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A review of the adaptation and mitigation of global climate change using sustainable drainage in cities

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ABSTRACT

Sustainable drainage (SUDS) is well known for its equal emphasis on water quality, water quantity, amenity and biodiversity. What is now beginning to be realised is that this approach can also help mitigate the impacts of global climate change (GCC) and provide assistance to city dwellers in adapting to the changes which have already occurred. By using case studies from around the world, this paper illustrates how vegetated SUDS devices can sequester and store carbon, cool urban areas and increase perceptions of health and well-being in the populace. Both vegetated and hard-engineered structures can evaporate water contained within them and are thus being used in cities to cool the overlying air. Also shown is the extent to which SUDS devices such as green roofs and wet pavements are being used to mitigate the urban heat island effect, which, while not caused by climate change, exacerbates its impacts.

Of the houses needed by 2040 in the UK, 80% already exist. In order to take advantage of the ability of SUDS to tackle some of the impacts of GCC, the emphasis must be placed on retrofitting technologies to existing buildings and this review proposes a simple hierarchy of suitable measures based on the density and land-use of the built-up area.

Key words | carbon sequestration and storage, flooding resilience, human health and well-being, mitigation and adaptation, planning, sustainable drainage, urban cooling, urban heat island effect

INTRODUCTION

Average temperatures have increased globally by 0.74°C over the past 100 years (AMICA 2007), but the extent of climate change and its future impacts are difficult to predict. Scenarios developed dependent on different storylines predict atmospheric carbon dioxide (CO_2) concentration of between 540 and 920 ppm by 2100 in comparison to today's value of about 400 ppm and pre-industrial concentrations of approximately 280 ppm (Nakicenovic *et al*. 2000). These changing CO_2 concentrations may (Murphy *et al*. 2009) be reflected in increases in temperatures of between 2.2 and 6.8°C by the 2080s and, while the average precipitation per year may be slightly lower than it is now, its temporal distribution will change such that summers may become drier, winters wetter and storms more common.

'Climate change is the biggest threat to the future development of human civilisation and poses a huge challenge to cities like London' (GLA 2007). London's *Climate Change Action Plan* goes on to state that the UK is the world's eighth largest CO_2 producer, of which London is responsible for 8% and alone produces 44 million tonnes CO_2 pa, which is projected to rise to 51 million tonnes by 2025 if preventive measures are not taken. The target set is to reduce emissions to 60% below 1990 levels by 2025 which means that current emissions need to be reduced by 4% annually in order to achieve such reductions. Adaptation and mitigation measures should therefore focus on three main areas: reduction in greenhouse gas (GHG) emissions, reducing temperatures and flooding resilience measures.

Architecture 2030 (2006) states that, contrary to the popular belief that transportation is responsible for the greatest percentage of GHG emissions, it is in fact *buildings* that globally emit 48% of the GHGs, stating furthermore that: 'stabilizing emissions from this sector and then reversing them…is key to keeping Global Warming to approximately 1°C above pre-industrial levels'. In general, these impacts are due to industrialisation and urbanisation leading to increased fossil fuel use for heating/cooling homes, increased impermeable surfaces in the built environment including those with heat absorbing properties, decreasing numbers of natural water bodies (e.g. canalisation, channelisation, straightening and simple infilling of small ponds), loss of vegetation on the whole and replacement of some street trees with small, non-native specimens. Cities such as London and New York emit up to 40% of their GHGs in this way and Metz *et al*. (2007) identified improvements to construction as an economically beneficial way of tackling the problem.

While flooding is a natural event, in cities with their associated infrastructure, flooding on a large scale can be catastrophic. In August 2002, for instance, a 1 in 100 year event occurred across Europe during a week of intense rainfall in which dozens died, thousands were made homeless and billions of euros of damage was caused, in particular to the Czech Republic, Austria, Germany and Poland. Whole villages in Eastern Germany were almost completely wiped out as overfull rivers changed their course.

The devastation caused by the summer storms of 2007 and 2008 in the UK highlighted that its ageing sewerage infrastructure cannot cope with the situation as it is now, let alone if some of the more conservative predictions of the possible impacts of global climate change (GCC) on storminess in the future ensue. In 2007 in the UK, 13 people died, 48,000 homes and 7,300 businesses were flooded and the total cost was £4 billion including the £1 billion for cleaning up the damage (ABI 2007). Water UK (2008: 5) states that ‘Bigger pipes are not the solution to bigger storms’, furthermore suggesting that sustainable drainage systems (SUDS) and ‘sacrificial areas’ are the ways forward.

Globally, surface water policy differs widely across regions. This is illustrated by the United Kingdom which is made up of four individual countries: England, Scotland, Northern Ireland and Wales. Scotland has policies which have enabled it to implement SUDS as a surface water management strategy for the last 15 years, whereas England, Northern Ireland and Wales have yet to fully embrace SUDS technology in their planning policies and guidance, and hence it is not widely implemented. As a result, a detailed coverage of policy will not be given here.

This paper discusses the concept of SUDS, and the individual devices which can be used to construct a sustainable drainage system. Sustainable drainage is a flexible and multiple benefit approach which goes far beyond simply mitigating flooding and water quality concerns. By proposing that SUDS can green and cool urban areas, reduce the urban heat island effect (UHIE) and have positive impacts on human health, it is argued that in the future SUDS will be a powerful weapon in the arsenal of techniques used to combat a changing climate.

SUSTAINABLE DRAINAGE

Conventional hard drainage tends to concentrate on managing water quantity (Figure 1a) by gathering all the runoff water from impervious streets and pavements into storm sewer systems which pass via gullypots, pipes and water treatment facilities into the receiving watercourse. These systems can either combine foul and surface water or separate them. Water quality is of less concern to conventional drainage, and biodiversity and amenity are of little importance, hence urban streams have become ‘neglected, abused, or modified’ (Keller and Hoffman 1977: 237).

SUDS are a suite of measures whose management approach is entirely different from that of conventional drainage. Instead of constraining surface water into pipes and conduits, forcing it to leave a city as quickly as possible, SUDS encourages infiltration and detention of surface water on site. It is a different way of managing water; instead of treating it as an embarrassment, to be hidden from sight and forgotten, it should be treated as a ‘liquid asset’ (Semadeni-Davies *et al*. 2008) in which society takes account of the behaviour of water, rather than water’s behaviour having to change for the sake of society.

