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Evidence for improved urban flood resilience by sustainable drainage retrofit

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The rapid growth of cities under modern development pressure has resulted in surface water flooding becoming an increasing hazard and future climate change uncertainties may exacerbate this threat still further: retrofitting sustainable drainage systems to attenuate stormwater runoff has been advocated as part of an integrated solution required to address this problem. Many of these adaptations not only enhance a community's resilience to flooding, but may also offer additional benefits in terms of improved environmental amenity and quality of life. The evidence base for sustainable drainage is critically evaluated in respect of the implications for urban planning, as applied to existing housing stocks and business properties in urban areas worldwide. It is concluded that this approach can make a substantial contribution towards urban resilience as part of an integrated approach to managing extreme storms. This will be of interest to urban planners and designers considering the implementation of integrated flood risk management.

1. Introduction

Surface water flooding is an increasing hazard for urban areas worldwide. The impacts range from self-evident damage to the built environment to less tangible effects such as long-term disruption to the economic health of the regions affected where infrastructure has been compromised (e.g. CIO, 2010). While the impact of major flood disasters seems clear and well documented (http://www.emdat.be), there are also many smaller flood events, potentially much more frequent, occurring in cities all over the world that go unreported, often attributable to surface water flooding caused by intense rainfall events. These regular floods can erode the resilience of those urban settlements that are ill-equipped to resist or, indeed, recover from, surface water flooding (Djordjević *et al.*, 2011). Such repeated stress on both the population and municipal authorities results in a lower capacity to plan for, or protect against, larger scale floods.

Increased areas of impermeable surface (roofs, pavements, roads and car parks) within urban locations are important contributing factors in the prevalence and growth in pluvial flooding (White and Howe, 2002). Stormwater runs off these surfaces far more swiftly than on pre-development permeable terrain, such as agricultural land, which would have permitted slower infiltration processes (Wheater and Evans, 2009). When extreme rainfall events occur, the resulting runoff can overwhelm drainage infrastructure where this exists. Furthermore, climate change projections suggest that this threat may be exacerbated still further in the future, with a greater proportion of the rain falling in very intense events (Met Office, 2007). It is now apparent that a continuing reliance on increasing the capacity of piped drainage systems, or the creation of underground storage facilities, is neither sustainable nor, indeed, adaptable in the face of future uncertainties (Digman *et al.*, 2012).

Measures designed to restore or mimic natural infiltration patterns can reduce the risk of urban flooding by decreasing runoff volumes and attenuating peak flows. Where successfully implemented, the resulting reduction in regular or 'nuisance' flooding may enhance both the economic wellbeing of urban populations and their capacity to plan for and cope with larger events. The terms used to describe this type of approach vary considerably, not only between countries, but also contextually and over time. As well as sustainable drainage systems (Suds) other relevant terms include surface water management measures (SWMMs), green infrastructure, stormwater control measures (SCMs), best management practices (BMPs), low impact development (LID) and water sensitive urban design (WSUD). In the interests of simplicity, the term Suds, which is most commonly used in the UK, will be used hereafter. Such measures are increasingly being recognised as desirable, and legislation has been introduced in many countries to address the issues where new developments are being planned, such as the sustainable urban drainage systems (Suds) regulations in Scotland, UK (SEPA, 2011). However, while there is the scope for including larger-scale Suds devices such as ponds or constructed wetlands, when designing for the urban periphery there is also a need for initiatives to retrofit improved drainage in urban centres and suburbs. It is possible to address this during urban renewal or refurbishment as, for example, in New York City's green infrastructure plan (NYCDEP, 2011, 2012) and in Portland, Oregon, USA, where financial incentives were offered to increase the uptake of green roofs (Escop, 2011) and disconnect downspouts (Escop, 2006). Although a comprehensive comparison to piped systems is beyond the scope of this paper, it is worthwhile to note that, in contrast to piped systems, Suds offer the flexibility of incremental implementation that enhances urban resilience to changing futures through increased adaptive capacity. An example is provided by Sieker *et al.* (2006) regarding a long-term project to disconnect 15% of clean runoff from an existing sewer system over a 15-year period, thereby reducing both volume and peak flow over time.

