The use of Sustainable Drainage Systems (SuDS) or Best Management Practice (BMP) has been made compulsory for virtually all new developments in Scotland. However, despite the design guidance (CIRIA 2007), systems are often implemented using “end of pipe” or source controls SuDS rather than an integrated series of SuDS devices—a “treatment train”. Indeed, in 2002, over 70% of sites in Scotland were reported as using only a single SuDS component (Wild et al. 2002). The management of runoff using a treatment train is preferred by the UK’s environmental regulators (SEPA 2006; Environment-Agency 2007) as it provides the following advantages:

- using different and complementary removal techniques can achieve enhanced pollutant removal;
- pollutant spills can be detected and managed in a more efficient manner by making the drainage infrastructure visible;
- an enhanced level of treatment is achieved by treating pollutants closer to their source; and,
- the shock load effect on regional controls is reduced, thus enhancing biodiversity by providing a stable habitat.

Although the benefits of SuDS have been reported for some time, land take, construction costs, uncertainty regarding maintenance and adoption of SuDS are generally seen as barriers to implementation of source and site controls. In contrast, providing a good quality of life by improving environmental amenity and biodiversity in urban areas are key drivers for planners. By considering these views, the underlying philosophy of the presented research is that the development of a surface water management plan at an early stage, coupled with advances in how the treatment train is modelled, would help optimise water management and planning objectives. The aim of the reported study is therefore to evaluate the potential benefits...
of using different treatment train solutions for a case study. Holistic evaluation of the different solutions is undertaken by focusing on four key stakeholder objectives:

- land take;
- whole life costs;
- water quality; and,
- managing flood risk.

The potential benefits achieved by the use of source and site controls are then used to reduce regional treatment facilities size, hence offering the opportunity for developers and planners to manage the footprint differently whilst still satisfying water quality and quantity objectives.

**METHODOLOGY**

The methodology developed can be divided into three modules:

1. Development of source, site and regional controls scenarios—this module focuses on selecting appropriate source and site controls that can be incorporated within the treatment train.

2. Treatment train assessment—this module aims to provide a novel holistic assessment of the treatment train based on key stakeholder objectives. The assessment of the treatment train aims to evaluate how the main stakeholder objectives are satisfied and is based upon:

   a. Land take: Determination of the land occupied by the SuDS devices is undertaken using recent design guidance (CIRIA 2007; Scottish Water 2007).

   b. Costs: Whole life costs over a 50 year period.

   c. Water quality: To estimate the pollutant removal capacities of a range of SuDS, first order decay kinetics (Kadlec & Knight 1996) will be used.

   d. Water quantity: Evaluation of the potential for source and site control to attenuate the volume reaching regional control was undertaken.

3. Proposal for regional controls size reduction—this module discusses the possibility of reducing regional control size by objectively incorporating attenuation and water treatment at source and site control level.

**Case study**

The Clyde Gateway, situated along the River Clyde in Glasgow, is a priority regeneration area for the Scottish Government. Recent flooding in Glasgow, poor watercourse quality and the need to regenerate this neglected area as a “sought after” location led to the development of a forward looking surface water management plan (Auckerman et al. 2008). The reported project uses a small part of the Clyde gateway, Dalmarnock Road area (Figure 1), to generate development scenarios. Due to its heavy industrial past, infiltration of water into the soil will be prevented to avoid migration of pollutants into the groundwater. The study area comprises 20 hectares where 1,500 houses will be constructed. If no source or site controls are used, a regional pond of approximately 2,200 m² will be required to treat runoff to an acceptable level, and an additional 2,600 m² will be required to store runoff up to a 100 year return period storm (2.5% of the catchment area).

