Journal of Environmental Management 340 (2023) 117949

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Sustainability performance of bioretention systems with various designs

Pär Öhrn Sagrelius [a,c,*], Godecke Blecken [a], Annelie Hedström [a], Richard Ashley [a,b], Maria Viklander [a]

[a] Department of Urban Water Engineering, Luleå University of Technology, Luleå, Sweden
[b] Department of Civil and Structural Engineering, University of Sheffield, Sheffield, United Kingdom
[c] Tyréns AB, Garvaregatan 4C, 602 21, Norrköping, Sweden

ARTICLE INFO

Handling Editor: Jason Michael Evans

Keywords:
Stormwater biofilter
Nature-based solutions
Raingarden
LID
SUDS
Sustainability analysis

ABSTRACT

Bioretention systems for urban drainage are one type of blue-green infrastructure that have gained more attention in recent decades. There are numerous design options for these systems, including various construction components, filter material mixtures, and plants. However, the research focus on the impacts of these many design options has mainly been technical, i.e., how different bioretention designs affect runoff pollution treatment and hydraulic control. Knowledge of the effects of various design elements on other sustainability criteria, such as economic, social, and environmental aspects, needs to be developed. This research aimed to evaluate and compare various design elements and bioretention types to gain a better understanding of the relative sustainability of various bioretention systems. This was accomplished by identifying relevant criteria and sub-criteria, covering social, economic, and technical-environmental indicators, in a multicriteria analysis. To evaluate the sustainability performance of various bioretention designs, 12 sub-criteria were allotted −100 to 100 points in a scoring process. The main finding was that while design features had a major impact on bioretention performance, no single design configuration excelled in all criteria. High scores in the social criteria were correlated with the use of trees and smaller volumes of pumice in the filter material mixture. In the economic criteria, extensive use of concrete and a complex mixture of filter material increased the costs. The system with a water-saturated zone and a variety of plant species outperformed the other systems in the technical-environmental criteria. The results can be utilized as a reference to assess design configurations that best satisfy specific needs for each unique bioretention implementation.

1. Introduction

The overall strategy for urban drainage has evolved from being pipe-based which only encompasses stormwater quantity control to being composed of a more multifunctional nature-based blue-green infrastructure (BGI) approach (Stahre, 2008). The ‘blue’ parts of BGI are characterised by open water and ‘green’ spaces represent the vegetation in the systems. The progression of BGI for urban drainage has also been reflected by the research community indicated by the number of citations and terminology used in scientific articles related to urban drainage, which have steadily increased during recent years (Fletcher et al., 2014). Nowadays, (blue-)green infrastructure (or equivalent concepts called sustainable drainage systems (SuDS), water sensitive urban design (WSUD)), low impact development (LID), best management practices (BMPs), Stormwater Control Measures (SCMs) and more, depending on provenance (Fletcher et al., 2014), utilise nature-based features that are viewed as ‘the sustainable approach’ to stormwater management (Cettner et al., 2012).

An example of BGI on a street scale is urban bioretention systems. A bioretention system usually consists of vegetation planted in a soil bed, where stormwater runoff is filtered through the filter material consisting of e.g., sand, soil, gravel, and additional materials such as compost, biochar, and/or pumice. Runoff is then infiltrated into the existing subsoil or via an underdrain system conveyed downstream. The main purpose of bioretention systems is to remove pollutants, for instance, nutrients, suspended solids, metals, and organic compounds from stormwater runoff. Dependent on system design, bioretention cells can also allow for groundwater recharge, peak flow reduction, and other benefits e.g., urban heat mitigation, urban biodiversity, and amenity (Jose et al., 2014).

Previously, the multifunctionality of bioretention systems has been studied based on several sustainability aspects, for instance: life cycle

* Corresponding author. Department of Urban Water Engineering, Luleå University of Technology, Luleå, Sweden.
E-mail address: par.sagrelius@associated.ltu.se (P.Ö. Sagrelius).

https://doi.org/10.1016/j.jenvman.2023.117949
Received 21 December 2022; Received in revised form 24 March 2023; Accepted 13 April 2023
Available online 19 April 2023
0301-4797/

performance (Bhatt et al., 2019; Wang et al., 2020), benefits evaluation (Li et al., 2017), cost-effectiveness (Wang et al., 2016), environmental impacts (Öhrn Sagrelius et al., 2022) and with a more integrated approach covering environmental, economic, and social aspects (Koc et al., 2021). However, in most literature, an important condition is often disregarded, ignoring the variety of design details of different bioretention systems. Previously, bioretention as a general concept has been compared with e.g., other green (Bhatt et al., 2019; Wang et al., 2020) and/or traditional, grey (O'Sullivan et al., 2015; Vineyard et al., 2015), infrastructure systems. This is despite the different bioretention systems having a wide range of design configurations without a preferred or 'one-fits-all' arrangement. When the operational characteristics of bioretention systems are examined, a diversity of construction materials, filter material mixtures, and plants are in use. Consequently, the reviewed assessments described above do not adequately account for the wide variety of systems in use. Some bioretention systems are constructed with concrete, while other types comprise e.g., kerb stones, with or without geotextiles. Furthermore, bioretention systems can have more or less complex filter material mixtures consisting of gravel, sand, and soil with additional substrates such as pumice, biochar, and compost. Moreover, the selection of vegetation can vary between systems including various flowers, grasses, bushes, and/or trees. Other design features such as overflow, submerged water zones, sediment pre-treatment, and water storage capacity can also be part of some bioretention systems.