Designers and planners now need information and support in order to enhance resilience by retrofitting these stormwater management measures in the world's existing urban environments. According to Digman *et al.* (2012), urban planning and design should be at the heart of integrating sustainable drainage practices into both new and existing urban areas within cities, to ensure the technical features of stormwater management are congruent with other urban functions. Urban designers and planners seeking to address surface water flooding problems not only need guidance as to the elements best suited to flood alleviation purposes, but also an understanding of some of the additional benefits and constraints associated with retrofitting these elements within existing cities. This study is therefore designed to draw together existing evidence from diverse strands of literature outside the planning arena to synthesise learning in the area of retrofitting sustainable drainage practices that can assist planners.

2. Approach

A systematic literature review protocol was designed in order to identify the available information on the use of Suds (and similar features) to reduce flood risk by way of reduced runoff and attenuation of peak flow. Databases from both academic and industry sources were searched, using standardised parameters encompassing a wide range of subject terms, intervention types and outcome descriptors. The results were then filtered to identify those elements most appropriate for retrofit applications, thereby creating an international picture of examples together with technical and performance considerations likely to be of relevance to the planning community.

The database of literature was then interrogated to address the following research questions.

- What are the most appropriate Suds devices for retrofit in urban areas to reduce surface water flood risk?
- What are the major constraints and considerations for urban planners in implementing retrofit?
- What are the additional benefits and opportunities for planners and designers in retrofitting Suds?
- Do Suds increase resilience to extreme events?

3. Suds elements suitable for retrofitting

Many alternatives to piped networks, designed in accord with the tenets of sustainable development, exist: these include measures such as soakaways, swales and detention basins. Such approaches have been termed sustainable drainage systems (Suds) or SWMMs in the UK (Digman *et al.*, 2012). In the USA, the term best management practices (BMPs) has often been employed, although these were primarily water-quality improvement techniques, some of which had stormwater management benefits. More recently, the designation stormwater control measures (SCMs) has been adopted for drainage-specific techniques (White and Howe, 2002). The term low impact development (LID) is also used in the USA (e.g. Escop, 2008) to describe a group of techniques that mimic an area's pre-development flow regime, by controlling stormwater runoff at its source: examples include rainwater harvesting, vegetated roofs and permeable surfaces. These approaches can be shown to reduce the volume of runoff and attenuate peak flows (Damodaram *et al.*, 2010). A further advantage of the LID approach is its suitability for retrofitting to the existing built environment, either replacing or augmenting extant drainage systems: roof drainage, for example, can be diverted away from a piped sewer system into a soakaway. For a full listing of methods for managing and disposing of initial runoff volumes, see Ciria (2009) for example. The main categories are now briefly discussed.

3.1 Infiltration devices

These devices are designed to mimic or enhance the natural infiltration process by making surfaces more permeable. Examples include soakaways, lawns, pervious paving and underground retention galleries (Allen *et al.*, 2010). The performance of such systems in reducing runoff is naturally dependent on groundwater conditions: where soil is saturated or the local groundwater level is high, infiltration will be slow or ineffective (Roldin *et al.*, 2012). There are also issues around maintenance regimes to address potential clogging, as discussed by Sansalone *et al.* (2012). Many of the infiltration techniques require significant land resources, which makes them unsuitable for retrofit in dense areas (Czemiel-Berndtsson, 2010). Pervious paving, restoration of lawns and multi-functional green spaces such as playing fields may be incorporated without loss of other urban functions.