These measures, devices or best management practices (BMPs in the USA) comprise above and below ground structures, essentially ‘hard’ constructions such as porous paving systems (PPS) and rainwater harvesting (RWH) which can usefully be combined (see Gomez-Ullate *et al*. 2010) or ‘soft’ ones utilising vegetation such as green walls and roofs, constructed wetlands and swales whereby water is infiltrated into the ground or detained and allowed to dissipate slowly, for instance in detention and retention ponds. This approach is represented by the SUDS ‘triangle’ in which there is an equal balance between water quantity, water quality and biodiversity/amenity (see Figure 1b), in contrast to that of conventional drainage. It is beyond the scope of this article to provide a detailed discussion of the design and construction of SUDS devices, and there are many sources of information which provide this (e.g. Charlesworth *et al*. 2003; GDSDS 2005; Castro Fresno *et al*. 2005; DTI 2006; CIRIA 2007; EA http://www.environment-agency.gov.uk/static/documents/Leisure/GEHO0308BNSS-e-e.pdf ; SEPA http://www.sepa.org.uk/water/water_publications/suds.aspx ; US EPA http://www.epa.gov/npdes/stormwater/menuofbmps). However, Table 1 lists some of the many devices used in sustainable drainage which can be used individually, or designed as a SUDS train, in which individual devices are linked together in series (see Figure 2) providing controls at the source, site and regional scales (Charlesworth *et al*. 2003; CIRIA 2007). Examples of such trains in the UK include the Environment Agency SUDS demonstration sites at the Hopwood Motorway Service Area (MSA) near Bromsgrove, UK, on the M42, junction 2 (see Heal *et al*. 2008) and also the Wheatley MSA at Oxford on the M40 (Bray (nd), 2000). Charlesworth *et al.* (2003) describe such trains as a ‘cascade’ which is able to tackle many of the negative impacts of GCC which a single strategy alone would not have been able to address.

The SUDS triangle shown in Figure 1b does not reflect the fact that these measures can be used in mitigating and adapting to climate change by, for example, carbon capture and urban cooling. By adding benefits accrued by utilising the sustainable drainage approach the usual triangle can be transformed into a rocket as shown in Figure 1c, enabling it to take off in the future.

BENEFITS OF SUDS IN A CHANGING CLIMATE

Vegetated SUDS devices provide the means to regulate climate, intercept stormwater and sequester or capture carbon leading to economic impacts of increased house prices and lowered energy costs (Tratalos *et al*. 2007). It has been found that, by greening and cooling the urban environment, negative impacts on human health due to GCC can be reversed (Maas *et al*. 2006). The value of SUDS in general and vegetated devices in particular is therefore not confined to a single aspect, but instead there are multiple benefits in the utilisation of this approach. The following sections explore these benefits which are later incorporated into a suggestion for urban design.

Carbon sequestration and storage (CSS)

Obviously, vegetated SUDS will be growing in some form of substrate; however, since Schlesinger (1999) states that the carbon cycle of soils is the least well known of all the carbon sinks, the focus for this section will be on CSS studies of the vegetation only.

The study of CSS in SUDS devices began within the last decade with most studies concentrating on urban trees (Pataki *et al*. 2006). There is a considerable literature on the CSS abilities of constructed wetlands, but since these are relatively unlikely to be incorporated within city boundaries, they will not be considered here. Nowak & Crane (2002) estimate carbon storage in urban trees in parks and on streets of around 700 Mt in the coterminous US with sequestration averaging 22.8 Mt C yr^{-1}. Pataki *et al*. (2006) list seven US cities with numbers of urban trees varying from about 17,000 up to nearly 200,000 and sequestration rates per tree of between 33 and 126 kg yr^{-1} leading to reductions in overall CO_2 of 80 to 250 kg per tree. It is difficult to assign a definite amount of carbon released from a building, since these vary a great deal according to use, construction and so on. However, a standard family car can release 1 tonne carbon yr^{-1}, and using figures calculated by Whitford *et al*. (2001) of carbon stored in residential areas in Merseyside, UK, stands of dense tree cover were capable of storing more than 16 tonnes C ha^{-1}, and sequestered up to 0.13 tonnes C ha^{-1} yr^{-1}. Thus one hectare of urban tree cover, or approximately 160 trees at 100 kg C stored per tree, could account for the emissions of 16 family cars per year. Crucially, areas storing the most carbon were found to be the most affluent because of their greater coverage of green space; this led to a better ecological performance in these areas in comparison with less affluent areas.

Some cities have implemented tree planting schemes amounting to urban forests, such as the Chicago Urban Forest Climate Project. McPherson *et al.* (1994) reported that the city's 4.1 million trees stored 855,000 tons of carbon, reduced surface runoff and also reduced air conditioning use because the trees intercepted up to 90% of incident solar radiation. They also found that the larger the trees the greater the benefits, and areas with few trees, such as the city centre, suffered the most during heatwaves. These findings led to the development of a targeted strategy whereby trees were not simply viewed individually, but were seen as being part of a city-wide approach, providing multiple cost-effective environmental functions. As a result, approximately 3,000 trees were planted during 2007 in 60 parks in Chicago (CABE, http://www.cabe.org.uk/case-studies/chicago-urban-forest/). McPherson *et al*. (1994) furthermore stated that 'the long-term benefits of trees are more than twice their costs'. Brack (2002) predicted that an urban forest of 452,200 trees in Canberra, Australia, would sequester 30,200 tonnes of carbon between 2008 and 2012. This could translate into a financial value of the whole forest of over US$20 million due to reduction in energy consumption and atmospheric pollution amelioration. Other benefits of such a scheme include shading, visual amenity and control of urban glare and reflection.

