capabilities of SuDS systems, explores SuDS devices such as pervious pavements equipped with excess storage capacity, cisterns and tanks harvesting roofwater, infiltration systems aimed at supporting the growth of urban plants and green roofs with the potential to store water in order to maintain water demanding planting scheme even during dry periods. It also covers systems where SuDS is the main driver to device installation and address issues and considerations surrounding applications of such systems in water harvesting for irrigation.

Keywords: Irrigation, Drainage, SuDS, Stormwater, rain harvesting

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1. Introduction

Urbanization can initiate undesirable local modifications to the water cycle. In particular, the effects of the spread of impermeable area both within and at the margins of towns and cities have highlighted the need to modify the way that society deals with stormwater. The problems of surface flooding in cities and overloading of foul sewers (when combined systems are in place) are the most headline-grabbing aspects of increasing impermeability but reduction in aquifer recharge can also be important when water demand rises due to increase in local population.

In many western societies, particularly in the United Kingdom, there is a preference for housing schemes with gardens (including, often, very water demanding planting regimes). This increases the demands for water well beyond traditional domestic use. Alongside these domestic developments, hotels, hospitals, office blocks, light industrial units and retail developments often try to show a supposedly green face to the world in the form of extensive landscaped areas around their equally extensive impermeable parking surfaces. We are thus faced with the dual problem of a demand for water for landscaping accompanied by rapid and wasteful run off from impervious parking areas. This can cause flooding problems in response to short heavy rain events. The problem is particularly important in summer months when the demand for watering domestic, commercial and municipal planted areas is at its highest, at the same time as the supply from surface sources is at a minimum.

The term SuDS was originally used in the United Kingdom as an acronym for 'sustainable urban drainage systems' but this term has more recently lost favour and is commonly replaced by SuDS (sustainable drainage systems). In the USA, the terms low impact development and best management practices (LID and BMP) cover the same approach to drainage and in Australia the term 'water-sensitive urban design' is favoured. While all of the above terms are used, sometimes interchangeably, to indicate a holistic approach to stormwater management, they are all dominated in their philosophy by the concept of stormwater source control. This entails controlling both the quality and quantity of stormwater as close to its site of deposition as possible. Commonly, parts of the United Kingdom can be under drought orders (which impose summer hosepipe bans which limit landscape irrigation) and still suffer from localized flooding during short-term storms. These occurrences are becoming an increasing feature in some parts of the United Kingdom and this adds extra incentive to retrofitting of SuDS systems that can also make a contribution to the reduction of water use. The principles of SuDS are often presented as follows:

1. Storing runoff so that it can be released slowly or used beneficially (attenuation).
2. Allowing water to soak into the ground so as to mimic the processes on an undeveloped surface (infiltration).
3. Where necessary to allow the water to move doing so at the surface and at a controlled velocity.
4. Using the processes of collection, storage and transportation to facilitate the removal of pollutants by sedimentation, precipitation, adsorption (in its widest sense) and degradation.

Most SuDS devices have the potential to be used for water storage with minimal or no modifications required. **Table 1** summarises the irrigation water resource potential of a range of hard SuDS devices that have been used for water harvesting, whereas **Table 2** outlines a number of green SuDS devices that themselves place a potential demand on water resources but which can be modified to harvest water for self-irrigation and sometimes for other uses.

Device	**Quantity issues**	**Quality issues**
Underground and above ground barrels, tanks and cisterns harvesting roof water only	The sizing of the system needs to be done carefully and the usage of the water be well established if both stormwater attenuation and water harvesting are to be achieved in the same system. With modern computer control the sizing can be reduced by actively draining tanks in response to predicted rain events.	The quality of water will be affected mainly by atmospheric fallout and the nature of materials used in roof construction. While this is not really considered an issue new UK guidance requires that even roof water should have some treatment before discharge to a watercourse
Underground and above ground storage harvesting both surface runoff and roof water	The additional resource will require a greater storage volume for it to be utilisable. If there is attenuation available upstream of the storage tanks this can be minimized as a problem	Surface water will generally be of much poorer quality than roof water alone (see above) but provided the system is correctly designed to retain day to day pollutant releases it will generally only be an issue if major pollutants releases overcome the pollution attenuation mechanisms. Salt applications in temperate zones can be a problem.
Pervious pavements and similar without off line additional storage	Unless taking runoff from impervious surfaces too the total inputs are limited to the water falling on the surface. Unless designed with extra storage capacity even an attenuation based system will have limited capacity to store water for more than short periods of time	Input of potentially harmful organisms from faecal contamination and chemical pollutants from atmospheric fallout. If exposed to traffic there will also be day to day input of automotive based pollutants and if not provided with upstream protection the water can be subject to contamination from the very rare losses of engine oil and fuel. In temperate areas de-icing salts can be an issue.
Pervious pavements with off- line additional storage	By directing water into off line underground or above ground tanks the storage required for attenuation or to overcome limited rates of infiltration will not be compromised by the need to recover water	

Table 1. Irrigation water resource potential of a range of hard SuDS devices.