3.2 Green roofs and walls

According to Voyde *et al.* (2010), green roofs are highly suitable stormwater controls for retrofitting in dense urban areas, albeit with the proviso that hydrologic response will be influenced by factors such as rain depth, rain intensity and antecedent moisture conditions. Green roofs store water within the substrate and in the plants themselves; the water is then released by way of evapotranspiration after the storm event, thereby relieving pressure on other stormwater devices. Green roofs can be extensive (incorporating shallow-rooted species in a relatively thin substrate) or intensive (deep-rooted species found in roof gardens) dependent on aim, roof structure and climate. Roofs can account for 40–50% of impermeable surface area in urban areas and are often feasible to retrofit, thus presenting a major opportunity to decrease runoff (Stovin, 2010). Figure 1 shows an extensive green roof garden in Portland, Oregon, retrofitted to a municipal building, which captures stormwater, provides amenity space and reduces energy demand. Research into the specification of green roofs has addressed the substrate or growing media. Ristvey *et al.* (2010) examined the effects of using varying proportions of a lightweight media additive to optimise stormwater holding characteristics while maintaining healthy plant growth. Beck *et al.* (2011) found that including 7% biochar reduced the discharge of nutrients, thus preventing runoff pollutants and improving stormwater quality.

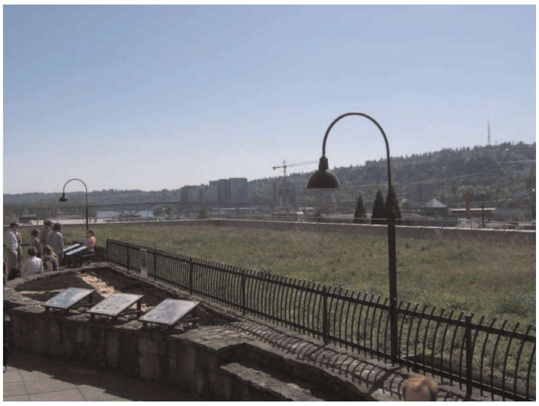

Figure 1. Amy Joslin memorial ecoroof, Multnomah County headquarters building, Portland, Oregon

While green walls have been used less than green roofs, they have the same benefits of heat reduction, storm peak attenuation and insulation, both for maintaining heat inside buildings in the winter and cooling the building during the summer. Ip *et al.* (2010) studied a 'vertical deciduous climbing plant canopy' in the UK and found seasonal benefits due to shading in the summer, reducing the internal building temperature by 4–6°C.

3.3 Rainwater harvesting

The collection of rainwater into cisterns, rain barrels or water butts has the potential to reduce runoff, particularly if the sizing of collection devices is appropriately designed to meet the requirements of storm events (Ciria, 2009). The hydrological performance of such systems under storm conditions will, however, depend on the volume of storage provided and the design of the collection system (Blanc *et al.*, 2012). Harvesting rainwater before it reaches the ground also has advantages in terms of water quality compared with water that has flowed over roadways, for instance. There is a direct (if small) financial benefit to householders and businesses where water supplies are metered, as a reduced volume will need to be purchased for applications such as watering gardens.

3.4 Detention basins, ponds and bio-retention devices

Detention basins are, essentially, dry ponds except when excess water needs to be accommodated within them, as opposed to retention basins that contain some water at all times; bio-retention devices include filtration media to treat runoff before infiltration takes place (e.g. rain gardens). The latter approach is useful where groundwater would otherwise be at risk from pollutants in the runoff (Barr Engineering, 2011). The problem with these devices is that clogging can occur, adversely affecting both the hydraulic performance of the system as well as the interception of pollutants, as discussed by Le Coustumer *et al.* (2009). Meierdiercks *et al.* (2010) modelled the performance of a system of detention ponds and demonstrated that, without them, peak discharge would have increased by 48–50% in a given storm event.

3.5 Management trains

Small-scale installations of any kind have the potential to reduce runoff in situ, but research suggests that combining devices into a 'train' may be more effective for flow attenuation and water treatment. Heal *et al.* (2008) found that a combination of measures installed at a motorway service station in the UK reduced peak flows, pond sediment depth and concentration of contaminants, thus reducing maintenance costs for the site. Applications in urban areas are rare, but an example can be found in Portland, Oregon (Figure 2) where downspouts are directed into rain gardens and then into a 33 m^3 (8700 gallon) underground storage tank for further treatment (Escop, 2006; Lampe *et al.*, 2004).