Regarding current development plans for the Dalmarnock Road area, the northern extent of the site has been described as a “new destination and gateway” and will benefit from major public investment to develop public transportation (Glasgow City Council 2007). Development density for the site suggests a decreasing density gradient from the north to the south: higher densities towards the city centres and then decreasing progressively towards the suburbs. Although more accurate development plans will be considered in the future, the view adopted in this paper...
is that development of SuDS will be dependent on existing pressure on land take due to development density. Adopting this view, it has been considered that the SuDS implemented will depend on the amenity they can provide to the surroundings (Apostolaki & Jefferies 2005):

- The northern part of the site will not see above ground SuDS devices unless they are part of the infrastructure (e.g. green roofs).
- The central part is more likely to adopt SuDS devices where they present a high amenity, thus improving biodiversity and urban well being (e.g. pond).
- The southern part of the site will be a low development site where development of low amenity SuDS is acceptable (e.g. swale).

The diffuse pollution arising from land use activities dispersed across the catchment mainly comprise suspended sediments, polycyclic aromatic hydrocarbons (PAHs), heavy metals, nutrients and phosphates issued from erosion, vehicles, maintenance of green spaces and animal droppings (SEPA 2006; Morgan 2007). However, dissolved particles such as PAHs and heavy metals have an affinity for suspended particulate solids and are bound to them—mainly to the smallest particles (Lee et al. 2005). Monitoring of pollutants generated by different land uses (Duncan 1999; Mitchell 2005; Gobel et al. 2007) has shown a certain consistency in the amount of pollutants that can be expected for different land uses. Within this context, the estimated pollutant concentrations for total suspended solids (TSS), total nitrogen (TN) and total phosphorous (TP) can be found in Table 1. Usually, roads are the main source of suspended solids where they are associated with major pollutants such as PAHs, oil and heavy metals.

**Development of source, site and regional controls scenarios**

Based on potential land use, site and catchment characteristics, the following seven key SuDS source and site controls have been considered:

1. Linear wetland (LW) or enhanced swale has been promoted within Glasgow as a method of reducing car use by providing a sustainable and safe green-blue link for pedestrians and cyclists.

| Total Suspended Solids, Total Phosphorous and Total Nitrogen vs Land Use (Duncan 1999) |
|----------------------------------|--------|--------|--------|
| Residential | Roads | Roofs |
| TSS (mg l\(^{-1}\)) | 160 | 200 | 35 |
| TP (mg l\(^{-1}\)) | 0.35 | 0.2 | 0.15 |
| TN (mg l\(^{-1}\)) | 2.63 | 3 | – |

2. Standard conveyance swales (SW) can be used in the southern part of the site where lower density development can be expected, provided infiltration is prevented. Design is following CIRIA’s recommendations (CIRIA 2007).

3. Site ponds (SP) are able to treat pollution from high density developments and if situated in the medium density development area would provide amenity for residents in close proximity. The pond has been designed to capture first flush runoff from the development using recently published guidance (CIRIA 2007; Scottish-Water 2007).

4. A regional pond (RP) which discharges into the River Clyde is the “default end of pipe” solution in the southern part of the site. Design of the regional pond is also based on recently published guidance (CIRIA 2007; Scottish-Water 2007) and has been designed to capture the first flush for the whole area. The design may include a volume dedicated to attenuate events up to the 100 year return period level.

5. Green roofs (GR) can be used instead of exposed roofs in the north part of the area were large roof surfaces are more likely to be developed due to increased density.

6. Concrete Block Pavement (CBP) can be used where traffic speeds are below 60 km h\(^{-1}\). As such, they can be used in very low density development and on a case-by-case basis in other areas. In this case, their use is applied in the low density development where a pavement distributed across the area will be able to drain rainwater falling on footpaths and roads.

7. Subsurface storage (SS) can provide storage for attenuation of water runoff anywhere on the area.

Logical combinations of the different SuDS devices allow consideration of twelve different treatment trains comprising one to four SuDS that can be assessed for water
quality performance and three SuDS that can be assessed on their ability to attenuate runoff. The impact of using source and site controls will be used to reduce the sizing of regional control.