This chapter, while covering the capabilities of all SuDS systems, gives particular emphasis to those that are particularly suitable for retrofitting. In this chapter, the greatest attention is given to devices such as pervious pavements equipped with excess storage capacity, cisterns and tanks harvesting roofwater, infiltration systems deliberately aimed at improving the growth of urban plants (including trees) and green roofs, which can offer the potential to store water in excess of the capacity of the substrate so as to maintain a water demanding planting scheme during dry periods. Inevitably, there will be some overlap with harvesting for purposes other than irrigation. Competing use for harvested water includes toilet flushing and washing machine use and with appropriate treatment, many of the types of use that normally demand potable water. We must also recognize that rainwater harvesting systems are commonly provided without involvement of the SuDS philosophy, being designed without any attempt to enhance the control of stormwater (but sometimes doing so by accident). This chapter only covers systems where SuDS is the main driver to device installation.

Device	Quantity issues	Quality issues
Green roofs with additional off line storage Green roofs with integrated storage.	Both need careful sizing taking into account predicted available rainfall and demand placed by both growing plants and any additional off-roof demands. Storage needs to take into account sufficient temporary storage to provide stormwater source control when substrate is close to saturated. Provision may need to be made for rapid dumping of stored water when large storms are predicted in a 'reservoir full' situation.	If used for self-irrigation of the roof or for additional off-roof irrigation there will be little problem but if, as in some installations, green roof drainage water is pooled with other water and used for such as toilet flushing the colour can become a source of user complaint. If fertiliser is used on the roof, then recycling the water via the roof will retain the nutrients where they are needed.
Infiltrating urban tree planters with subsidiary methods of storage.	Maintaining sufficient moisture for the trees can be a problem. Proprietary systems which incorporate water storing foams (as used by florists) can offer a solution. Species selection for the variability of available water needs to be done carefully.	There will be day-to-day input of automotive based pollutants and if not provided with upstream protection the water can be subject to contamination from the very rare losses of engine oil and fuel. In temperate areas de-icing salts can be an issue.

Table 2. Green SuDS devices that can be modified to harvest water for self-irrigation and other uses.

Harvested rainwater from urban environments (even water directly from roofs) will inevitably contain pollutants that would not be expected if the water was collected from rural upland catchments or extracted from protected aquifers. If water is to be used for irrigation after being in contact with pollutant materials inevitably generated by both the daily activities of urban living and by fallout from industry, a first question must be whether the quality of the water is good enough for purpose. Irrigation water limits vary from place to place and not all organisations include all the possible pollutants (see Ref. [1]). A useful comparative table is provided by Nnadi et al. [2] which presents the irrigation water limits provided by a range of authorities.

2. Roofwater harvesting: rain barrels and cisterns

While many SUDS systems have been used to harvest rainwater for a combination of both irrigation and indoor uses (such as toilet flushing and washing machine pre-wash) it is the direct harvesting of roof water (and sometimes water from non-trafficked paved areas) into barrels and cisterns that has seen the greatest uptake as a component of the LID programmes in the USA. The relatively high quality of this source of harvest (although well short of potable water standards in most jurisdictions (see Ref. [3]) that makes this source attractive for internal use as well as for irrigation. The primary differences between a cistern or rain barrel which forms part of a SuDS system and one which is simply a water supply device are the way the container is sized and the way the water is managed. Whether managed manually by an individual householder (possibly backed up by an advice and education program) or through an automated system, unless efforts are made to maintain enough available storage to contain at least a significant proportion of a design storm and unless the stored water is managed either by using the water or by releasing a proportion before the next storm then this is not SuDS at all but purely a water harvesting exercise. Jones and Hunt [4] made the point that the greatest problem with roofwater harvesting as a stormwater control mechanism is that many of the cisterns and barrels remain full all of the time because water is not utilized. Managing the cistern by using the water regularly or releasing during a dry period is necessary if roofwater storage is to be seen as SuDS.