In selecting an appropriate train or device, surveys may be necessary in order to determine the local conditions with respect to hydrology, geology, flood risk and environmental considerations (Wong, 2000); the design must also take into account system requirements and downstream capacity. Digman *et al*. (2012) also highlights the issues around differing performance standards that may be adopted in relation to the nature of the benefits being sought. As a guide to typical characteristics of individual devices, Table 1 shows the applicability of devices (low/medium/high) for retrofit within dense urban areas. Green roofs and pervious surfaces can be seen to contribute to stormwater management without undue land grab, but are rarely designed to cope with extreme weather events in isolation. Subsurface storage, on the other hand, can more readily be designed to the 100-year event but has minimal impact in terms of other environmental benefits.

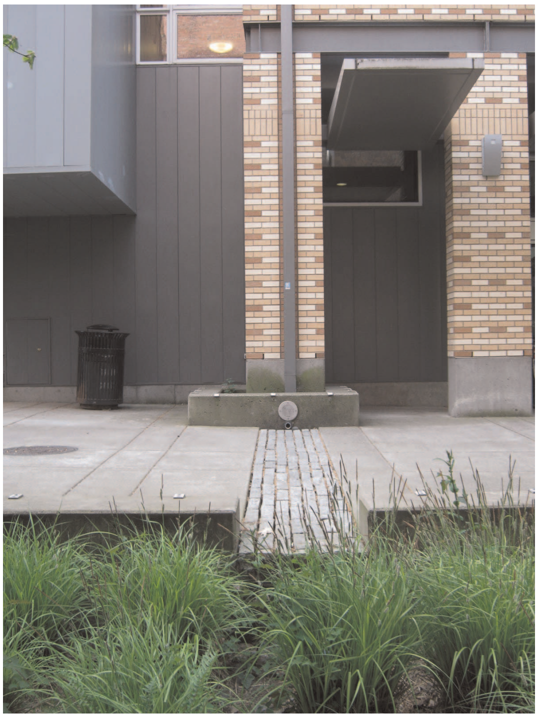

Figure 2. Downspout issuing into rain garden, Portland, Oregon

This view of infiltration devices is supported by evidence on performance from the literature. Rose and Lamond (2013) noted that statistics within studies for vegetated roof performance relating to annual percentage of stormwater controlled ranged from 42–90% of annual rainfall, implying that in extreme events some runoff is inevitable. Average retention during storm events is even more variable, from 30–100%. Similarly, permeable paving studies were found (Blanc *et al.*, 2012) to show performance ranging from 30–100%, with factors such as prior conditions and clogging affecting infiltration rates. While, theoretically, rainwater harvesting systems can be designed to accommodate expected volume of runoff, studies of existing systems show that practical considerations usually imply systems are often overtopped (Blanc *et al.*, 2012).

4. Planning and urban design considerations

Urban planners and designers are well equipped to deal with the aesthetic and spatial aspects of Suds (which are not covered in this paper) and it has been noted and illustrated above that Suds may be a great asset in the streetscape. However, there are additional considerations and particular challenges that need to be highlighted in implementing Suds. Limitations may arise due to pollution controls, land availability, ownership of land and buildings, and other regulatory factors. Urban planners, designers and other stakeholders also need to consider additional aspects, such as spatial scale, cost effectiveness, aesthetic design limitations and planning for more extreme events that cause Suds capacity to be exceeded.

In some countries, a major challenge faced by stormwater managers is ensuring compliance with stormwater quality regulations while achieving a cost-effective design (e.g. Sim *et al.*, 2010). Surface water flooding can have a negative impact on receiving water quality – foul water contamination can occur, particularly with combined sewers and where other pollutants (such as sediments, oils, fuels and toxic metals) can be washed from urban surfaces into receiving waters (Gordon-Walker *et al.*, 2007). There is therefore a need to consider the management of pollution alongside flood risk (Ellis *et al.*, 2012), and retrofitting multi-functional measures such as green roofs can maximise the benefits available from such a programme (Ashley *et al.*, 2011; Digman *et al.*, 2012).