Treatment train assessment

To apply the methodology, water quality modelling tools will be applied using recent design guidance for the UK and Scotland. As detailed in this section, where pollutant data for the yet to be developed catchment is not available, appropriate surrogate values have been sourced from peer reviewed literature.

MUSIC (model for urban stormwater improvement conceptualisation)

Developed independently of the reported research by eWater Cooperative Research Centre, MUSIC is a hydrological model coupled with a water quality model (Wong et al. 2006). Hydrological modelling of SuDS is achieved by representing the elements as a series a well mixed water bodies or Continuously Stirred Tank Reactors (CSTRs)—mimicking potential dispersion. The number of CSTRs (N) used for the different SuDS is linked to the hydraulic efficiency (λ) determined by Persson et al. (1998) for a range of structures (Equation (1)). Water quality performance is modelled using first order kinetics (Equation (2)) observed in SuDS monitoring studies (Wong et al. 2001; Ackerman & Stein 2008).

\[ \lambda = e_v \left(1 - \frac{1}{N}\right) \]  

where:
- \( e_v \): effective volume defined by the proportion of the storage actively engaged by the flow path,

\[ \frac{dC}{dx} = -k(C - C^*) \]  

where:
- \( q \): hydraulic loading rate (m/y)
- \( x \): fraction of distance from inlet to outlet (m)
- \( C \): concentration of the water quality parameter (mg m\(^{-3}\))
- \( C^* \): background concentration of the water quality parameter (mg m\(^{-3}\))
- \( k \): decay rate constant (y\(^{-1}\))

When using Equation (2), a key consideration is that the hydraulic loading is related directly with the expected discharge per unit area. Thus, the plan area of devices are key factors in the determination of water quality performance (Wu et al. 1996). For the SuDS considered in this case study, theoretical calculations derived from sedimentation equations and calibration surveys (e.g. Wong et al. 2001) for a range of treatment devices have allowed an array of values for \( k \) and \( C^* \) to be determined. It should be noted that the calibration of \( k \) and \( C^* \) relies heavily on particle size distribution. In the absence of such data for the Glasgow area, data from surrogate catchments has been used (Walker & Wong 1999).

Using this approach, the MUSIC model was used to estimate water quality improvements for SuDS where areas of facilities are considered as an important factor in the removal of pollutants (ponds, swales and linear wetland). To estimate water quality benefits of the treatment train for the case study, a one year return period rainfall event of 60 minutes duration (M1-60—corresponding to 12 mm of rainfall) with a suspended solids Event Mean Concentration (EMC) of 160 mg l\(^{-1}\) (Duncan 1999) has been used as this event and the resultant pollutant concentrations will represent standard conditions for which SuDS have been designed (Figure 2).

SuDS performances, depending on their position in the treatment train are presented in Table 2. It can be seen that the model performance is within the range of reported values, confirming that MUSIC can be used to estimate realistic SuDS performance. As would be expected, the water quality performance of ponds varies with their position in the treatment train—this can be explained by

![Figure 2](https://iwaponline.com/wst/article-pdf/61/1/263/447807/263.pdf)

**Figure 2** | Example of a SuDS treatment train modelled with MUSIC.
the fact that high removal efficiencies are more difficult to obtain where pollutant levels are low or the flow has been pre-treated. Conversely, improving water quality performance for the linear wetland can be explained by the capacity of upstream SuDS devices to regulate hydraulic discharge and improve filtration performance within the linear wetland.

Whole life cost estimation

For all the SuDS considered, the costs have been determined based on the construction costs of the devices and associated maintenance over a 50 year period (Table 3). As these systems have been chosen to provide a high amenity to the community and support urban biodiversity, a high level of maintenance has been used to determine the costs. The net present value of costs has been calculated by adjusting future costs with a discount rate of 3.5% up to 30 years, followed by 3% for the remaining years (HM Treasury 2003). Potential economies realised on infrastructure have been calculated and taken into account (i.e. pipe network, asphalt pavement or exposed roof).