North Carolina State University (NCSU) offers online a very comprehensive review of rainwater harvesting [5] and also one of the best sources of information provided for home owners on water cisterns and their use [4]. Their document usefully attempts to guide the owners in relation to the need for additional ground support for cisterns in gardens, an often overlooked factor. NCSU also provides an informative guide to roof water quality [6]. Many other American universities provide a similar extension literature and the various States of the USA represent such a broad diversity of climates that the guidance from either state regulators or that provided through local university extension programs should be selectable if someone is looking for information that suits their climate elsewhere in the world. That is not to say that authors from outside the USA have not been active in reporting their work in a variety of jurisdictions (although in many cases, the stormwater source control element is missing).

Cisterns can be either above ground or below ground, but the land take and unattractive appearance of reasonably sized water cisterns are often a barrier to adoption. Underground tanks can be expensive and offer significant structural problems if they are to be covered with a trafficked surface or even one with a reasonable dead load. Unlike above ground storage, where irrigation use can often be achieved under gravity flow, they will normally need a pump.

Underground tanks are not normally suitable for occupier retrofit even by the most capable householders. An option that addresses this is the Skeletank®, where the thin polyethylene tanks get their structural strength from internal interlocking polypropylene skeleton. This provides structural strength while maintaining a system that can be carried, if necessary, on the roof of a car and can be lifted easily by two people. They are easily linked together to achieve the size required. The system was originally designed to provide stormwater attenuation and soakaway tanks (used upside down) within individual domestic curtilages. The system has since been adopted for rainwater harvesting and lightweight pump and filter chambers are available as accessories. Apart from the wiring for the pumps, the system is totally suitable for installation by an amateur. **Figure 1** shows an installation in Preston (Lancashire, UK) which provides an interesting example of a householder built retrofit water harvesting SuDS project particularly since the primary aims of harvesting the water was to provide irrigation water to landscaped areas and to support a small pond on site while allowing total disconnection of

Figure 1. Left: Skeletanks® in place and connected together. Right: lightweight pump chamber.

drainage from the combined sewer. The owners of the property in question were undergoing conversion works which included the installation of a new patio area. The tanks were installed underneath the proposed patio area. The concept of the system begins with the collection of rainwater in a downpipe chamber. On this site, three downpipe chambers were installed, two chambers for a 94 m^2 roof area at the main house and the final chamber positioned to collect water from a 55 m^2 area (serving an adjacent outbuilding). These chambers are intended to pre-clean the rainwater and allow silt to deposit within the sump of the chamber. Water passes through a fabric filter on the outlet spigot of the chamber before running into the tanks which were connected together using standard underground drainage pipe to provide a combined reservoir. For this site, sixteen tank units, providing a total storage capacity of 4800 litres, were used. The required number of units was determined by a modelling to fit available storage to the various demands including sufficient temporary storage, with controlled discharge to accommodate stormwater during rain events when the temporary storage is full. The rainwater pump chamber is the final component in the chain and is primarily used to pump rainwater on demand for irrigating flower beds and grassed areas.

When available in excess stored rainwater is also pumped into a header tank for internal household use, such as, flushing toilets and water feed for washing machine pre-wash. The primary re-use of the harvested rainwater is to irrigate the flower beds and grassed areas surrounding the property and also for supporting the flora and fauna of the pond. Since the installation of the system, both use of mains water for irrigation and for topping up the pond has been minimal. Checks have shown the public health microbiological qualities (including legionella) are not a problem.

3. Pervious and macro-pervious pavements as a water harvesting system

Pervious pavement systems (PPS) have been around as SuDS elements since the 1970s and are extremely well documented (see Refs. [7–12]). In the United Kingdom, their origin is largely associated with Chris Pratt's design which utilized concrete block pavers provided with infiltration channels as the wearing course [13].

The pervious wearing course surface can also be porous asphalt or porous poured concrete. The wearing course is usually laid on a bedding layer of, typically, 10 mm material and there is often a geotextile as a separation and filtration layer between the bedding layers and either the subbase of aggregate (typically a uniform 50 mm, with a void ratio of about 30%) or on a subbase replacement of plastic load-bearing boxes (a typical void ratio of 90%). If the pavement is to be used for water harvesting, it requires a reliable under-sealing layer which can be a folded or welded polyolefin membrane or, particularly within individual curtilages, can be conveniently provided by one or more of the sub-surface tanks discussed in the example above. These can also be used below pervious pavements to capture a proportion of the stormwater with the number of tanks selected in relation to demand with both unharvested and overflow water disposed of by infiltration or at a controlled rate to a surface water body or a combined sewer.