There are very few studies of green roofs that estimate their CSS capabilities, but the Los Angeles Environmental Affairs Department (LA EAD 2006) quotes an area of prairie grass which sequestered 700 tonnes of carbon in 2000; however the size of the area was not given. Getter and Rowe (2009) report a study in which they assess the carbon sequestration ability of extensive green roofs over 2 years of monitoring. They admit that green roofs have often been studied from their energy saving and heat island mitigation abilities, but rarely in their climate change mitigation role. They detail the 'terrestrial carbon sequestration' pathway via vegetation from photosynthesis taking up CO_2 to transfer of the carbon eventually into the substrate through the incorporation of plant litter. They therefore sampled above-ground biomass, below-ground biomass and substrate carbon, finding 167.9 gCm^{-2}, 106.7 gCm^{-2} and 912.8 $gC\ m^{-2}$, respectively. The whole roof system sequestered 375 $gC\ m^{-2}$. Taking the latter figure as an average, they calculate that if the city of Detroit, USA, greened its total of nearly 15,000 hectares of rooftop, then potentially 55,252 tonnes of C could be sequestered.

It is not only vegetated devices that can be instrumental in CSS. Studies by Downing *et al*. (2008) calculated that the world's farm ponds capture more organic carbon in a year than the oceans; with between 148 and 17,000 $gC\ m^{-2}\ yr^{-1}$ incorporated into their bottom sediments and essentially trapped there for the life of the pond. Takahashi *et al*. (2002) estimated that the sea captures approximately 2.2 $Pg\ C\ yr^{-1}$ ($1\ Pg = 10^{15}\ g$) total based on 1995 measurements, and Feely *et al*. (2001) report that the oceans have captured between 97 and 113 Pg C since industrialisation began. However Park *et al*. (2008) have found that the uptake of carbon has halved in the East Japan Sea, so increasing the numbers of terrestrial ponds by incorporating them into a SUDS strategy will provide some terrestrial carbon storage space to make up for some of that lost to sedimentation in the oceans. According to Pondconservation.org (Carbon uptake by UK ponds, http://www.pondconservation.org.uk/aboutus/ourwork/climatechangeandponds/climatechangemitigation.htm, accessed August 2010) a 15 m^2 pond could trap 5,000 $gC\ yr^{-1}$, whereas if trees were used, an area of 100 m^2 would be needed to trap the same amount of carbon. Retention and detention ponds, and to a certain extent swales and constructed wetlands could therefore provide a means to store some of the excess anthropogenic carbon.

Urban cooling

All urban areas will obviously be affected by GCC to some extent, but nearly two centuries ago society was already having a profound impact on climate at the city-scale. The urban heat island effect (UHIE) was first noted in 1819 in London (GLA 2006) and is peculiar to cities where, even in winter, urban areas can be several degrees warmer than the surrounding countryside. The UHIE has the potential to have adverse impacts on human comfort, and even health (Coutts *et al*. 2007), especially during extreme events; for instance night-time temperatures in London can be some 6–9°C higher than those in rural areas (GLA 2006). Distribution of this heat is related to the reasons for the existence of so-called heat 'islands', including: lack of vegetation, anthropogenic activities such as transport, heating, cooling and the thermal properties of the fabric of urban structures which store and then release heat (Memon *et al*. 2008). Remote sensing of urban areas (Wilson *et al*. 2003) has revealed a patchwork of discrete heat islands related to the distribution and structure of buildings and streets, as well as areas with much lower temperatures associated with parks and green space (Yu & Hien 2006). Warm air and associated pollutants such as ozone can become trapped because of the lack of convective overturn in these warmer areas. Energy is therefore used to cool building interiors so that people can live and work in them in comfort, but the very act of trying to reduce temperatures increases outside temperatures, as excess energy is released from the building and into the environment.

According to Yu & Hien (2006) the incorporation of vegetation in urban areas is one of the main ways of mitigating the UHIE, creating what they called the 'oasis effect' whereby temperatures are reduced at the local level near planted areas, whether for buildings surrounding a park, or with vegetation planted around the individual construction. SUDS devices which have been used extensively for this purpose are green roofs, which have the added advantage that they can be retrofitted to suitable buildings without the need for extra space. In fact, as Mentens *et al*. (2006) state, unused roof space can represent up to 50% of the impermeable surfaces of cities. Like many cities, therefore, New York's Heat Island Reduction Initiative centres on increasing vegetation, in particular green roofs (Solecki *et al*. 2005). Similar to predictions in Tokyo, should 50% of New York's flat roofs be greened, the UHIE effect could be reduced by up to 0.8°C (Rosenzweig *et al.* 2006). The escalation of the UHIE in Tokyo has driven its use of green roofs to adapt and mitigate the effects of an increase of 3°C over the last 100 years, an effect four times the impact of climate change globally and in part driven by it. Not only is the temperature predicted to peak at 43°C by 2030, but studies have shown that the central UHIE area is also spreading to encompass more of the city. ‘Tokyo summers are…fast becoming unliveable’ (S. Trautlein, Seeing Green, http://archive.metropolis.co.jp/tokyo/485/, accessed August 2010). In April 2001, the Tokyo Metropolitan Government (TMG) brought in a requirement that one-fifth of roofing on new build should be green, which would lead to 2,965 acres (1,200 ha) of new greenery (TMG 2007). Only Germany currently has such a requirement for new build. The TMG Transport Ministry found that hard roofing in summertime had an average temperature of 60°C, whereas that of a green roof was 38.6°C; in the substrate under the green roof the temperature was 28.1°C. The internal temperature of any building under a green roof is likely to be cooler, reducing the need for air conditioning use, and hence cutting energy usage and carbon release. The Tokyo-based Organisation for Landscape and Urban Greenery Technology Development estimated that if half of Tokyo’s roofs were green, the daytime summer temperature in the city could fall by as much as 0.84°C.

Germany has been utilising green roofs for approximately 30 years with at least 20% of the country’s roofs greened (CIRIA 2005). Kochan (2007) called Germany the ‘world leader in roof greening’ and CIRIA (2005) estimated that areas of green roofing increased from 1 million m^2 in 1989, to 11 million m^2 in 1997 and by 2001 13.5 million m^2 of green roofs had been installed across the country, an investment of some £153 million. An exemplar of the use of urban greening is Stuttgart, which, owing to its geographical location, is vulnerable to what could amount to a runaway UHIE. Since 1938, therefore, planning has been climate-based and has resulted in the city being hailed as one of the ‘best examples of heat island management’ by Sustainable Cities (CABE, http://www.sustainablecities.org.uk/greeninfrastructure/heat-island/heat-island-strategy/). The city structure utilises wind paths containing trees encouraging unimpeded air flow and in the inner city trees of a certain size are not allowed to be felled. As a result, Stuttgart is 60% covered in greenery. Hough

(1995) praises Stuttgart at both the city and the individual human scale as being ‘among the most climatically functional, socially useful and aesthetically pleasing of any modern city in the Western World’.