Proposition to reduce regional control size

The size of the regional control size, and hence its land take, is a function of the volume allocated to the permanent pool and the attenuation storage. The volume allocated to the permanent pool and the attenuation has initially been driven by the need to capture the first flush and the required attenuation storage of runoff to limit impacts of increased peak flows on downstream watercourses (Roesner et al. 2001). Consequently, reduced land take can either be achieved by providing attenuation at source and regional control level, or by taking into account the treatment provided upstream (usually not taken into account unless it is designed on the basis of treatment volume) by source and site controls as described below:

Reduction of treatment volume

A pond’s performance is largely driven by pond surface area (Wu et al. 1996). Consequently, reducing the pond’s surface area will reduce pollutant removal efficiency by increasing the hydraulic loading. Using the water quality model, the estimation of water quality performance is achieved using the hydraulic and water quality models described previously, thus giving the opportunity to move away from the traditional capture of the treatment volume used in the UK to design SuDS.

Reduction of attenuation storage

Regarding water quantity benefits, the extent to which the water should be stored in the catchment before discharge is decided in consultation with the environmental regulator (regarding the protection of watercourse for environmental reasons) and with the local authority (as part of their flood prevention duties). Attenuation at source and site control levels will allow a reduction in the volume dedicated to attenuation at the regional control level.

### Table 2 | Comparison of removal efficiencies for TSS (as % of mass removed)

<table>
<thead>
<tr>
<th>SuDS position in the treatment train and MUSIC performance</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>Reported removal efficiency</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site pond</td>
<td>68</td>
<td>–</td>
<td>–</td>
<td>26–92</td>
<td>e.g. Morgan (2007)</td>
</tr>
<tr>
<td>Regional pond</td>
<td>65</td>
<td>57–64</td>
<td>0–50</td>
<td>30–98</td>
<td>e.g. Deletic (2005)</td>
</tr>
<tr>
<td>Swales</td>
<td>87</td>
<td>–</td>
<td>–</td>
<td>50–95</td>
<td>e.g. Gilbert &amp; Clausen (2006)</td>
</tr>
<tr>
<td>Linear wetland</td>
<td>64–66</td>
<td>68–96</td>
<td>–</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Adopted value based on reported literature.
RESULTS AND DISCUSSION

Using the novel methodology presented in the previous section, assessment of the different treatment trains was undertaken. The results of this analysis are presented in this section along with proposals for a framework whereby the size of regional ponds may be reduced based on the water quality and quantity benefits of using source and site controls.

As illustrated in Figure 3, by using SuDS in series, significant benefits in terms of water quality improvements can be achieved. From a basic removal of 65% of TSS for a single regional pond, the removal efficiency can reach 95% when several SuDS are used in series. Removal rates for TP and TN vary accordingly. By increasing the removal of TSS, the removal of small particles is improved, thus improving the treatment for heavy metals and PAHs—these pollutants are more likely to be bound to the small fraction of TSS (Lee et al. 2005).