These design variations have primarily been evaluated in prior research based on the technical performance that, for example, various filter material mixtures (Chahal et al., 2016; Tian et al., 2019) or other design features attain (including sediment pre-treatment, submerged water zones, etc. Evaluated by e.g., Søberg (2019)). Consequently, knowledge of bioretention performance that also includes environmental, economic, and social elements based on these various design possibilities needs to be developed. Hence, the purpose of this study was to assess and compare the social, economic, technical, and environmental performance (referred to as sustainability performance) of 12 constructed bioretention system designs with different characteristics to better understand the relative sustainability of the different designs. The intended contribution was to support BGI practitioners dealing with design decisions for bioretention systems. This expands previous knowledge, which is often limited as bioretention has been investigated as one single concept ignoring these design differences between different facilities.

2. Method

Twelve bioretention design configurations were selected from bioretention systems constructed between 2015 and 2019 in Sweden. The systems mainly differed in terms of size, the construction materials used, filter media and vegetation (see details in Table 1). For comparison reasons, the systems were assumed to be located at the same place to avoid specific impacts associated with e.g., the localization (for example, material transportation distances). Instead, the aim was to theoretically encompass the technical, environmental, social, and economic impacts that various bioretention design components incur. Fig. 1 shows the typology of the bioretention systems, and Table 1 provides details on the construction materials, filter material mixtures, plant selection, and design elements of the 12 bioretention systems assessed. Although all evaluated systems were implemented in Sweden, they cover bioretention designs typical for other regions/countries as well. Sand is a commonly used filter material (FAWB, 2009; Fassman et al., 2013; Tirpak et al., 2021), compost amendment (Fassman et al., 2013) and a submerged zone (Blecken et al., 2009; Zinger et al., 2013) has been evaluated internationally. The implementation of biochar and (to limited extend) pumice has received increasingly interest (Mohanty et al., 2018; Cheng et al., 2017).

The social, economic, and technical-environmental performance of these different design components, construction materials, and plants was evaluated in this study using a multicriteria analysis (MCA) methodology. An MCA was appropriate since it allowed for the consistent use of a variety of performance data - both qualitative and quantitative - with different units, facilitating the inclusion of the various design factors in Table 1. In the MCA, the criteria were the measures of performance by which the bioretention systems were assessed. Foxon et al. (2002) emphasised the importance of including sustainability assessment in the decision-making processes of water management. Based on a literature review and the UK definition of sustainable development,

Table 1
Specifications for the bioretention systems that address various design parameters, construction components, and filter material mixtures.

		A					B		C		D	
		A1	A2	A3-S/A3	A4	A5	B6	B7	C8	C9	D10	D11
Footprint	m^2	91	91	91	30	30	300	368	99	99	52	115
Catchment area	m^2	1590	1590	1590	530	530	1500	1500	2000	2000	1400	3100
Excavation	m^3	360	360	360	120	120	450	550	100	100	105	225
Construction material												
Concrete	m^3	68	68	68	23	23	7	9	6	6	3	4
Reinforcing steel	kg	1200	1200	1200	400	400	68	92	66	66	27	45
Paving stone	kg	540	540	540	180	180	7150	9900	6820	6820	2750	4950
Geotextile	m^2	0	0	120	0	0	0	0	0	0	76	135
PVC pipe 110	m	75	75	75	25	25	45	55	60	60	0	0
PEH pipe 110	m	0	0	0	0	0	0	0	0	0	18	31
Filter material mixture												
Sand	m^3	176	189	361	5	5	9	11	84	84	2	2
Gravel	m^3	127	115	120	36	36	51	63	11	11	13	19
Pumice	m^3	177	177	0	0	9	15	0	0	0	2	6
Biochar	m^3	0	0	0	0	0	0	0	0	11	0	0
Soil	m^3	0	0	0	119	118	241	331	17	6	16	52
Compost	m^3	0	0	0	25	9	15	0	0	0	2	6
Other design features												
Overflow		✔	✔	✔	✔	✔	✔	–	✔	✔	✔	✔
Saturated zone		–	–	✔	–	–	–	–	–	–	–	–
Pre-treatment		✔	✔	✔	✔	✔	–	–	✔	✔	–	–
Water storage capacity		med	low	med	low	low	high	high	med	med	low	low
Vegetation		a, b, c, d	a, b, c, d	a, b, c, d	a, b, c, d	a, b, c, d	a, b, c, d, e	a, b, c, d, e	b, d	b, d	a, b, d	a, b, d

a) shrubs b) perennial c) bulbs d) grasses e) trees.

