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Optimising regional sustainable drainage systems pond performance using treatment trains

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ABSTRACT

The use of sustainable drainage systems (SuDS) or best management practice (BMP) is becoming increasingly common. However, rather than adopting the preferred "treatment train" implementation, many developments opt for end-of-pipe control ponds. This paper discusses the use of SuDS in series to form treatment trains and compares their potential performance and effectiveness with end-of-pipe solutions. Land use, site and catchment characteristics have been used alongside up-to-date guidance, Infoworks CS and the model for urban stormwater improvement conceptualisation to determine whole-life-costs, land take, water quality and water quantity for different SuDS combinations. The results presented show that the use of a treatment train allows approaches differing from the traditional use of single SuDS, either source or "end-of-pipe", to be proposed to treat and attenuate runoff. This outcome provides a more flexible solution where the footprint allocated to SuDS, costs and water quality can be managed differently to more comprehensively meet stakeholder objectives.

Keywords: Sustainable drainage systems (SuDS); Treatment train; Best management practice (BMP); Swale; Pond; Green roof; Permeable paving; Runoff quality

1. Introduction

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 [1], 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 [2].

The management of runoff using a treatment train is preferred by the UK's environmental regulators as it provides the following advantages:

- Using different and complementary removal techniques can achieve enhanced pollutant performance;
- By making the drainage infrastructure visible, pollutant spills can be detected and managed in a more efficient manner;
- 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.

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Although these and other 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 develop a high value case study which may be used to evaluate the potential benefits of using different treatment train solutions for a case study. The case study allows the holistic evaluation of the different solutions undertaken by focusing on four key stakeholder objectives [3]:

- Land take;
- Whole life costs;
- Water quality; and,
- Managing flood risk.

Based on this analysis, the potential benefits achieved by the use of source and site controls may then be used as a basis for the objective reduction in regional treatment facility size, thereby offering the opportunity for developers and planners to manage the footprint differently whilst still satisfying water quality and quantity objectives.

2. Methodology

The methodology developed can be divided into three modules:

- 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.
- Treatment train assessment based on key stakeholder objectives—this module aims to provide a novel holistic assessment of the treatment train. The key stakeholder objectives considered are:
- Land take: Determination of the land occupied by the SuDS devices is undertaken using recent design guidance [1,4].
- Costs: Whole life costs over a 50 year period.
- Water quality: To estimate the pollutant removal capacities of a range of SuDS, first order decay kinetics [5] will be used. This analysis will concentrate on the removal of total suspended solids (TSS), total nitrogen (TN) and total phosphorous (TP).
- Water quantity: Evaluation of the potential for source and site control to attenuate the volume reaching regional control.
- Proposal for regional control optimisation—this module discusses the possibility of reducing regional control size by objectively incorporating attenuation and water treatment at source and site control level.

2.1. 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 [6]. The reported project uses a small part of the Clyde Gateway, Dalmarnock Road area (Fig. 1), to generate development scenarios. The Dalmarnock Road area, at the heart of the Clyde Gateway, is a former industrial area and due to this, infiltration of water into the soil will be prevented to avoid migration of pollutants into the groundwater. The study area comprises 20 hectares where a residential area encompassing 1500 houses will be constructed. If no source or site controls are used, a regional pond (RP) of approximately 2200 m^2 will be required to treat runoff to an acceptable level, and an additional 2600 m^2 will be required to store runoff up to a 100 year return period storm (2.5% of the catchment area).

Fig. 1. The Dalmarnock Road area contained within the Clyde Gateway boundaries.

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 improve public transportation [7]. Development density for the site suggests a decreasing density gradient from the north to the south: higher densities towards the city centre and decreasing progressively towards the suburbs. Although more detailed development plans will be considered in the future, the view adopted in presented research is that the development of SuDS will be dependent on land take and development density. Adopting this view, it has been considered that the SuDS implemented will vary in the amenity they provide depending on their location [8]:

- The northern part of the site will not see above ground SuDS devices unless they are part of the infrastructure (e.g., green roofs [GR]).
- 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., linear wetlands [LWs]).
- The southern part of the site will be developed at a low density, where the use of lower amenity SuDS is acceptable (e.g., swales [SW]).