The most common application of PPS has been parking areas, whether they are extensive parking lots or individual house driveways and courtyards. The efficacy of pervious pavements in intercepting and immobilising or degrading traffic-derived pollutants has been the subject of a large body of research in many countries including England [14, 15], Scotland [16], Spain[17], Australia [18, 19] and the USA [20].

One of the most extensive experimental studies of PPS-derived water quality, with respect to irrigation, from pervious parking surfaces was instigated by Nnadi [21]. This was an indoor simulation experiment on a relatively large scale. The experimental outline was to apply oil drops (simulating oil dripping onto pavements from parked vehicles) and street dust to pervious pavement system models built into 1200 mm × 1000 mm × 600 mm heavy-duty polypropylene boxes (used for heavy industrial storage). Models were created with a selection of wearing courses including several cross-sections of new porous asphalt, a 10-year aged asphalt from a quarry parking surface, porous poured concrete and concrete paving blocks with infiltration channels. Thirteen millimetre simulated rainfall events were applied to the models at 15 mm/hour (52 min rain events) twice monthly. These were applied a day before and a day after the monthly application of used motor oil and dust. The effluents were captured and analysed for total suspended solids (TSS), metals and total petroleum hydrocarbons (TPH). The results were considered in relation to water quality as applied to irrigation and other forms of re-use as detailed in Nnadi et al. [2]. The results indicated that the porous asphalt and porous concrete are as good as the block paved permeable pavements in the treatment of stormwater pollution with all surfaces delivering water quality that is suitable for irrigation and clearly demonstrated the capability of the porous asphalt and concrete pavement system to trap hydrocarbons within the system.

While the use of pervious pavements for control of day-to-day automotive-derived pollutants is well established, it must be remembered that the traditional PPS has shown a poor pollution retention performance when challenged by major hydrocarbon releases [22]. Modification of the permeable pavement to incorporate a gravity separator just below the laying course has been reported for both aggregate-based [15] and plastic box-based pavements [23] showing a capability of retaining sufficient oil should every car in a parking lot simultaneously lose the content of their sump.

The first pot trials to investigate the acceptability of water quality from pervious pavements for irrigation originated at Coventry University as a PhD programme by one of the authors [21]. The source of water was a series of laboratory models. The models used were based on the modified designs by Newman [24] which incorporates a gravity separation system to ensure that free oil can never escape from the system and were artificially fertilized by adding Osmocote® slow release fertilizer and brushing it into the infiltration channels. This was to enhance the biodegradation rate of the hydrocarbons. The pot trial investigation showed that where the effluent water could be used for irrigation the excess nutrients provided distinct advantages to the growing plants [25]. In all cases, the plants irrigated with effluent grew much better than those irrigated with tap water. In effect, the system was being used for fertigation.

There has also been more recent work using a live car park, this case based on a highly modified design called a macro-pervious pavement system (MPPS) (**Figure 2**). In 2011, an investigation was initiated [26] on an MPPS installed as a prison car park in Scotland.

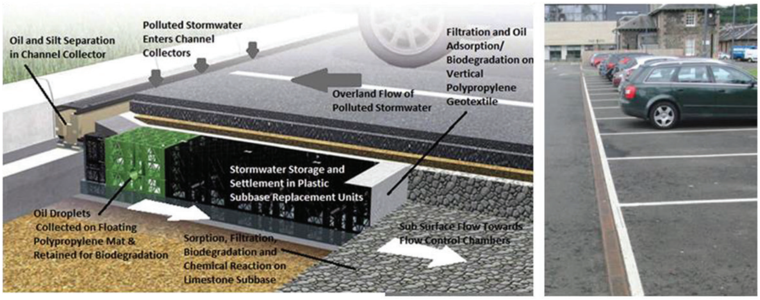

Figure 2. The macro-pervious pavement system as installed at Perth Prison, Scotland. The line of 'Channel Drain' is actually a series of oil and silt separating infiltration points, which direct stormwater into the sub surface storage and attenuation layer.