Green walls have been used less than green roofs, but they, too, have the same benefits in terms of heat reduction, storm peak attenuation and insulation, both for maintaining heat inside buildings in the winter and cooling the building during the summer. The study of a ‘vertical deciduous climbing plant canopy’ by Ip *et al*. (2010) in the UK, for example, found seasonal benefits due to shading in the summer leading to a reduction in internal building temperature by 4–6°C, but when the leaves fell in autumn, any incident solar radiation was allowed through the windows, heating the room inside. Augmentation of vegetative cover in cities at the *local* level (i.e. mitigation of the UHIE) can have *regional* benefits (i.e. mitigation of climate change) (Sailor 1998). In fact, in a study modelling hypothetical cities, Sailor (1998) computed that increasing vegetative cover by as little as 6.5% could reduce summertime temperatures by between 3 and 5%.

‘Arguably one of the most efficient ways of passive cooling for buildings and urban spaces in hot regions’ is evaporative cooling (Robitu *et al*. 2006: 436), which can be carried out biologically in plants or physically by ponds and PPS, the latter declared by Asaeda and Ca (2000: 363) as ‘the most effective method to moderate the thermal conditions of the pavement surface’. Evaporative cooling occurs from a wet surface when moisture is evaporated into the overlying air, releasing latent heat and cooling the atmosphere and the following sections briefly consider the efficacy of this process in PPS, ponds and vegetation.

PPS were primarily designed to allow storm water to infiltrate, dissipate into the ground or be stored and released slowly. There are many surface types, such as block paviours, porous asphalt and porous concrete, as well as various subsurface structures (Okada *et al*. 2008; Gomez-Ullate *et al*. 2008). Moisture can evaporate from the surface or within the substructure, leading to a cooling effect.

This effect has been maximised by the design of PPS with water-retaining materials, and those with optimal evaporative properties (Okada *et al*. 2008), such as slag, bentonite and diatomite. However, according to Okada *et al*. (2008), these materials do not release their absorbed water slowly enough, and hence ‘wet pavements’ have been tested (e.g. Yamagata *et al*. 2008) in which reclaimed wastewater is applied to the pavement surface during the daytime. Results indicate that not only was the daytime temperature reduced by 8°C, but night-time temperatures were also reduced by up to 3°C. Combined with what the US EPA (2009) term ‘cool pavements’, those which have higher solar reflectivity than conventional paving, the design and utilisation of a variety of PPS for urban cooling looks promising. However, while the efficiency and efficacy of PPS on reducing storm peaks is well researched and understood, more work is needed to better understand the role that PPS can play in urban cooling.

According to Pondconservation.org, ponds are heat sinks, and studies of large basins such as gravel pits (e.g. Novo *et al*. 2010) have shown that they can be used as a means of seasonal heat storage. However, there are few studies of the evaporative benefits of SUDS ponds and wetlands. Robitu *et al*. (2004) found that a pond can cool an urban environment in summer, quoting the difference in temperature between the pond and a road surface in full sun at 3 p.m. as 29 K. Givoni (1998) suggests that roof ponds can cool individual buildings, finding temperature differences of 2–3°C between the cooler ceilings beneath a roof pond and the temperature of the air indoors. It is suggested by Robitu *et al*. (2006) that ponds should therefore be integrated into urban design to improve thermal comfort in cities.

The evaporative cooling benefits from vegetative devices are due to the process of evapotranspiration from the leaf surface into the overlying air. Wanphen and Nagano (2009) suggest that green roofs, therefore, can reduce building surface temperatures as well as those in the surrounding atmosphere and hence reduce the need for air conditioning. This has been proven not only by field trials, but also by computer modelling (e.g. Onmura *et al*. 2001), and is a technique which has been used globally as discussed above with particular reference to mitigating the UHIE. However, one of the main reasons in the UK for the lack of uptake of SUDS is anxiety over maintenance, in particular that of vegetated devices, such as green roofs. While not arduous, nonetheless a certain amount of care is needed to keep the green roof in optimal condition. Wanphen and Nagano (2009) therefore tested a variety of porous and non-porous materials for use on roofs without plants, mainly for their evaporative properties and found that siliceous shale had the ability to reduce daily average surface temperature by up to 8.6°C. These materials are lightweight and of simple construction; however, the plants making up a green roof anchor the substrate into position and while Wanphen and Nagano (2009) suggest using a net to hold the unconsolidated shale in place, as water passes through during a storm, it still may not be robust enough to avoid particles being dislodged to fall into the street below. However, its simple design and structure, allied with the lack of plant maintenance make this a positive addition to the SUDS ‘menu’ of available techniques (US EPA, nd).

Flood resilience

SUDS were first conceptualised as a reaction to increased urbanisation and industrialisation paving over swathes of the original countryside. These built-up areas subsequently suffered flash flooding, first-flush pollution, reduced biodiversity and amenity as a result. With the threat of increasing storminess due to GCC, the original role of SUDS devices as flooding resilient infrastructures is becoming even more important. SUDS has been used for this purpose for several decades in the USA, Scandinavia, particularly Sweden, and continental Europe, in particular Germany and France. As a result, the flood attenuation benefits of SUDS devices are clear and unequivocal and there is a considerable literature detailing their performance. For example, installing a green roof can absorb up to 100% of incident rainfall, dependent on conditions, and regionally with only 10% of roofs greened, a 2.7% reduction in storm water runoff can result, with a 54% average reduction in runoff per individual building (Mentens *et al*. 2006). In a review of the performance of PPS, Scholz & Grabowiecki (2007: 3833) cover many of the structures available stating that 'high peak flow…[is]…effectively controlled' and Booth (2000) further states that, regardless of PPS structure, they 'dramatically reduce surface runoff volume and attenuate peak discharge'. In a review of the performance of the Scottish SUDS train at DEX (Dunfermline eastern expansion), MacDonald & Jefferies (2003) found that the six ponds, wetland and associated upstream detention basins and swales yielded significant lag times and in a parallel study of one of the two English EA demonstration SUDS trains at Hopwood MSA (see above) Malcom *et al*. (2003) reported significant reductions in peak flow for all but the largest events.