Table 3 | Maintenance activities for the SuDS considered

<table>
<thead>
<tr>
<th>SuDS maintenance costs (sources)</th>
<th>Routine maintenance</th>
<th>Infrequent and corrective maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green roofs (turfs) (Wong et al. 2003)</td>
<td>Barrier vegetation pruning, weeding and management</td>
<td>Vegetation replacement</td>
</tr>
<tr>
<td></td>
<td>Drainage inspection</td>
<td></td>
</tr>
<tr>
<td>Regional and site ponds (UKWIR 2005)</td>
<td>Inspection and reporting</td>
<td>Sediment removal</td>
</tr>
<tr>
<td></td>
<td>Litter and minor debris removal</td>
<td>Vegetation replacement</td>
</tr>
<tr>
<td></td>
<td>Grass cutting</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Barrier vegetation pruning, weeding and management</td>
<td></td>
</tr>
<tr>
<td>Swales and linear wetland (UKWIR 2005)</td>
<td>Inspection and reporting</td>
<td>Sediment removal</td>
</tr>
<tr>
<td></td>
<td>Litter and minor debris removal</td>
<td>Vegetation replacement</td>
</tr>
<tr>
<td></td>
<td>Grass cutting</td>
<td></td>
</tr>
<tr>
<td>Subsurface storage (Duffy et al. 2008)</td>
<td>Inspection and reporting</td>
<td>Blockages—Jetting</td>
</tr>
<tr>
<td></td>
<td>Litter and minor debris removal</td>
<td>Repair broken components</td>
</tr>
<tr>
<td></td>
<td>Grass cutting</td>
<td></td>
</tr>
<tr>
<td>Concrete block pavement (UKWIR 2005)</td>
<td>Desilt inlets and outlets</td>
<td>Relocation of block paving</td>
</tr>
<tr>
<td></td>
<td>Jetting</td>
<td>Replacement of jointing and laying material</td>
</tr>
<tr>
<td></td>
<td>Repair broken components</td>
<td>Mechanical cleaning</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrastructure maintenance costs</td>
<td>Routine maintenance</td>
<td>Infrequent and corrective maintenance</td>
</tr>
<tr>
<td>Asphalt pavement (Interpave 2006)</td>
<td>Surface course repairs</td>
<td>Surface dressing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excavation and reinstatement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cleaning of drainage facilities</td>
</tr>
<tr>
<td>Pipe network (Langdon 2009)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Exposed roofs (Wong et al. 2003)</td>
<td>Drainage inspection</td>
<td>Roof membrane replacement</td>
</tr>
</tbody>
</table>

Estimation of the costs associated with the different treatment trains (Figure 4) shows that using multiple SuDS source and site controls has a significant cost impact. However, it should be noted that the implementation of swales in the low density area does not add a significant cost to the project as their construction can partly be offset by economies on infrastructure costs (Astebol et al. 2002). For this case study, the cost of implementing SuDS for water quality treatment can increase by up to a factor of 5 compared to the end of pipe pond. Notwithstanding this, Figures 4 and 5 show that, in some scenarios, significant increases in water quality performance may be obtained for only a modest additional cost (e.g. the use of a regional pond and a linear wetland).

A further point to note is that unless SuDS are part of the infrastructure (e.g. CBP), they can add significant land take to that of the initial regional control (Figure 5). In this case, the land take associated with the use of source and site
controls can multiply up to seven times the land take of the regional control pond. Reviewing Figures 3–5, it can be seen that significant water quality benefits can be achieved using a SuDS treatment train. However, in many cases, these improved benefits must be seen within the context of increased land take and/or construction costs in most of the cases.

Proposition to reduce regional control size

Regional control size can be reduced by two different means:

- Reduction of the treatment volume by taking into account benefits of source and site controls.
- Reduction of the attenuation volume by providing attenuation at source and site control levels.

Reduction of the permanent pool

Considering that 65% suspended solids removal is adequate and if the treatment train produces a level of treatment beyond that level then the regional pond may be reduced in size until the target performance is reached.

Using the results summarised in Figures 3–5 and Table 2, it is possible to consider reducing the size of the regional pond. The rational for doing this is based on the current practice in the UK—end of pipe ponds provide an acceptable level of treatment (shown to be 65% TSS removal in analysis presented in Table 2). In doing this it should be noted that although the reduction of TSS achieved by upstream SuDS devices gives a good indication of how SuDS are performing, the dissolved solids performance, including most TN and TP, is significantly reduced in this case as the treatment train does not provide any permanent pool where biochemical degradation of dissolved particles is achieved. As illustrated in Table 4, in most cases, the reduction in land take of the regional control does not compensate for the land used by upstream source and site controls unless these are part of the infrastructure (e.g. CBP). Although this may be viewed as a disadvantage, it may be considered by the developer as an alternative way to spatially manage the SuDS footprint. An example of this is the land take associated with swales: their position along the roads may make them more acceptable than setting aside a large area for a regional pond.