Planning-level decision-making models, such as those developed by Allen *et al.* (2010) and Sim *et al.* (2010), can help to optimise this process, not only by assisting with initial site planning and cost estimation but also providing evidence of, for example, the regulatory priorities taken into account in selecting the Suds options chosen. Planners need to be aware, however, of the limitations associated with such models. For example, Guo *et al.* (2010) suggested that modifications to the US Environmental Protection Agency's SWMM computer

UDS group	Technique	Net land grab	Cost	Annual/seasonal runoff volume reduction	Suitable for flow rate control 1 in 2-year event	Suitable for flow rate control up to 1 in 30-year event	Suitable for flow rate control 100-year event	Maintenance	Habitat creation potential
Retention	Retention pond	H	M	L	H	H	H	M	H
	Subsurface storage	L	M	L	H	H	H	L	L
Wetland	Various	H	H	L	H	M	L	H	H
	Submerged gravel	M	H	L	H	M	L	M	M
Infiltration	Infiltration trench	M	L	H	H	H	L	L	L
	Infiltration basin	H	L	H	H	H	H	M	M
	Soakaway	L	M	H	H	H	L	L	L
Filtration	Surface sand filter	L	H	L	H	M	L	M	M
	Subsurface sand filter	L	H	L	H	M	L	M	L
	Perimeter sand filter	L	M	L	H	M	L	M	L
	Bio-retention/filter strip	H	M	L	H	M	L	H	H
	Filter trench	L	L	L	H	H	L	M	L
Detention	Detention basin	M	L	L	H	H	H	L	M
Open channels	Conveyance swale	H	L	M	H	H	H	L	M
	Enhanced dry swale	H	M	M	H	H	H	L	M
	Enhanced wet swale	H	M	L	H	H	H	M	H
Source control	Green roof	L	L/H	H	H	H/L	L	M	H
	Rainwater harvesting	L	H	M	H	H	L	H	L
	Pervious pavement	L	M	H	H	H	L	M	L

Table 1. Suds selection matrix indicating high (H), medium (M) or low (L) suitability of measure types (after Jha *et al*. (2012) and with adaptation from Blanc *et al.* (2012), after Woods Ballard *et al.* (2007)). It must be noted that this table treats elements in isolation and reports average performance. Careful and innovative design including management trains may allow for enhanced performance

model are needed to calculate the effective surface imperviousness and proposed a pavement area reduction factor.

In existing cities, the requirement to 'grab' land to retrofit sustainable urban drainage is a major barrier to implementation. Spatial scale considerations are critical because, while the encouragement of piecemeal adoption of Suds by individuals can make a large contribution to runoff reduction, there may also be the need for a Suds train and that will require a great deal of coordination, planning and potentially regulation. The city of Portland, Oregon, instigated a widespread 'green streets' programme including stormwater gardens – the intention was to reduce surface water flooding while obviating the need to install new piped drainage in the city (Kurtz, 2010). Although green roofs are encouraged, the uptake is much smaller: in Melbourne, Australia, Wilkinson and Reed (2009) found that most of the buildings suitable for green retrofit were privately owned and therefore in the hands of a disparate group not readily influenced to undertake sustainable retrofitting.