However, the incorporation of SUDS into new build requires their addition at the planning stage. They need to be *designed* to be fit for purpose as is conventional drainage, which in general is designed for the 1 in 30 year storm. A simple example of drainage design using the SUDS approach is the use of a single swale which has design considerations as set out in Table 2; this illustrates that SUDS is most effective when dealing with the smaller, more frequent event, rather than large floods.

Many developed country's planning laws (for example England's Planning Policy Statement 25 (PPS25), DCLG 2009) stipulate that new build must render the site able to deal with surface water at greenfield runoff rates; that is, the rate at which the site would have infiltrated or stored the water prior to development. Specific details of the calculations required for computing greenfield runoff rates are beyond the scope of this paper, but further information can be found in HR Wallingford (2007), Wilson *et al*. (2004) and Gibbs (2004) and greenfield runoff estimation methods are reviewed in Balmforth *et al*. (2006, Appendix 7).

GCC, human health and well-being

The 2003 heatwave across Europe caused €17 billion in damage and is thought to have caused up to 50,000 additional deaths (AMICA 2007). Nicholls & Alexander (2007) cite intensification of heat stress due to both GCC and changes to the local climate, such as the UHIE, as being one of the prime factors negatively impacting residents' quality of life. As a result, human health is affected (EEA 2005) and perceptions of well-being are similarly reduced. The Met Office (2009) predicts that by 2040 more than half of the summers in the UK will be warmer than 2003 and that the temperatures in 2003 would be classified as cool by 2040; health and well-being in such a scenario can therefore only decline.

Various authors (e.g. de Vries *et al*. 2003; Groenewegen *et al*. 2006; Maas *et al*. 2006) have also shown that proximity to green space in an otherwise dense urban area has a positive impact on perceptions of health and well-being. A study by Lafortezza *et al*. (2009) demonstrated such a relationship in times of intense heat stress and they furthermore recommended that green space 'adapted for climate change by providing access to water and shade' (Lafortezza *et al*. 2009: 106) should become UK policy. Many cities around the world have already enshrined mitigation and adaptation measures based on SUDS and green infrastructure (GI) into their climate change strategies. Table 3 summarises the SUDS devices specified in the strategies from 13 of the 17 C40 Participating Cities which originally met in 2005 in order to join together in tackling GCC under the auspices of the Clinton Foundation. Only 2 of the 17 cities make no mention of drainage infrastructure at all and instead concentrate on reduction of energy use and hence emissions through more efficient transport (Madrid and Houston). A further two (Bogotá and Rome) do not have their strategies available. However, of the remainder, seven cities pledge an increase in GI overall with 11 and 9 specifying green roofs and street trees, respectively. Water sensitive urban design (WSUD) is at the heart of Melbourne's strategy, and Chicago uses 'green urban design' to embed SUDS infrastructure in its GCC document. Many cities identify mitigation of the UHIE and flooding resilience as the focus of their adaptation approach, while others such as Los Angeles, Melbourne and Sydney reflect their drier climate in identifying the importance of water resource management, with both Melbourne and Sydney emphasising the human health benefits.

It would seem, therefore, that SUDS have a significant role to play in any strategy implemented to adapt to or mitigate GCC in cities globally. However, incorporating SUDS devices into new build is relatively easy by planning them in at the design stage; it is the residential, commercial and industrial estates which have already been built which present the most difficulties in terms of retrofitting. The following section suggests devices which can be retrofitted and specific areas of the city which lend themselves to those devices.

INTEGRATING SUDS INTO THE BUILT ENVIRONMENT

Studies have shown that the densest areas in cities, such as the central business district (CBD) have the least vegetation (e.g. Akbari *et al*. 1999, 2003; Rose *et al*. 2003), and Whitford *et al*. (2001) have shown that less affluent residential areas also lack green space. Pauleit *et al*. (2005) argue that there is a scarcity of models to quantify urbanisation in terms of land cover change and land use, which can then be used to predict environmental impacts. As a consequence, a simplistic means of suggesting the integration of SUDS devices into cities is presented here. The terminology used here is less than satisfactory, but is used in the absence of more suitable nomenclature. Hence 'city centre' describes an area with the highest density of buildings which is therefore the most impermeable. This area probably has the least amount of vegetative cover, highest percentage of concrete and if there are any water bodies these are probably located underground or are bounded on all sides by the built environment. It can include the CBD, dense retail areas and even residential areas where gardens may have been sealed and the houses built in close proximity to one another, perhaps as terraces or high-rise blocks. SUDS devices can be retrofitted to such existing built up areas, but some do need space which is not readily available under such circumstances, or may have to be part of Water UK's (2008) 'sacrificial areas' mentioned above. Once a development is built, it is not normally possible to allocate space for greening as is suggested by Wilby (2007), although proprietary, or hard constructed devices such as PPS, soakaways and infiltration trenches have minimal land-take and can be designed with climate change adaptation in mind; however, their amenity and biodiversity benefits are limited (Stephenson 2008;

British Water 2010). By taking a simplistic bull's-eye approach as shown in Figure 3, therefore, it is possible to structure a hierarchy of suitable devices from the urban centre to the periphery, very like a combination of the zonal and multiple nuclei models of urban structure (Burgess 1924; Harris & Ullman 1945, respectively). Figure 3 illustrates this approach whereby small-scale patches of retrofit are undertaken in densely occupied urban centres, such as green roofs and walls, areas of PPS and RWH; in the urban centre, SUDS is therefore a supporting mechanism, relieving the pressure on conventional systems. Suburban areas can support larger devices such as roadside swales, ponds incorporated into roundabouts such as the Dunfermline eastern expansion roundabout detention basin (see Figure 4) and larger areas of PPS (e.g. on supermarket and industrial estate car parks) with the largest devices such as constructed wetlands and ponds used in suitable areas on the urban periphery. Here combinations of devices can be used in trains (see Figure 2); examples of these are the Hopwood and Oxford MSAs in England, further details of which were given above. New build needs to design SUDS in at the outset, whereby trains of ponds, wetlands and swales provide the area with the multiple benefits associated with a sustainable drainage system.