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 [9,10]. 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 [11]. Monitoring of pollutants generated by different land uses [12–14] 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 TSS, TN and TP can be found in Table 1. In most residential areas, roads are the main source of suspended solids and they are associated with major pollutants such as PAHs, oil and heavy metals.

Table 1
Expected pollutants concentrations for a residential development [15].

Residential development	Median	Coefficient of variation
TSS (mg.l^{-1})	101.0	0.96
TP (mg.l^{-1})	0.383	0.69
Total Kjeldahl Nitrogen (mg.l^{-1})	1.900	0.73
Nitrite-N; Nitrate-N	0.736	0.83

2.2. Selection of potential SuDS techniques

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

- 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.
- Provided infiltration is prevented, standard conveyance SW can be used in the southern part of the site where lower density development can be expected. Design is following CIRIA's recommendations [1].
- RP which discharges into the River Clyde is the "default end-of-pipe" solution in the southern part of the site. Design of the RP is based on recently published guidance [1,4] aimed at ensuring it captures the first flush for the whole area. The design can also include a volume dedicated to attenuate events up to the 100 year return period level.
- Extensive GR can be used instead of exposed roofs in the north part of the area where large roof surfaces are more likely to exist due to increased density. It should be noted that although the use of intensive GR, which offer a higher amenity, would achieve better attenuation (at a greater cost) they have not been considered in the reported research.
- 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 concentrated in the areas of low density development.
- Water butts (WB) can be used in low density development to store and reuse water for gardening purposes.
- Subsurface storage (SS) can provide attenuation of runoff anywhere it is deployed in the study catchment.

The typical locations of these devices are illustrated in Fig. 2.

Logical combinations of the different SuDS devices allow consideration of 23 different treatment trains comprising one to six SuDS that can be assessed for water quality performance and three SuDS that can be assessed on their ability to attenuate runoff.

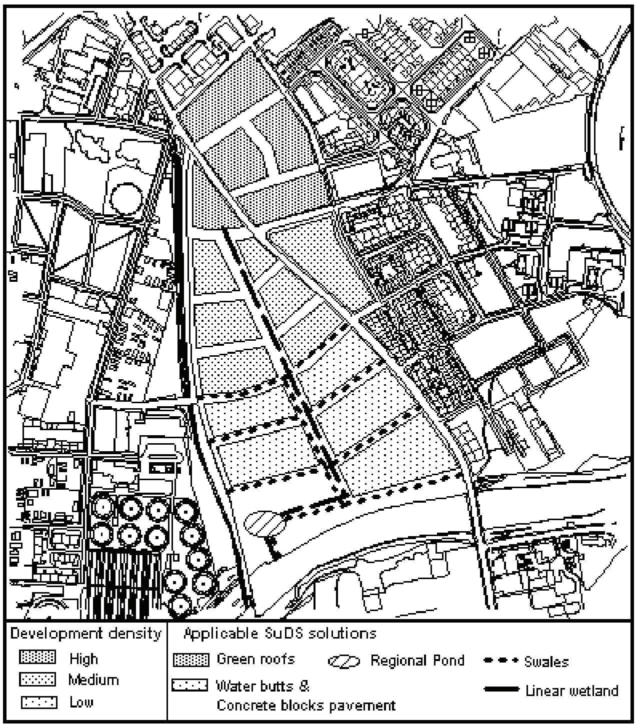

Fig. 2. SuDS deployment.

2.3. Treatment train assessment

To support the methodology, water quality modelling tools and costs identified from the literature are used.

2.3.1. Model for urban stormwater improvement conceptualisation

The model for urban stormwater improvement conceptualisation (MUSIC) developed by eWater Cooperative Research Centre is a hydrological model coupled with a water quality model. The hydrological and water quality performances of the different SuDS are modelled by a series of well mixed water bodies and using first order kinetics observed in SuDS monitoring studies [16]. Where sedimentation is the main removal mechanism, theoretical removal rates based on sedimentation equations are determined. When other removal mechanisms (e.g., biological or filtration) dominate or compete with sedimentation, the pollutant removal is considered as a unique process and rates are determined based on calibration surveys. For the SuDS considered in this case study, theoretical calculations derived from sedimentation equations and calibration surveys for the different treatment devices have allowed a range of values for k and C* to be determined [17]. It should be noted that the calibration of k and C* relies heavily on the particle size distribution of the sediment. Despite much of the work in this field being site specific, a review undertaken by Walker et al. [18] indicated a certain consistency regarding the particle size distribution at different sites. In the absence of site specific data for the Glasgow area, it was therefore considered acceptable to adopt particle size distribution data from surrogate catchments.