In terms of retrofitting in dense areas, the cost of allocating land to Suds features is a major consideration in the selection of appropriate devices, leading to a preference towards dual-purpose installations such as permeable pavements, rainwater harvesting, green roofs and amenity features. Indeed, cost effectiveness is a critical factor in designing and selecting appropriate Suds and can be a major barrier to their implementation. There is, however, strong evidence that, in many circumstances, the retrofit of Suds can prove cost beneficial. The use of ecoroofs in Portland, Oregon was calculated to be capable of saving the public purse US$60 million compared with the cost of improving the stormwater system; the estimated benefit to an individual property owner was estimated to be US$43 500 over the expected 40-year life of the roof (in reduced energy bills for heating and cooling) (Escop, 2008). Similarly, Doneux (2011) reported that an overall saving of US$0·5 million had been made by employing multiple BMPs instead of replacing stormwater sewers in Arlington, Mississippi, USA. Adams *et al.* (2010) observed that, in three redevelopment contexts in the USA, the provision of either traditional or LID drainage made no difference to the costs over a 50-year scenario. Recent research indicates that improvements in design are likely to make the cost–benefit equation more favourable. For example, Jia *et al.* (2012) modelled a variety of improvements to the Beijing Olympic Village and found that the optimal solution (maximising flood control benefit while minimising cost) was to modify the existing green roofs by doubling the soil depth (from 0·3 m to 0·6 m).

In planning drainage schemes, there are a number of sources of information on the costs and benefits of installation of Suds. For example, Ciria (2009) provides a list of the principal research studies on Suds costs and a benchmarking exercise for the Minnesota Pollution Control Agency (USA) by Barr Engineering (2011) includes detailed costings for both construction and maintenance of a range of BMPs in the US context. In general, the most cost-effective opportunities for Suds installation exist during new construction and development (e.g. Bloomberg and Strickland, 2012), but Gordon-Walker *et al.* (2007) conclude that the retrofit of permeable paving in the UK would be cost beneficial. While the expertise and software for technical design of Suds is not yet as commonly available as that for conventional systems, which can result in higher design costs, the passage of time should see improvements in this area. Some of the guidance available for planners with reference to new build may be transferable; in the UK, Dickie *et al.* (2010) cover both new and retrofit applications.

While installation and design of retrofit measures may be more expensive than for new development, the maintenance costs can, in some instances, be similar or even lower. Duffy *et al.* (2008) found that, when well designed and maintained, Suds can cost less to maintain than more traditional drainage. MacMullan and Reich (2007) reached a similar conclusion and also highlighted the (usually uncosted) environmental and amenity benefits possible with these methods, which are lacking in conventional systems.

If regular maintenance is lacking, however, Suds systems not only function inefficiently but the amenity benefits can be diminished. While green infrastructure is often favoured as a result of recreational and biodiversity advantages (Ashley and Nowell, 2010), the liability resulting from poor maintenance (particularly vegetation cutting and litter) may also be much more all-encompassing: Ciria (2009) notes the possibility of local residents utilising Suds structures for dumping grass clippings, thereby compounding maintenance problems. Stevens and Ogunyoye (2012) report that, compared with conventional piped systems, Suds systems can still offer robust performance even if maintenance schedules have not been adhered to. More research on the long-term costs of operation and maintenance of Suds, including quantification of the biodiversity, amenity and aesthetic benefits, is needed. Furthermore, the multiple benefits of Suds installation are spread over a wide populace: flood reduction benefits go beyond the property that installs them, stormwater benefits may be spread among all customers of a given utility company and amenity benefits accrue to local businesses, residents and visitors to an urban area. The apportionment of costs and benefits for green infrastructure is an area that has received minimal research attention and studies in this area could support improved implementation procedures.

Aesthetic value is a matter of taste. Although the implementation of green roofs may be held to be a positive design feature, it could be resisted in historic city centres as being out of character. A vegetated roof may be effective in terms of stormwater management but, in climates where lengthy dry seasons occur, the vegetation may become brown, rather than green: at these times the public may perceive (incorrectly) that the plants have died off, not appreciating that this is a natural process, as noted by Liptan and Strecker (2003). In reviews of planting within stormwater gardens in Melbourne (SNIFFER, 2004; Land and Water Constructions, no date), it was found that the choice of species needs to go beyond aesthetics alone: retarded plant growth can be advantageous in signalling poor infiltration, thus prompting remedial measures to be implemented. Conversely, where plants that thrive in waterlogged conditions were used, their apparent health can belie an underlying structural problem such as clogging of filter media. More research is needed into the performance of vegetation in respect of differing aspects of Suds performance and aesthetic appeal.