Street trees can be retrofitted where existing service infrastructure such as cables and pipes allow (Antonelli 2008) and provide shade for buildings, both from the sun and also from the prevailing winds; their benefits in terms of CSS were outlined above. Rain gardens or street planters (Figure 5) can also be retrofitted at street level; made of stone, they integrate well into the built environment (DTI 2006). While providing storm peak attenuation, they also provide visual amenity and, with street trees, will roughen the profile of the street surface, cutting down on wind canyoning and hence increasing physical and thermal comfort for the residents (Mochida & Lun 2008). They will also encourage turbulent wind flow and hence the dispersal of pollutants within the city's friction layer (Buccolieri *et al*. 2009).

Private gardens can be used as rain gardens, encouraging water to infiltrate and dissipate slowly. The importance of individual front gardens was highlighted by the London Assembly (2005) where it was found that ‘sealing’ of frontages by impermeable materials to provide off-road parking for resident’s cars had led to the loss of up to two-thirds of London’s front gardens. This could amount to a total area of 12 square miles, or 32 km^2 of vegetation and potential habitat lost. Previously, these permeable surfaces would have infiltrated excess rainfall in the event of storms, the incidence of which is likely to increase with time as a result of climate change. The RHS (2005) quote a figure of 10 litres of rainfall per minute as the capacity of an average suburban garden, or 10% of the incident rainfall absorbed. Cumulatively across a city, this could represent thousands of litres of water which does not subsequently contribute to flooding.

To further encourage disposal of surface water on site, RWH, using a tanked PPS system as described above and in Gomez-Ullate *et al*. (2010), or simple water butts or barrels, can capture water for later reuse outside the home to water a green roof, for example, or inside for toilet flushing. Harvesting and reuse of rainwater in this way will reduce the amount of water having to be subsequently managed as it leaves an individual plot. In areas of the world where droughts are becoming common (e.g. Australia), RWH will enable a resource to be saved when it is available.

A large-scale approach which integrates well into a SUDS strategy is that of river restoration (RRC 1999 and 2002); in fact Bray (2006) suggests that both SUDS and river restoration share common objectives. Whereas rivers and streams passing directly through the city may be straightened, channelised and canalised, those in the urban periphery can be returned to a more natural profile of meanders and riparian vegetation. Upstream and downstream of an urban area, a restored river can slow water and allow flooding onto a restored floodplain, so protecting the urban area.

By optimising the bull’s-eye approach, it is possible to quantify the benefits of SUDS for climate change adaptation and mitigation. For instance, in a study in Greater Manchester, UK, Gill *et al*. (2007) calculated that if towns and cities increased their green cover by as little as 10%, surface temperatures would remain the same in spite of climate change. There are many strands to the reasons for climate change and therefore approaches to its mitigation. There will therefore not be a single technique which can be used to solve the problem as a whole, but rather a suite of approaches, tailor-made depending on the situation (geographical location, local climate, city structure, etc.), which can be applied (Yamamoto 2006). There is an opportunity to undertake the ‘smart landscaping’ and’ smart design’ suggested by Antonelli (2008) to make the most use of the ecosystem services SUDS can provide.

DISCUSSION

The phrase: ‘Think globally, act locally’ has entered the lexicon of sustainable development, and is an entirely appropriate concept when applied to the SUDS approach as individual cities are implementing strategies to mitigate and adapt to the potential ravages of GCC in general, but the UHIE in particular as shown in Table 3.

Unfortunately, urban areas are complex at the best of times, or as Turner (1992) put it: ‘multicomponent, multiphase’. While this was a reference to the chemistry of urban metal pollutants, the statement is equally valid when considering the urban fabric. The addition of GCC makes this complex environment even more uncertain, especially when it is not known which factors may be synergistic or antagonistic. Adaptation and mitigation therefore do not afford easy options, but now that the majority of the world accepts that GCC is inevitable, ways of adapting to the changes to come, and also of mitigating further change, should be implemented. This review has shown that SUDS can provide a multiple-benefit approach by CSS, mitigation of the UHIE, urban cooling, flooding resilience and improving human and environmental health in cities. SUDS are also very flexible in being able to combine, for instance PPS, RWH, high reflectance and evaporative cooling. However, the SUDS approach should not be implemented alone (Mentens *et al*. 2006); it needs to be integrated with the wide range of other strategies being developed for more efficient, sustainable buildings. The many vegetated devices comprising the SUDS arsenal, however, can green and cool the city, exemplified by the findings of both Pauleit & Duhme (2000) and Whitford *et al*. (2001) who determined that there would be a difference in temperature of between 6 and 7°C if city vegetative cover rose from 15 to 50%. These devices also provide opportunities for wildlife and amenity for the city's human inhabitants and aid in providing a sustainable, healthy urban future. SUDS will not be efficient if not designed properly, or if local conditions are not accounted for. The same is true for overall urban design which must take a holistic approach to climate-proofing individual buildings, streets and cities. This review has concentrated on the physical structures which make up SUDS, rather than the policies which encourage their use, but implementation of any strategy must be 'guided and supported by national policies and strategies' (Burton *et al*. 2006: 9) having regard to the fact that these structures are effectively local and will be managed and owned locally.

While some areas have been researched relatively comprehensively, for example the benefits of SUDS devices in attenuating the storm peak and mitigating pollution, there are others applicable to GCC which require further investigation. These areas include the CSS of vegetative devices such as green roofs, swales and vegetative pavements and the evaporative cooling roles of open water such as urban ponds and wetlands. More research is therefore needed in order to gain a better understanding of the role SUDS can play in mitigating and adapting to a changing climate in the built environment. However, from the case studies given here and in Table 3, it is clear that SUDS are already proving valuable in giving cities the means to meet the challenges of climate change. The lesson to be learnt is that only a multifaceted approach of various integrated strategies will provide long-term answers to the problem of a warming climate.