The MUSIC model has been used due to its ability to model a wide range of SuDS devices. The MUSIC model is used to estimate water quality improvements for SuDS where surface areas of facilities are considered as an important factor in the removal of pollutants (ponds, SW and LW). To estimate water quality benefits of the treatment train for the case study, one year return period rainfall event of 60 minutes duration (M1-60) corresponding to 12 mm of rainfall associated with event mean concentrations determined by Duncan have been used [12]. It is expected that both the chosen rainfall event and the associated concentrations will represent standard conditions for which SuDS have been designed.

2.3.2. Whole life cost estimation

For all the SuDS and infrastructures considered, the costs have been determined based on the construction costs of the devices and associated maintenance over a 50 year period (Table 2). 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 [19].

3. Results and discussion

3.1. Preliminary results

Based on the data determined for each SuDS device, assessment of the different treatment trains on the aspects of water quality, land take and costs is illustrated in Fig. 3a, Fig. 3b and Fig 3c. It should be noted that, at this stage, each SuDS device and treatment train has been designed to maximise pollutant removal.

As illustrated, by using SuDS in series, significant benefits in terms of water quality can be achieved. From a basic removal of 68% of TSS for a single RP, the removal can reach more than 90% when several SuDS in series are used. By increasing the removal of TSS, the removal of small particles is improved, thus improving the treatment for heavy metals and PAHs as these pollutants are more likely to be bound to the small particle size fraction of TSS [11]. Although the improvement in water quality is

Table 2
Maintenance activities and associated costs for the SuDS devices considered [4,19–426]

	Capital cost (k£)	Maintenance activities	Frequency (months)	Maintenance activities	Frequency (months)	Maintenance costs (k£) [1]	Present value (k£)
SuDS [reference]							
Regional pond [21]	27.7	Inspection, reporting and info management	1	Sediment removal from engineered silt trap	6	192	220.0
		Litter and minor debris removal	1	Sediment removal from forebay	36		
		Grass cutting	4	Sediment removal from the pond	120		
		Barrier vegetation pruning	36	Vegetation replacement	300		
		Barrier vegetation weeding	12	Removal and disposal of construction sediments	Once after 12 months		
		Aquatic vegetation management	12				
		Algae removal	4				
Swale [21]	50.1	Inspection, reporting and info management	1	Vegetation replacement	300	106	156.1
		Litter and minor debris removal	1	Removal and disposal of construction sediments	Once after 12 months	143	202.6
Linear wetland [21]	59.6	Grass cutting	1				
		Sediment removal	120				
Sub-surface storage [22]	$124.6 \cdot V^{(2)} + 14614$	Grass cutting	1.5	Controlled disposal/Haulage of silt	120	$0.375 \cdot V^{(2)} + 2780$	—
		Litter removal	1.5	Remove blockages	120		
		Inspection of structures	6	Jetting	120		
		Desilt inlets and outlets	12	Repair broken components	120		
Concrete block pavement [20,21]	2782.5	Inspection, reporting and info management	1	Remove block paves and stockpile to be washed	300	792	3574.0
		Litter and minor debris removal	1.5	Install replacement geotextile, install new 5 mm single aggregate bedding layer and reinstate block	300		
		Permeable pavement sweeping	4				
Water butts [23]	61.0	—	—	—	—	0.0	61.0
Green roofs [24]	1048.2	Inspection of drainage system	6	Water and weed of the turf/replacement if necessary	0.5	463	1511.5
		Replacement of water proofing membrane	480				
Infrastructures							
Exposed roofs [24]	574.5	Inspection of drainage system	6	Replacement of water proofing membrane	120	1144	1718.6
Asphalt pavement [25]	1961.7	Inspection of drainage system	120	Surface dressing	Once after 120 months, then every 60 months	925.3	2887.0
		Surface course replacement	240				
		Surface course repairs in 6% of the surface	240				
		Excavation and full reinstatement on 0.5% of the surface	240				
Pipe network [4,26] [3]	—	—	—	—	—	—	—