The parking lot consists of two major sub-catchments of around 1350 m^2 and a minor one of 300 m^2 (which was not included in the irrigation water study). The majority of the surface of the parking lot consists of traditional asphalt with stormwater entering the subbase/storage and attenuation layer of crushed limestone through miniaturized, linear, gravity separator units (which look like normal channel drains from the surface) through a chamber containing a floating mat of oil-sorbing textile. It then flows into the subbase, which drains towards separate flow control chambers (with orifice plate flow control) in each of the sub-catchments. These provided convenient sampling points and in-line storage chambers which would be available for landscape irrigation. Samples were analysed for a wide range of determinants.

For the heavy metals, all results were below the most stringent of irrigation water limits. For suspended solids, all measurements were below 20 mg/l, a concentration below which blockage of drip irrigation systems is not a problem. For TPH, the irrigation limits that were adopted are dependent on the solubility of the various carbon chain fractions (except for C_9–C_{14} where a limit of 1.8 mg/l applies). Since no measurements of TPH ever exceeded 1.8 mg/l and in the absence of any observed free product (indicating that solubility was never exceeded for any fraction), it can be concluded that hydrocarbons should have no detrimental effect if this water was harvested and used for irrigation.

BTEX concentrations were all below the 1 μg/l limits of detection for these compounds. The irrigation water limits for benzene and substituted benzenes proposed by the New Zealand Government [27] range from 800 μg/l for benzene to as high as 39 mg/l for toluene. MTBE was also invariably below its detection limit (10 μg/l). Irrigation water standards for MTBE could be found in the literature but since the State of Florida mandates a limit of 50 μg/l in drinking water, this value could be seen as a very conservative irrigation water limit. Boron was always below the 40 μg/l limit of detection and thus well below the 500 μg/l soil pore water limit for the most sensitive plants [28]. Examining the major cation concentrations, it was shown that calcium, magnesium and potassium were low compared to any irrigation water limits and most authors would expect that at least magnesium and potassium would need to be supplemented for optimum plant growth. For most of the year, neither the sodium (**Figure 6**) or sodium absorption ratio (SAR) values were a concern at this site, but in the winter months, following the application of de-icing salt (which will vary from year to year) the values of both these parameters show the water to be unsuitable for irrigation with sodium values in January up to 1200 mg/l. By March, the sodium concentrations were below 100 mg/l but above the 50 mg/l irrigation water limit until May. It was concluded that if water is to be stored for irrigation purposes it would be necessary to divert the meltwater (and the rainwater falling onto a salt contaminated pavement) away from the storage tanks during the winter months after filling them as much as possible during October and November and then topping them up in April and May before the need for irrigation is established in the summer. If the worst of the salt contaminated water can be diverted, the direct effect on plants will be minimized. Another issue from this particular site was the pH that was higher than optimal, but this was due to the limestone used in the subbase and would have been much lower if a granite subbase had been chosen. Adjustment of pH with addition of calcium sulphate was proposed as a potential solution, but species selection for high pH tolerance would be an alternative.

Pot trial experiments were carried out using both ryegrass and tomato plants (using the experimental protocol previously proposed by Nnadi [21] irrigated with effluent collected from this pavement in September with initial results being reported to the SuDSnet conference in 2015 [29] and continued experiments (and tissue analysis) have shown that at this site, the water is perfectly suitable for irrigation, if harvested before the salt application. However, the data represents only relatively short-term use of the water. Hence, further work in this area is required and this provides a good research opportunity for anyone interested in this area of study.

One problem with block paving surfaced PPS is that they can become a habitat for weeds and chemical methods of weed control still dominate as the most preferred in the United Kingdom [30] and most European cities [31, 32]. Although several herbicides are in use, glyphosate-containing herbicides (GCH) are by far the most widely used herbicide for weed control on hard surfaces [32–35]. Recent work on the impact of GCH on pollution attenuation and biodegradation in a PPS indicated that GCH is not retained in the PPS structure and is subject to rapid wash through in response to water movement thus increasing the potential risk of reaching receiving environments [36]. Hence, not only does one need to consider the herbicide itself, but the breakdown of other pollutants such as hydrocarbons within the PPS can be potentially affected [35] with potential impact on the quality of irrigation water. In a recent study to determine the suitability of stormwater harvested from PPS for reuse purposes in conditions where GCH was applied as part of PPS maintenance procedure, Mbanaso et al. [37] observed that effluent from the test models including those dosed with high GCH concentration of 7200 mg/l do not pose infiltration or salinity problems when used for irrigation. They, however, indicated that high dosage of the herbicide could lead to an elevated electrical conductivity of the recycled water. Hence, if PPS-derived water is used for irrigation; chemical methods of weed control should be avoided until the dynamics of breakdown of the particular herbicides are better understood. Further work needs to be done on establishing the lifetime of such compounds in both the PPS and the stored irrigation water.