Considerations for retrofitting green roofs must include the strength of the building structure intended to take the load, as well as suitable orientation and avoidance of overshadowing that might inhibit the growth of vegetation. Wilkinson and Reed (2009) found that a relatively small percentage of the roofs in the central business district of Melbourne would be suitable for installation of green roof technology. The addition of lightweight material (e.g. ‘crumb rubber’ from recycled tyres) to the substrate may be beneficial in such contexts (Ristvey *et al.*, 2010; Vila *et al.*, 2012). Similarly, Compton (2006) investigated the use of specially treated waste expanded polystyrene foam (a material otherwise destined for landfill) to create a lightweight soil substitute that combined water-retentive properties and longevity.

These considerations do not imply that retrofit is not achievable, merely that the involvement of a structured process of scoping, detailed design and consultation may be necessary in realising the planned vision. This is particularly true if the full potential for multiple benefits is to be realised, as discussed below.

5. Evidence for other benefits

The foregoing discussion of constraints and costs–benefits demonstrates the importance of considering Suds as an integral part of urban design. It is clear that in some cases the decision to install Suds is justified purely on the basis of flood or stormwater control. The case can sometimes be strengthened, however, and the choice of Suds may be informed by the other benefits that can ensue from some Suds elements (Ashley *et al.*, 2011). As an example, regeneration of the neighbourhood of Augustenborg in Malmo, Sweden, was initially driven by considerations that included flood risk management (Kasmierscak and Carter, 2010). It was found that the installation of significant amounts of green infrastructure has not only reduced runoff but has also improved the reputation of the neighbourhood as a pleasant place to be. Quantification of such urban planning gains can pose a challenge: one possibility lies in the concept of ‘natural capital’ (e.g. Dickie *et al.*, 2012), which – it has recently been suggested – can be employed to value natural assets that provide a positive economic or social value. The main retrofit measures considered above have varied benefits: for example, rain gardens and tree pits alongside roads can offer improved amenity value within the street scene as well as enhanced biodiversity. These benefits are, however, often listed without robust evaluation of the interaction between flood control and drainage benefits and other functions of green infrastructure.

Green roofs act as an insulation layer, thereby reducing a building’s heating and cooling costs (Bastien *et al.*, 2011): Bamfield (2005) estimated fuel savings from green roofs to be £5·20/m^2 per year. Getter and Rowe (2009) assessed the carbon dioxide sequestration ability of extensive green roofs over a 2-year period and found that an average of 375 g carbon dioxide/m^2 was achieved; they calculated that if the city of Detroit, Michigan greened its 15 000 ha of rooftop, then potentially 55 252 t of carbon dioxide could be sequestered. With the acknowledged need to reduce global greenhouse gas emissions, evidence such as this increases the cost effectiveness of this retrofitting option; the relationship between optimal co-benefits and flood mitigation is, however, not yet clear.

Permeable paving and other installations that increase infiltration can help to restore groundwater recharge, with water that would otherwise be lost to sewers or watercourses (Gilroy and McCuen, 2009), although optimal contaminant removal may come at the expense of fast infiltration. Suds employing vegetated areas for retention or infiltration may also contribute to attenuation of the urban heat island effect (Stovin *et al.*, 2012; Vila *et al.*, 2012). For maximum cooling to be achieved by way of transpiration effects, however, the vegetated areas need to be watered, thereby reducing the capacity for runoff reduction (Salagnac *et al.*, 2013).