Reduction of the attenuation volume

The attenuation of the runoff volume can be undertaken at source and site control levels. The land take associated with
the storage of the 1, 30 and 100 year return period events in addition to the land take of the permanent pool is respectively of 3,529, 4,363 and 4,788 m² for respective volumes of 2,616, 5,560 and 7,220 m³. Reduction of volumes reaching the regional control through the use of source and site control will help reduce land occupied by the regional control. Within this context, the SuDS can either be designed as specific attenuation devices or to simply slow the runoff.

Regarding SuDS slowing the runoff:

- Swales and linear wetlands: Infoworks simulations have indicated that equivalent reduction achieved is less than 15% for the linear wetland and less than 0.5% for the swales for 100 year return events. There will be no additional costs as these SuDS have been designed previously for water quality.

Regarding SuDS designed specifically for attenuation:

- Site and regional ponds: retention of water can take place either at the regional pond level to attenuate runoff for the whole area or at the site pond level to attenuate high density development runoff following Scottish-Water (2007) recommendations.

- Subsurface storage can store the designed volume and impacts only on costs (Duffy et al. 2008).

- Green roofs: Literature on the performance achieved by green roofs in terms of attenuation reports a wide range of values depending mostly dependant on the depth of substrate (CIRIA 2007). Deutsch et al. (2007) recommend designing for the green roof retaining the first 25 mm for each rainfall event. This value together with the costs

### Table 4

<table>
<thead>
<tr>
<th>SuDS treatment trains</th>
<th>Initial treatment train land take (m²)</th>
<th>Achievable reduction of regional SuDS land take based on TSS removal (m²)</th>
<th>(%)</th>
<th>Achievable reduction of SuDS treatment train's land take based on TSS removal (m²)</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP, SP, LW, SW</td>
<td>14,824</td>
<td>0</td>
<td>100</td>
<td>12,624</td>
<td>15</td>
</tr>
<tr>
<td>RP, SP, LW, CBP</td>
<td>9,300</td>
<td>0</td>
<td>100</td>
<td>7,100</td>
<td>24</td>
</tr>
<tr>
<td>RP, SW, LW</td>
<td>13,824</td>
<td>0</td>
<td>100</td>
<td>11,624</td>
<td>16</td>
</tr>
<tr>
<td>RP, SP, LW</td>
<td>9,300</td>
<td>0</td>
<td>100</td>
<td>7,100</td>
<td>24</td>
</tr>
<tr>
<td>RP, SP, SW</td>
<td>8,724</td>
<td>850</td>
<td>61</td>
<td>7,374</td>
<td>15</td>
</tr>
<tr>
<td>RP, LW, CBP</td>
<td>8,300</td>
<td>0</td>
<td>100</td>
<td>6,100</td>
<td>27</td>
</tr>
<tr>
<td>RP, SP, CBP</td>
<td>3,200</td>
<td>850</td>
<td>61</td>
<td>1,850</td>
<td>42</td>
</tr>
<tr>
<td>RP, LW</td>
<td>8,300</td>
<td>850</td>
<td>61</td>
<td>6,950</td>
<td>16</td>
</tr>
<tr>
<td>RP, SW</td>
<td>7,724</td>
<td>1,600</td>
<td>27</td>
<td>7,124</td>
<td>8</td>
</tr>
<tr>
<td>RP, SP</td>
<td>3,200</td>
<td>1,600</td>
<td>27</td>
<td>2,600</td>
<td>19</td>
</tr>
<tr>
<td>RP, CBP</td>
<td>2,200</td>
<td>1,600</td>
<td>27</td>
<td>1,600</td>
<td>27</td>
</tr>
<tr>
<td>RP</td>
<td>2,200</td>
<td>2,200</td>
<td>0</td>
<td>2,200</td>
<td>0</td>
</tr>
</tbody>
</table>