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Figure 1 | (a) Conventional drainage; (b) SUDS triangle; (c) SUDS rocket

Figure 2 | SUDS management train (based on CIRIA 2007)

Figure 3 | SUDS design bull's eye

Figure 4 | Detention pond incorporated into a road traffic island, Dunfermline eastern expansion (DEX), Scotland (Urban Water Technology Centre, University of Abertay, Dundee, UK)

Figure 5 | Water from the downspout flows into a rain garden in Berlin

Table 1 | Sustainable drainage devices

Vegetated devices	**Hard devices**
Green roofs and walls	Porous paving (PPS)
Rain gardens	Concrete built street rain garden
Constructed wetlands	Rainwater harvesting
Filter strips	Proprietary devices
Swales Vegetated PPS Individual householder’s rain garden Street trees	Other: using existing urban green infrastructure – front gardens, school playing fields, traffic islands, grass verges, parks

Table 2 | Design criteria for incorporation of a swale into a SUDS; HRT= hydraulic residence time (Escarameia *et al*. 2006)

Side slope (vertical/horizontal)	**Long slope**	**Depth (mm)**	**Grass height (mm)**	**Design storm event**	**Velocity/ HRT**	**Minimum length (m)**
< 1:3	<1:50	300–500	100–200	5 year/24 hour Check for: 10 year/24 hour	<0.25 m s^{-1}/8–10min	60

Table 3 | Sustainable drainage (SUDS) devices quoted in the climate change strategies of the Participating Cities in the C40 Clinton Climate Initiative; all quotes are taken from those strategies

City	**SUDS devices**	**Role**
Chicago	PPS in ‘green alleys’; rooftop gardens; rain barrels; rain gardens; increasing urban forest canopy; green roofs; bioswales; street trees	Green urban design; runoff reduction; reducing flooding; urban cooling; provide shade; cool individual homes and hence the city; reduce UHIE; reduce GHG; increase energy efficiency of buildings with green roofs
Hong Kong	Increased green space; street trees; green roofs and walls	CSS; urban cooling; reduced air conditioning usage
London	Urban greening programme; street trees; green roofs and walls; river restoration; pocket parks; ‘SUDS and flood storage in riverside parks’; green space connectivity	Surface water flood risk; increase the quality and quantity of green space and vegetation as a buffer from floods and hot weather; ‘increasing green space and vegetation… Manage and offset rising temperatures (and manage flood risk)’; UHIE mitigation; provide biodiversity
Los Angeles	Stormwater capture and reuse; street trees; ‘skylight’ reaches of the Los Angeles River; stormwater infiltration; more parks; green and	Water conservation and recycling; recharging of aquifers; heat waves

	cool roofs	
Melbourne	Water sensitive urban design (WSUD): ‘all water streams in the urban water cycle are a resource’	WSUD guidelines applied to climate change mitigation and adaptation including references to: human health; water resource resilience; flooding; UHIE mitigation
Mexico City	Green roofs	Medium-term impact to adapt to climate change
New York	Source controls; green infrastructure for bioretention and biofiltration; low impact developments; best management practices; blue and green roofs; ‘Bluebelt’ areas using open spaces to absorb excess water; cisterns; RWH; PPS; street trees	Stormwater management and control because of ‘more intense and frequent rainfall expected from the effects of climate change’. Reduction of UHIE. Benefits include: ‘cooling and cleansing the air, reducing energy demand, sequestering and reducing emissions of greenhouse gases’
Philadelphia	Increase green space; green infrastructure; PPS; street trees; green roofs; ‘skylight’ waterways; clean and green vacant lots; increase street trees	Reconnect land and water so that ‘green infrastructure becomes the City’s preferred stormwater management system’. Reduce air pollution, manage stormwater, moderate UHIE, sequester carbon, increase property values
Sao Paulo	Permeable areas; water absorption zones	UHIE mitigation
Seoul	Green space; green roofs; stream restoration	‘to increase urban climate control ability’

Sydney	RWH; street trees; open space; urban forest; green roofs	Water efficiency; promotes 'environmental, health, social and financial outcomes for the City'. Reduction of human health impacts
Tokyo	Promotion of green space; street trees; PPS; urban forests; water-retaining pavement	Reduction of UHIE; recharge of groundwater; reduction in stormwater flow
Toronto	Street trees; rainwater harvesting; PPS; vegetative landscaping; cool/reflective surfaces; 'greening projects'; green roofs	Increase shade; clean and cool the atmosphere; water reuse; flooding resilience; reduction of the UHIE. 'To reduce climate change impacts'. Reduction in air conditioning demands, reduce storm runoff

Note: Reports not available from: Bogotá and Rome. Reports focusing on energy with no mention of water or drainage: Madrid and Houston. All the above city climate change strategies are available through the C40 Cities website: http://www.c40cities.org/cities/ apart from that for London which can be found at: http://www.london.gov.uk/climatechange/strategy (both websites accessed September 2010).

Key: PPS, porous paving systems; RWH, rainwater harvesting systems; UHIE, urban heat island effect; CSS, carbon sequestration and storage.