[1] Maintenance over 50 years [19]
[2] Stored volume (m3)
[3] Calculated in function of pipe length, diameter, material, depth and manholes following Scottish Water requirements [4]

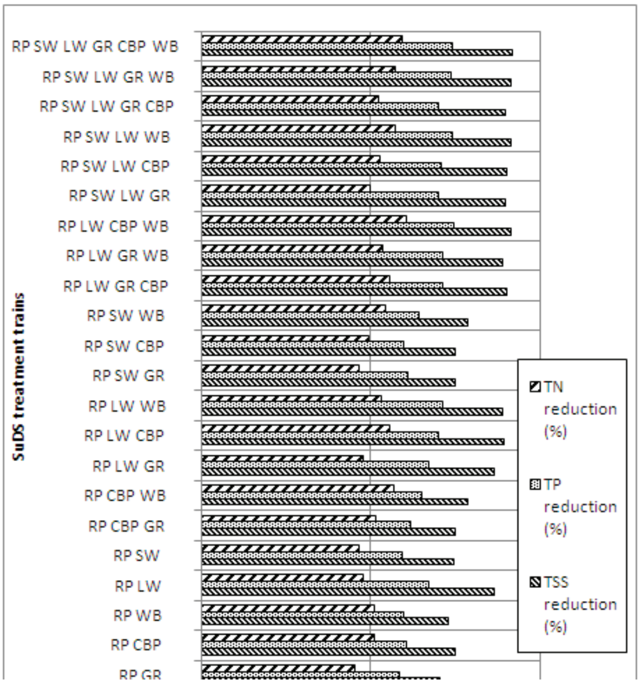

Fig. 3a. Water quality estimation for the different catchment wide SuDS treatment trains.

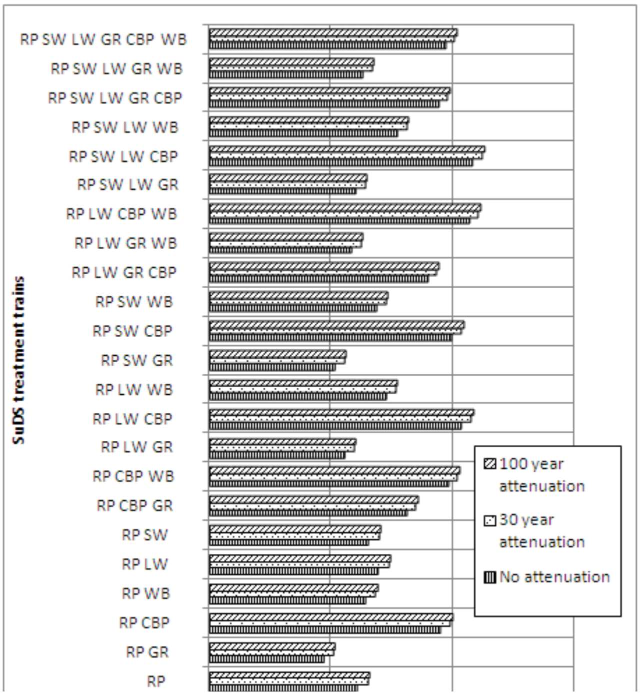

Fig. 3c. Whole life costs for the different catchment wide SuDS treatment trains.

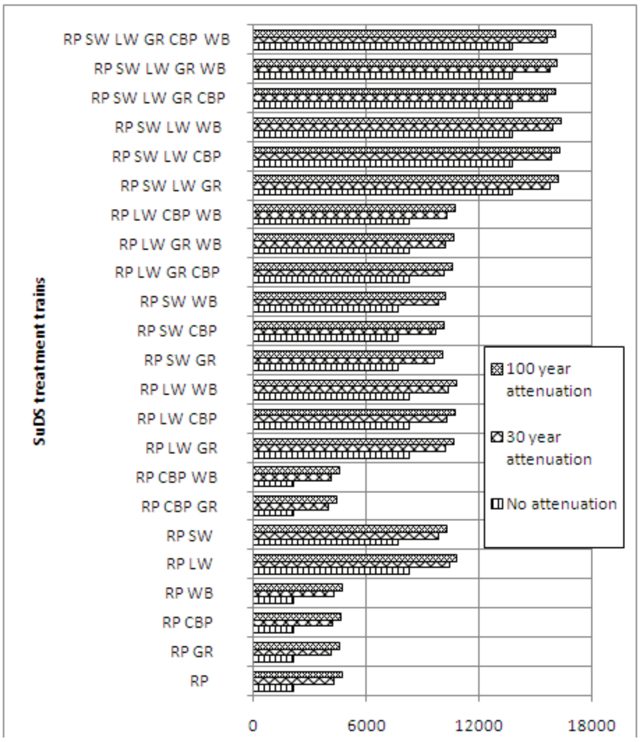

Fig. 3b. Land take estimation for the different catchment wide SuDS treatment trains.