![Figure 5](https://iwaponline.com/wst/article-pdf/61/1/263/447807/263.pdf)
determined by Wong et al. (2003) for the development of an extensive green roof and taking into account potential economies realised on the construction of conventional roof lead to the development of Equation (4). The relationship suggests that, although the runoff volumes considered are modest, green roofs will be beneficial in the longer term. This view, supported by several authors (Acks 2006; Carter & Andrew 2008), is based on the theoretical assumption that the choice of a low maintenance vegetation associated with an extended lifespan can offset the construction and maintenance of an exposed roof. The longer term benefits may be reinforced by evaluating the extent to which green roofs provide better insulation and reduce heating and cooling costs as a result (Wong et al. 2003; Carter & Andrew 2008). The use of intensive green roofs, presenting a higher amenity, would achieve better attenuation at a greater cost and will not be investigated here.

The whole life costs as a function of the stored volume that can be stored have been estimated for each SuDS device (Equations (3–5) for ponds, sub-surface storage and green roofs respectively). The associated whole life costs for each SuDS have been calculated either as an additional cost for SuDS initially designed for water quality (e.g. pond) or as a supplementary cost for SuDS only designed for water attenuation (subsurface storage and green roofs) and taking into account potential economies realised on infrastructure (use of exposed roofs).

\[ \text{WLC}_P = 19.31 \times V + 43.309 \]  
\[ \text{WLC}_{SS} = 220.7 \times V + 13.259 \]  
\[ \text{WLC}_{GR} = \frac{-710.3 \times V + 20.5}{V_{\text{max}}} \]  
\[ V_{\text{max}} = 650 \]  
\[ \text{WLC}_{GR} = \frac{-710.3 \times V + 20.5}{V_{\text{max}}} \]  
\[ V_{\text{max}} = 650 \]

with:
- WLC: Whole Life costs (US$)
- \( V \): Stored volume (m³); \( V_{\text{max}} \): Maximum volume stored

In summary, the use of swales and linear wetland can be considered as cost efficient considering these are providing water quality benefits but benefits in terms of water quantity cannot be considered as a good solution where attenuation of high return periods is required. The use of green roofs appears to be the most cost effective solution to store runoff, but they offer only a limited storage volume. Thus, integrating the attenuation storage within the existing retention pond is the most cost effective solution to store high return period events when compared to traditional subsurface storage. However, where land take is an issue, subsurface storage will remain attractive.

Overall, the choice of SuDS devices to attenuate runoff will depend on the design return period. Low return period events can be attenuated using source and site controls designed to store frequent rainfall events whereas attenuation of high return period (>30 years) will need dedicated structures adding either land take or costs to the project.

**CONCLUSIONS**

Based on the conclusions presented at the end of the water quality and attenuation sections of this paper, it can be concluded that a novel methodology has been presented which offers an opportunity for the key stakeholders involved in the drainage of surface runoff in urban areas to maximize the benefits of using SuDS in a treatment train. The reduction in regional land take can be achieved based on water quality performance or source and site control attenuation. Despite the problems associated with offsetting regional land take with source and site controls, it has been shown that a different footprint for SuDS can be achieved by using SuDS in series rather than as an end of pipe control. The results obtained should be seen in the context of several SuDS related considerations which will vary greatly between catchments:

- land value in urban areas;
- increased amenity and biodiversity in urban areas;
- better management of accidental pollution; and
- improved degradation of pollutants.

Further work will comprise investigating the potential value of SuDS source and site controls from the point of view of people living in close proximity. This will enable the definition of preferred treatment trains for urban areas depending on land use, catchment characteristics and stakeholders objectives.
ACKNOWLEDGEMENTS

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REFERENCES


Kadlec, R. H. & Knight, R. 1996 Treatment Wetlands. CRC Press, Baton Rouge, FL, USA.


Scottish-Water 2007 Sewers for Scotland, 2nd edition. WRC.