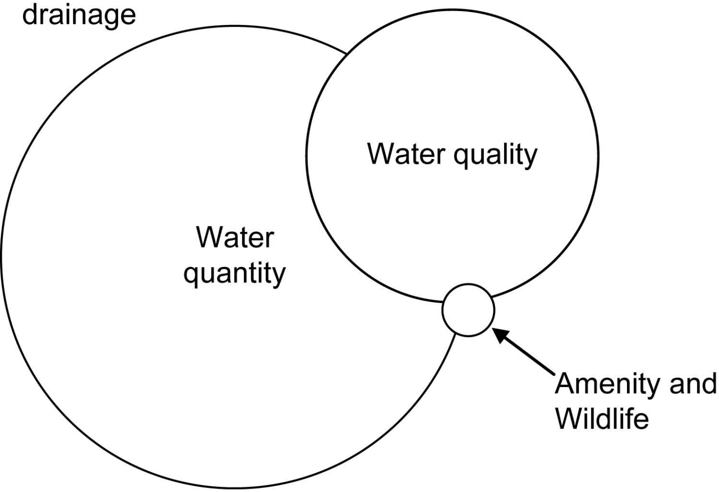

Fig 1a Conventional drainage

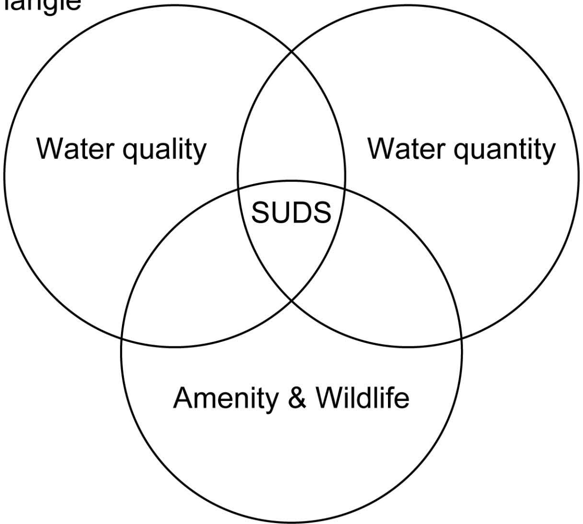

Fig 1b SUDS Triangle

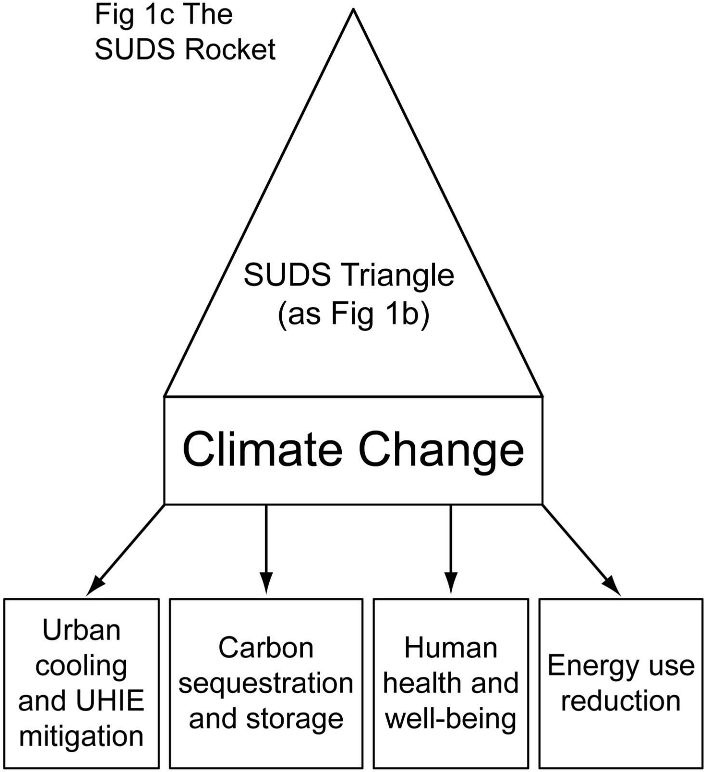

Fig 1c The SUDS Rocket

Fig. 2 SUDS Management Train (based on CIRIA, 2000)

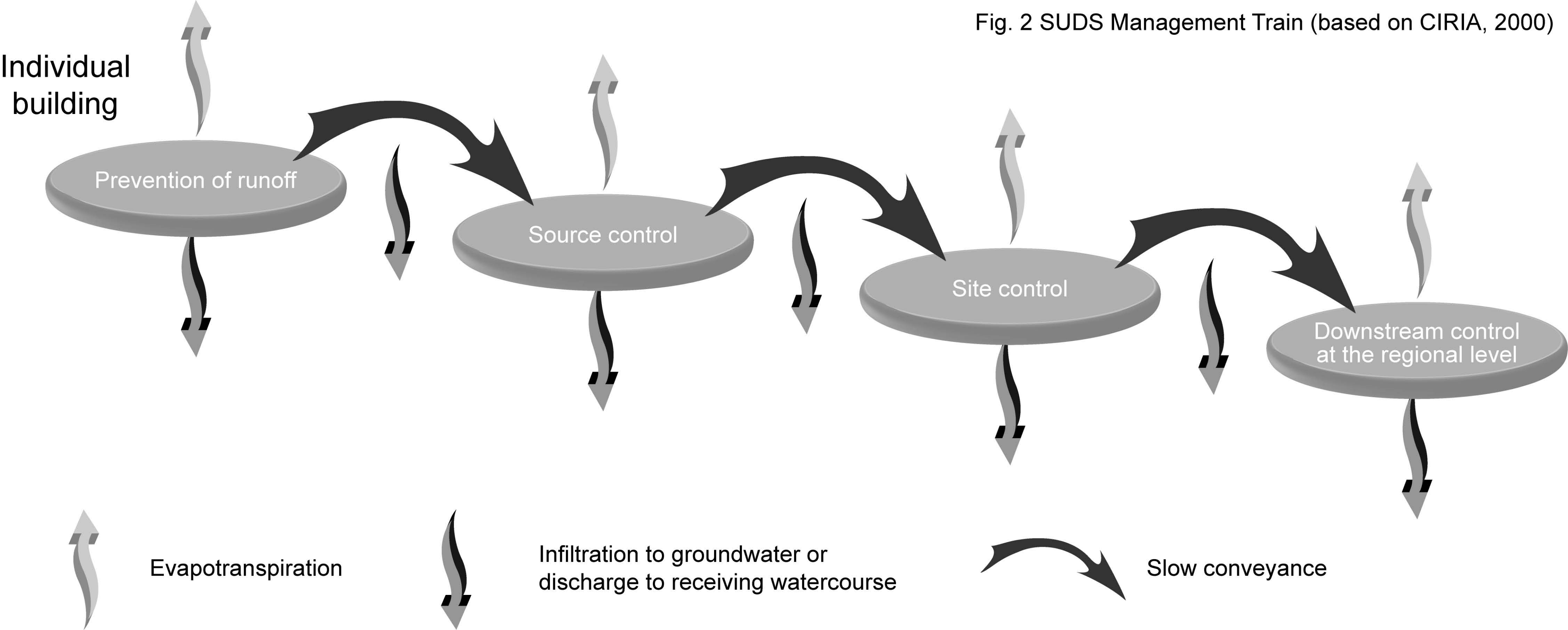

Fig 3 SUDS design Bull's Eye