desirable, the whole life costs associated with the different treatment trains show that using multiple SuDS source and site controls has a significant cost impact and in this case can multiply the cost of the initial project by up to five times. However, it should be noted that the implementation of some devices, although initially expensive, yields significant benefits. In particular, GR appear to be beneficial in the long term. This view, supported by several authors [27,28], 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 GR provide better insulation and reduce heating and cooling costs as a result [24,27]. Similarly, the implementation of SW in the low density area does not add a significant cost to the project and they can easily be incorporated in roadside verges.

A further point to note is that unless SuDS are part of the infrastructure (e.g., CBP or GR), they add significant land take to that of the initial regional control. The attenuation of different return periods also adds significant land take despite the opportunity to size some source and site SuDS to attenuate up to 30 year return period events.

Overall this section confirms the main stakeholder fears (e.g., whole life costs and land take) regarding the use of SuDS treatment trains rather than using only single regional SuDS. Indeed, this initial analysis has shown that despite an improved treatment of up to 20%, 19% and 15% for respectively TSS, TP and TN, some treatment trains add significant land take and/or costs to the project.

3.2. Proposition to reduce regional control size

In new developments there is often pressure to reduce the size of a RP. Logic would suggest that a reduction in land take can be achieved by optimising the design of the upstream treatment train. Within this context, 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.

3.2.1. Reduction of treat ment volume

Pond performance is largely driven by pond surface area [29]. Consequently, reducing pond surface area will reduce pollutant removal by increasing the hydraulic loading. As shown in Fig. 3, the use of a single pond achieves a theoretical 68% removal of suspended solids. If this performance is considered adequate, then if the treatment train produces a level of treatment beyond that level, it follows that the RP may be reduced in size until the target performance is reached. Table 3 illustrates the land take of source, site and regional controls achieving at least a reduction of 68% of TSS. For some treatment trains, the regional control appears to be unnecessary because the upstream treatment train achieves a removal of suspended solids beyond 68%. However, this solution may not be acceptable for two reasons:

- The pond is the last control before the runoff is discharged and it could be considered as security in case source and site controls do not perform to the required standards.
- More importantly, it should be noted that if better treatment and degradation could be achieved upstream for suspended solids (and bound pollutants such as heavy metal and PAH's), the reduction of treatment volume reduces the opportunity to degrade dissolved pollutants [30].

As illustrated in Table 3, 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

Table 3
Achievable reduction in land take for regional control based on 68% TSS removal.

SuDS treatment trains with CBP, GR, LW, RP, SW, WB	Initial treatment train land take (m^2)	Achievable reduction of regional SuDS land take (m^2)	Achievable reduction of regional SuDS land take (%)	Achievable reduction of SuDS treatment train's land take (%)
RP	2200	0	0	0
RP GR	2200	0	0	0
RP CBP	2200	433	20	20
RP WB	2200	288	13	13
RP LW	8300	2200	100	27
RP SW	7724	433	20	6
RP CBP GR	2200	433	20	20
RP CBP WB	2200	719	33	33
RP LW GR	8300	2200	100	27
RP LW CBP	8300	2200	100	27
RP LW WB	8300	2200	100	27
RP SW GR	7724	433	20	6
RP SW CBP	7724	433	20	6
RP SW WB	7724	571	26	7
RP LW GR CBP	8300	2200	100	27
RP LW GR WB	8300	2200	100	27
RP LW CBP WB	8300	2200	100	27
RP SW LW GR	13824	2200	100	16
RP SW LW CBP	13824	2200	100	16
RP SW LW WB	13824	2200	100	16
RP SW LW GR CBP	13824	2200	100	16
RP SW LW GR WB	13824	2200	100	16
RP SW LW GR CBP WB	13824	2200	100	16

spatially manage the SuDS footprint. An example of this is the land take associated with SW: their position along the roads may make them more acceptable than setting aside a large area for a RP.