3.1. Green roofs

As well as the need to control rapid water runoff in urban areas, there are several other problems to which SuDS can make a contribution. The urban heat island effect [38, 39] and reduction in green space with associated loss of both amenity and biodiversity [40] are important issues. Much of this is being exacerbated by climate change. A contribution to the mitigation of such problems is to apply green SuDS techniques and foremost amongst these is the attempt to utilise the roof spaces of buildings to create green roofs. Green roofs can be either extensive, usually planted with a mat of relatively drought-resistant species such as sedum or intensive [41], or being more ‘garden like’ where the aim goes beyond the immediate environmental benefits with aesthetic and social aims being contributed to by a more varied and attractive planting scheme with the potential to contribute more to biodiversity.

The potential of green roofs to contribute to the mitigation of rainwater runoff is well established, see Refs. [42–45]. What is less often stressed, however, are the problems in certain climates associated with the fact that after a heavy rainstorm, the water in the saturated substrate can take a considerable time to drain or evaporate and a subsequent storm will be offered significantly reduced attenuation.

The capability of green roofs to contribute to the cooling of buildings and combating the heat island effect has been widely reported [45–50]. Green roofs can also play a role in improving biodiversity within urban areas [40, 51] and, the aesthetic value of a green roof can often be a dominant factor in its adoption [52] even though aesthetic planting schemes can come into conflict with biodiversity aims [53].

Particularly where the green roof is intended to be accessible and provide, in part, the function, for example, of an urban park, it is important that the provision of water, to maintain adequate growing conditions (for a wide range of plants), during dry periods is recognised. This helps to enhance the amenity value. One of the factors is the maintenance of adequate soil moisture content. The limited load-bearing capacity (LBC) of the roofs of (existing) buildings often dictates the amount of water that can actually be safely retained on the roof itself. Designing traditional intensive green roofs to satisfy the load-bearing capacity of a roof thus involves finding a balance between storing as much rainwater as possible, maintaining conditions for plant growth and respecting the LBC of the construction [54, 55]. Adding more substrate typically achieves a water-stored-to-weight ratio (WSWR) of just 0.2 l of water per added kg of soil for loamy sand, or 0.4 l/kg for a typical, specialised, extensive green roof substrate [56].

An alternative to storing the water solely within the substrate is to drain the water into a cistern to allow the water to be used to irrigate the roof during dry periods and, if correctly sized, can offer temporary storage during storms occurring when the substrate is close to saturation. A green roof with a cistern for reuse was the subject of a modelling study by Hardin et al. [57]. Their system included a green roof with its drainage system connected to a cistern which in turn supplied irrigation water to the roof via a pump. A supplemental water source is also connected to the cistern to provide water should there not be sufficient water to perform the irrigation event. It was proposed that the irrigation should be managed via a controller, similar to what is widely used for home lawn irrigation, which only irrigates on the prescribed times unless sufficient rain has fallen within 24 h of the intended irrigation event.

Building rainwater cisterns inside or adjacent to the building and using pumps and irrigation systems is thus an option which will provide both runoff attenuation and on-site rainwater reuse. However, the running costs, capital costs and building space/land take combined with the need for maintenance and the propensity for active systems to break down are factors which would militate against their choice. There is also a need to consider the trade-off between energy used to pump the water from ground or basement level and the loss of space if the cistern is maintained in one of the higher floors of the building.

An alternative to using a separate cistern is to maintain ‘ponding elements’ under the substrate. Green roofs.com [58] presents a useful summary of some of the systems available, some of which are dependent on a slightly sloping roof, one which incorporates active pumped elements and a system that stores up to 40 mm of water in a plastic drainage layer equipped with an overflow device (although little extra capacity is available for temporary stormwater storage during rain events). However, without a separate cistern, the volume available for storage will be relatively small unless special steps are taken. One such approach has been developed in the Netherlands [56]. This modified green roof stores the water directly under the substrate within modified load bearing plastic void formers originally developed for pervious pavement applications. The water is not required to be pumped up to the substrate, this being achieved by capillary actions through ‘capillary cones’ inserted into the load-bearing vertical struts [59].