Vegetated roofs can add to biodiversity/wildlife habitat (Stovin *et al.*, 2012; Vila *et al.*, 2012). One example of this is the 400 m^2 roof area of the tower block housing Barclays Bank in London, UK, which was converted into a green roof (Livingroofs.org, 2005). Soon after completion, it was found that around 10% of the invertebrate species identified on the roof were considered nationally rare, while two of the 20 beetle species found were very rare and had previously only been recorded six times before in the UK (Warwick, 2007). ‘Brown’ roofs are an alternative design that can mitigate for loss of brownfield habitat on the ground, but are less effective at water retention (Bates *et al.*, 2009). Green roofs have been found to aid the protection of waterproofing materials from solar damage and sound insulation (Vila *et al.*, 2012; Wilkinson and Reed, 2009) and improve air quality (Stovin *et al.*, 2012). It has been demonstrated by various authors (de Vries *et al.*, 2003; Groenewegen *et al.*, 2006; Maas *et al.*, 2006) that proximity to green space in an otherwise dense urban area can have a positive impact on perceptions of health and wellbeing which, in turn, could result in cost savings for health service providers (a point worthy of consideration in respect of multi-level building design and public access roofs).

It is clear that there are many potential benefits from Suds that may add desire to include them in urban retrofit and will greatly enhance the urban environment and urban resilience. However, these benefits should also be rigorously evaluated on an individual basis rather than assumed, as optimising installations for the reduction of flooding may conflict with the most environmentally beneficial options. For example, the plant species offering greatest water absorption capacity on a green roof may not be those native to the area concerned (TCPA and TWT, 2012). Urban planners therefore need to bear in mind the multiple functions of the urban environment when selecting Suds options. Furthermore, while there may be aspirations to create urban blue–green corridors in existing neighbourhoods, a recent UK report (URS and Scott-Wilson, 2011) has identified potential barriers in terms of gaining residents' support for such initiatives.

6. Conclusion

Sustainable drainage systems are an important aspect of modern urban design in a new-build context, and new regulation and guidance is emerging in many parts of the world. The case for Suds retrofit is, however, much less developed than that for new development. Many Suds devices are suitable for retrofit to reduce runoff, but in dense urban areas this can be difficult. The most appropriate candidates – with a combination of low land grab and high moderate to runoff reduction – are green roofs, rainwater harvesting/underground storage, rain gardens and permeable paving. The incorporation of larger green corridors and multi-functional areas can also be extremely effective where regeneration is ongoing, as opposed to recreation or restoration of watercourses in extant urban locations.

Infiltration devices can reduce annual runoff significantly and reduce the incidence of surface water events. Suds installations may, however, be exceeded in extreme events, unless they are specifically designed to accommodate high return periods (a feature they share with piped drainage systems). They should therefore be seen as part of an integrated solution.

Other considerations that may be particularly problematic for retrofit within dense urban environments include practical issues such as access for installation and maintenance, ownership of buildings and urban spaces, lack of subsurface space, pollution controls, aesthetics and suitability of building types in historic districts. It is important to be aware of the costs and benefits of retrofitting: practice suggests reduced need for installing conventional drainage in dense urban settings is often a driver. Most of the available cost–benefit guidance currently available relates to new development, therefore more research is needed to support the case for retrofit. In addition, there is a research gap in the evaluation of beneficiaries against payees: this may be critical in negotiation of retrofit, with the need to balance the public good as a whole against the need to incentivise individuals to act.

Other benefits associated with features of Suds, such as increased green spaces, can contribute to the quality of life within urban spaces and may add to the case for Suds retrofit. It is important to be selective in the choice of Suds if flood control is a consideration and flood functionality may conflict with other benefits; therefore, these benefits need to be evaluated on a case by case basis. The improvement of urban spaces may also add to urban resilience by improving the capacity of populations to cope with stressors in general and, therefore, to extreme events such as flooding.

The evidence considered in this paper demonstrates that retrofitting of Suds for flood control in existing cities should always be considered as part of an integrated solution comprising blue–green and grey elements as appropriate to the specific location and conditions. Suds can make a substantial contribution towards making cities and their populations more resilient. Planners and urban designers need to be at the forefront of plans to retrofit Suds in existing urban areas, backed by specific regulations, good guidance and further research targeted at retrofit. In designing schemes, an integrated approach is essential because the benefits impinge upon so many functions of urban management and careful design is needed to realise the multiple benefits of Suds.

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