3.2.2. 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 3529, 4363 and 4788 m2 for respective volumes of 2616, 5560 and 7220 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 LWs: Infoworks simulations have indicated that the equivalent reduction volume achieved is less than 15% for the LW and less than 0.5% for the SW for 100 year return period events.
- Regarding SuDS designed specifically for attenuation:
- CBP: The sub-grade is designed to store up to a 30 year return period event.
- WB: these are designed to store 0.3 m3 per dwelling.
- GR: Literature on the performance of GR in terms of attenuation reports a wide range of values depending mostly on the depth of substrate [1]. Deutsch et al. [31] recommend assuming the retention of the first 25 mm of each rainfall event. This value is associated with the costs determined by Wong et al. [24] for the development of an extensive green roof and takes into account potential economies realised on the construction of a conventional roof to determine the whole life cost as a function of the stored volume.
- RPs: Retention of water takes place at the RP level to attenuate runoff for the whole area runoff.
- SS can store the designed volume and impacts only on costs.
- Based on the costs estimates detailed previously (Table 2) and the expected performances, the whole life costs as a function of the stored volume have been estimated for each SuDS device. The associated whole life costs (Table 4) for each SuDS has been calculated:
- As an additional cost for SuDS initially designed for water quality when additional costs due to storage could be dissociated from the costs associated with water quality benefits (e.g., pond).

Table 4
Equations with WLC: Whole life costs (£); V: Stored volume (m^3) ; Vmax: Maximum volume stored (m^3).

	Equation	References
RP	WLC=13.41*V+16284	[21]
WB	WLC=571.7*V; Vmax+106.5	[23]
GR	WLC=318.6*V+9.197; Vmax+650	[24]
SS	WLC=133.3*V+21349	[22]
CBP	WLC=179.5*V+98998	[21,25]

- As a supplementary cost when water quality and water quantity benefits are not dissociable (e.g., concrete blocks pavement and GR).
- As a supplementary cost for SuDS only designed for water attenuation (SS).

The whole life costs calculated take into account the potential economies realised on infrastructure (e.g., exposed roofs coverings).

In summary, the use of SW and LWs can be considered as cost efficient when designing for water quality alone. However, where attenuation is also considered, the benefits are less attractive. WB are the most expensive solutions and are limited to the attenuation of small rainfall events. The use of GR appears to be the most cost effective solution to store runoff, but they offer only a limited storage volume. Thus, when compared to traditional SS, integrating the attenuation storage within the existing retention pond is the most cost effective solution to store high return period events. However, where land take is an issue, SS 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 require dedicated structures which require additional land take or costs to the project.

3.3. Cost, land take and water quality performance relationships

Based on the results outlined thus far, it is possible to consider how different attenuation and water quality improvement levels impact on both cost and land take. This is best done by considering three design scenarios:

- Where the design is for water quality improvement only.
- Where the design is for water quality improvement and limited retention.
- Where the design is for water quality improvement and robust retention.

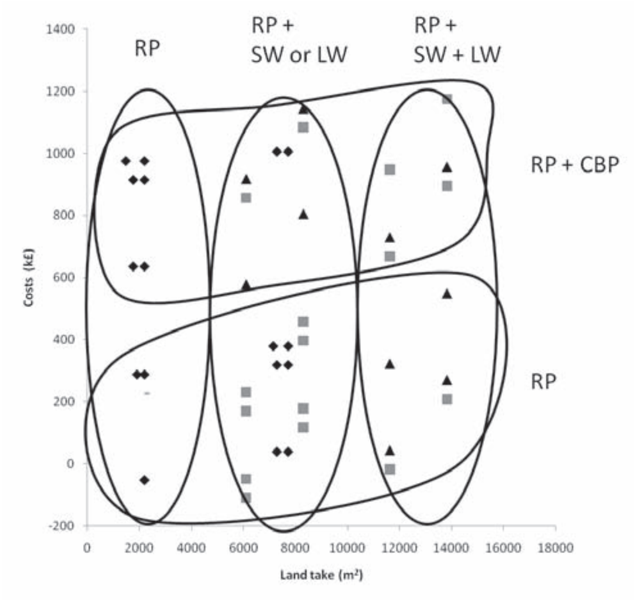

Fig. 4a. Cost size attenuation relationship when no attenuation is required.