An excellent example of an application of this type of system is adjacent to the elevated railway station at Orlyplein in Amsterdam [56], shown in **Figure 3**. This is a remarkable installation which has transform the former rooftop bus station (vacant for some time after it being moved to ground level) into a popular public park area with a resulting increase in economic development into the form of many additional rooms constructed in adjacent hotels.

Figure 3. The roof park built on the former Orlyplein Bus Station *deck*, before, during and after construction.

The previously lonely and threatening exit from the rail station has been transformed into a place that is popular and well-populated whenever the station is open.

The system of capillary irrigation outlined above has also found application in ground level applications. A very recent example of this is the 'Green Stream' in Zuidas an Amsterdam city district in the Netherlands. Zuidas is a very densely build urban area and therefore prone to urban flooding during intense rain events. With the city district being under re-development, aiming to become the major business hub in the Amsterdam Metropolitan region, the city is developing innovative multifunctional designs to improve urban quality, reduce the urban heat-island effect by improved evaporative cooling by plants and increase water retention (and reuse) to prevent urban flooding. The 'Green Stream' is a project in which rainwater from rooftops and adjacent sidewalks is collected in a 2 m wide planting strip that runs along the houses and sidewalk (**Figure 4**). The strip is deeper than its surroundings, making it a natural water collection point in the street design. To get from the sidewalk to the houses, bridges are used to cross the 'green stream'. This planting strip is designed to be dry throughout the year, but is allowed to flood during rain events. Planting species are selected to be able to withstand occasional flooding. Innovative in the design is the 150 mm high water attenuation system 40 cm below the planting, which is fed with water from the roofs. A continuous chain of plastic void forming units, as used in the Orlyplein roof park, is placed in a waterproof liner to create a subsoil water-tank and features the same capillary irrigation system, capable of returning water to the soil when plants are using water without the use of pumps (and thus energy). The improved water availability for plants maintains their evapotranspiration rates at close to the potential evapotranspiration generated by the local weather, improving their urban cooling capacity. Surplus of water can drain freely to ground water level alongside the water drainage and capillary irrigation system. To prevent the Green Stream from overflowing onto the sidewalk, extra emergency overflows are created at the maximum fill level, connected to the conventional sewer.

Figure 4. Left to right: Schematic of the green stream system, under construction and on the day of completion.

Another application of this technology has been on sports surfaces such as football pitches both on rooftops and at ground level. The system provides water to the growing grass turf, while the void space can be made sufficiently deep to satisfy the most stringent stormwater attenuation requirements for new stadium construction. Even if supplemental water has to be used to maintain the playing surface in very hot dry countries, the application of water from below by capillary action is more efficient than spray irrigation from above. Currently, trials are underway in preparation for the soccer world cup in Qatar.

3.2. Irrigation of urban trees

Novel below ground water storage options provide a significant opportunity for the reliable delivery of acceptable water to trees in the urban environment. In a non-urban environment and under natural establishment conditions, a mature tree have grown partly due to a favourable water regime that has provided sufficient water reliably over the life of the tree. Historically, urban trees have faced significant challenges that are not faced by non-urban trees which include:

- Establishment in unfavourable environments
- A deficiency in total water volume provision
- Runoff of water from non-permeable surfaces away from tree roots, even where local rainfall totals are adequate
- Low retention rates of applied water, where water evaporates or percolates away from tree roots before uptake
- Insufficient mature and productive soil/substrate for nutrient regeneration and incomplete establishment of beneficial microbial processes (e.g. limited growth of mycorrhizae)
- Tree removal or inappropriate management resulting in damage to trees if land use changes regard existing trees as an obstacle

Thus, water supply considerations provide some of the major challenges faced by urban trees and depending on the tree species, a mature tree with a 500 mm trunk diameter could require 860l of water to be provided for survival and normal function during drought conditions. It is important to acknowledge the local hydrological benefits of urban trees in times of intense and or prolonged rainfall where the drainage system may be at capacity. The positive impacts of trees include rainfall detention, retention and uptake, which may remove significant volumes of water from runoff totals, or delay local peak discharge in comparison with a location without trees [60].