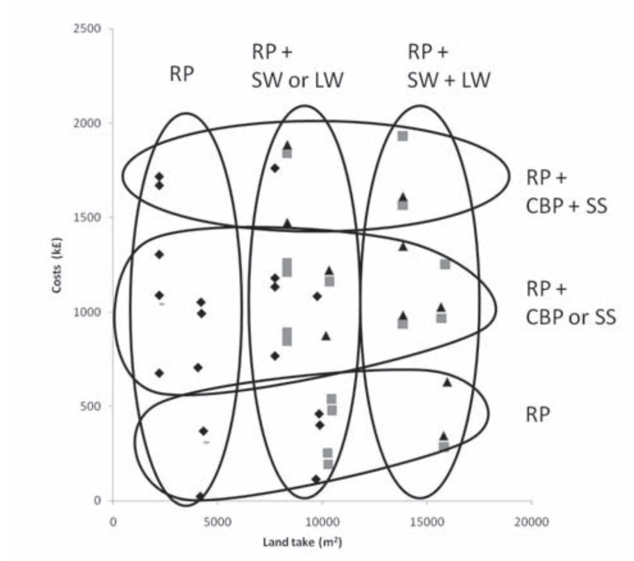

Fig. 4b. Cost size attenuation relationship with 30 years attenuation.

Data for these three scenarios are presented in Fig. 3 where relationship between land take, costs, water quality and water quantity are illustrated.

Considering the Fig. 4a, significant water quality improvements can be obtained compared to the

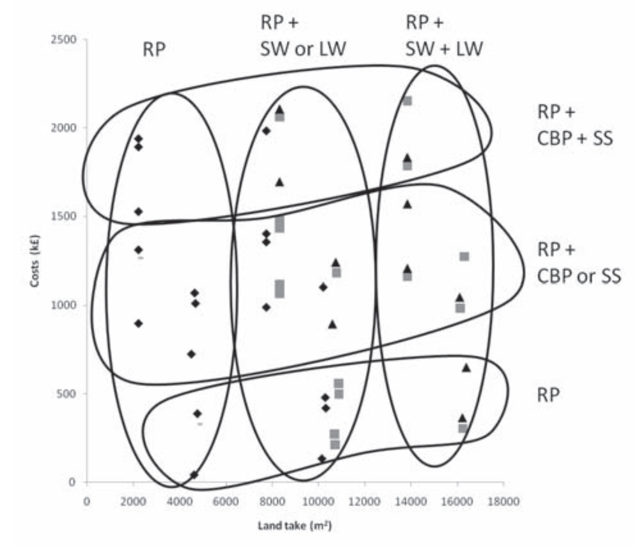

Fig. 4c. Costs size attenuation relationship with 100 years attenuation.

initial solution of using an end-of-pipe pond: the initial removal rate, below 70% for TSS can be improved beyond 90% by either:

- Implementing a swale network and a LW; or,
- By using pervious pavement in the low density area in conjunction with the implementation of the swale network or the LW.

The first solution presents the advantage of managing efficiently the costs whereas the second solution offers the opportunity to reduce the land takes for an equivalent water quality improvement. For these specific solutions, a land take reduction of 5500 m^2 can be achieved for an equivalent cost of ~£250 k.

A further 2000 m2 to 2400 m2 are necessary to attenuate the 30 and the 100 year return periods respectively (Fig 4b and Fig 4c). In addition to the reduction in land take achievable based on water quality benefits of source and site controls, a further land take reduction can be achieved by using SS to attenuate water quantity to the required standards. Thus maximum reduction of land take for a TSS removal rate beyond 90% can be achieved by the use of a swale network or a LW in association with CBP and SS. The costs appear to be mainly driven by the use of SS and concrete block paving in addition to the use of a regional control pond. Whereas land take is driven by the use of SW and LWs. GR and WB have a relatively limited impact in comparison to the use of other SuDS.

These plots can serve as a basis for discussion between all the stakeholders involved in the drainage of the Dalmarnock Road area.

4. Conclusions

A novel methodology is 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 pollutants degradation.

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.

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