In theory, it would be acceptable to deliberately divert stormwater from a new development to supplement existing urban trees to meet the total water need. This could include disconnection of downpipes into soil and conveyance to areas where trees are located. However, this retrofit option could result in standing water in the case of intense events if infiltration and percolation are not sufficient and a bypassing of the tree if the water is not retained by the soil. Hence, solutions are required that provide the required volume of water, but allow this to be retained close to the roots and provide useful water. In practice, this is necessarily targeted at new developments and is usually provided by tree pits, where a selected soil medium is placed into a structural chamber. Landscaping solutions can incorporate this type of structure into bioretention schemes as shown by the image below of a parking area for a shopping Centre drained by bioretention cells, which often successfully incorporate trees (**Figure 5**).

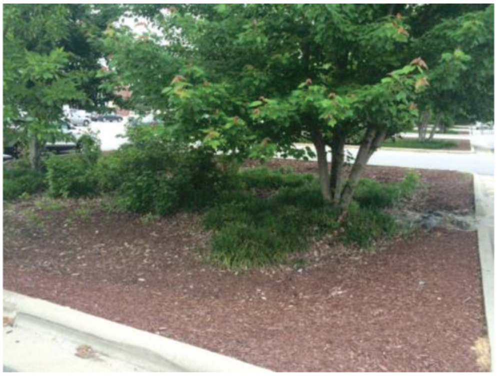

Figure 5. A bioretention cell with trees and shrubs in Raleigh, North Carolina, USA.

The medium can be an engineered soil or a replacement medium such as absorbent foam-filled structurally resistant void forming boxes. An ultra-absorbent foam that is available commercially as a component in a tree box system was tested independently in a laboratory for its impact on hydraulic conditions and was shown to be a promising solution for runoff management and water absorption [61]. This material also has the potential for water transfer to woody plants.

The use of engineered materials, including allochthonous soils, in providing water to trees has not been proven to fully replicate the functioning of the biological component of mature natural soils, nor have an equivalent of the nutrient recycling and regeneration of soil. However, it has been established that drainage systems that include trees and soil can improve water quality in sustainable drainage applications, including the absorption and retention of heavy metals, nitrogen and phosphorus [62]. The addition of urban pollutants in the form of sediment moved by stormwater is shown in **Figure 6**. In such circumstances, however, the blinding of the surface can become an issue and a means of pre-filtration or sedimentation to take

Figure 6. A tree pit receiving urban sediment from an adjacent parking area, Greensborough, North Carolina, USA.

out the worst of the sediment may be advisable and if not available close control of maintenance may be required.

The understanding of the requirements for successful irrigation of urban trees has improved in recent years, particularly as the recognition of the full range of benefits provided by urban trees has become apparent and the use of trees in the urban landscape has been more readily encouraged. As shown in the plates in this section, care must be taken to prevent waterlogging of supporting soils, partly due to the confined nature of tree pits and also the provision of water in excess from large impermeable areas, which may exclude the air that is found in natural soils and may, if serious enough, lead to anoxic conditions and the production of greenhouse gases. Where possible, water should be directed to a sub-root zone position without passing through the root ball itself. Consideration of aeration and an under drain in design should prevent this, alongside a consideration of local rainfall totals and the nearby landscape conditions.

4. Conclusion

SuDS elements, by their nature, store water but it is not always simple to either make a SuDS system provide a suitable supply of irrigation water or to make a water harvesting system contribute to stormwater source control. Both quality issues and quantity issues are important and in areas where road salt is used ground level collection needs to be carefully managed to prevent stored water becoming heavily contaminated with salt that could make the water unsuitable for irrigation and the collection mechanism needs to provide attenuation of automobile-derived pollutants sufficient to allow plants to grow without inhibition. Where the prime aim is to harvest a good quality of water such as on a roof, whether this is used directly to irrigate plants on the roof or is collected for offline irrigation sizing of tanks needs to allow enough excess storage to deal with storm events and the tanks need to be managed to ensure such volume is routinely available.

Author details

Andrew B. Shuttleworth[1], Ernest O. Nnadi[2]*, Fredrick U. Mbanaso[2], Stephen J. Coupe[3], Joris G.W.F. Voeten[4] and Alan P. Newman[2]

*Address all correspondence to: dr.nnadi@gmail.com

1 SEL Environmental Ltd, Blackburn, Lancashire, United Kingdom

2 School of Energy, Construction and Environment, Coventry University, Coventry, United Kingdom

3 Centre for Agroecology, Water and Resilience, Coventry University, Coventry, United Kingdom

4 Permavoid Ltd, Amsterdam, Netherlands

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