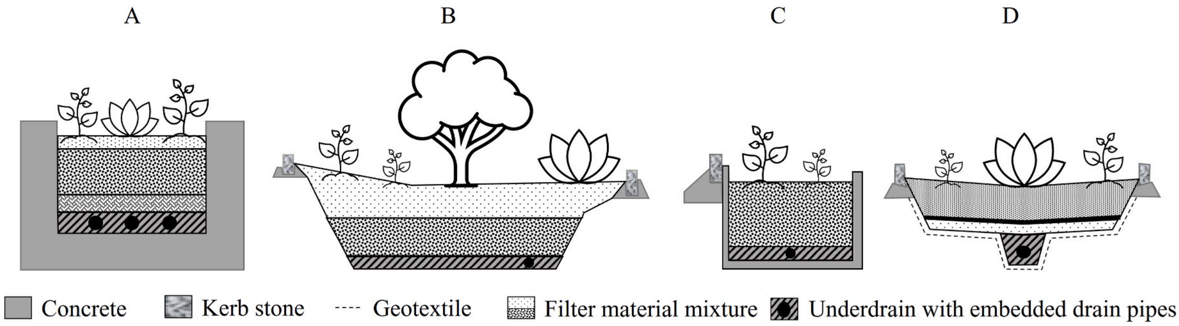

Fig. 1. Schematic illustrations of the design of bioretention types A, B, C, and D. For details regarding quantities of construction components and filter materials, see Table 1.

Foxon et al. (2002) selected four categories to encapsulate the core of sustainability concepts concerning water/wastewater management: economic, environmental, and social categories together with a technical category, which related specifically to water/wastewater systems to encompass technical performance with design objectives. These categories were selected as the criteria used for the sustainability assessment in this study with a modification that the technical and environmental criteria were assessed both jointly in a technical-environmental criterion and separately as technical and environmental criteria. This was done since the technical and environmental aspects of bioretention systems are often interdependent and challenging to distinguish. For instance, the main technical objective of bioretention systems, i.e., pollution control, incurs environmental benefits to e.g., receiving waters. Furthermore, any fertilizers required to maintain a healthy plant environment, improving for example, urban biodiversity (environmental impact) could increase the nutrient load discharged in the treated runoff, potentially impacting receiving waters.

Several processes, such as scoring options, weighting criteria, and aggregating scores and weights, can be applied in an MCA (Dodgson et al., 2009). Since the goal of this study was to evaluate and compare the social, economic, and technical-environmental performance of bioretention systems with a variety of design parameters, construction elements, filter material mixtures, and plants, the focus of the study was on the scoring of each bioretention option, rather than to weigh the criteria/sub-criteria and to identify the system that would be most appropriate in a given situation. The scoring process was based on the social, economic, and technical-environmental performance of each bioretention system as determined by calculations, modelling, literature review, and expert judgments. These evaluation methods included a wide range of qualitative and quantitative measures in various units, see Table 2. The scoring process was used to overcome the evaluation discrepancies and enable comparisons of the performances. The conversion of performance to value scores used relative scaling, with the least preferred system on the criterion receiving a value score of zero points (with one exception regarding phosphorous (P) removal: the least preferred system received a value score of −100 points, to account for the occurrence of P leaching), and the most preferred system receiving a value score of 100 points. All other value scores were computed as a function of the inputs in relation to these maximum and minimum values. This scoring process was intended to evaluate the specific sustainability performance of the different design configurations. It is important to note, though, that this approach restricted the study to only consider the bioretention technique and limits comparisons to other BGI measures (like ponds or green roofs).

2.1. Criteria, sub-criteria, and indicators

Technical-environmental, social, and economic sub-criteria were defined to account for the relevant performance based on the criteria used. In previous literature, several sub-criteria have been used to assess bioretention systems (Jia et al., 2013; Liquete et al., 2016; Li et al., 2017; Hua et al., 2020; Koc et al., 2021), as summarized in Table S1 in the Supplementary material. With reference to previous assessments, sub-criteria and corresponding indicators were defined by including the most important aspects. In the sub-criteria selection process, certain requirements were applied: completeness, redundancy, independence of preferences, and operationality requirements as stated by both Dodgson et al. (2009) and Foxon et al. (2002). These requirements directed the selection towards sub-criteria that contributed with relevant information specific to the various bioretention design components. Hence, the selection requirements also reflected the study limitation and if one sub-criterion could not meet the requirements, it was excluded from the analysis. Each sub-criterion and indicator (Table 2) are described in detail in the sections that follow. In Table 2, the 'aim' column refers to how the sub-criteria should ideally be performing, which was used to assess how high or low point values were defined in the scoring process. The area-dependent indicators were normalised with the corresponding drainage catchment area (m^2, see Table 1) of each bioretention system

Table 2
Criteria, sub-criteria, and indicator selection for sustainability performance assessment of the bioretention systems. SEK is the cost in Swedish currency.

Criteria	Sub-criteria	Indicator	Quantitative/qualitative (unit)	Aim
Social	Amenity	Vegetation type	Qualitative (low/medium/high)	High - low
	Human toxicity impact	Comparative Toxic Unit for human (CTUh)	Quantitative (per m^2 catchment area)	Low - high
Economic	Construction cost	Calculation of costs	Quantitative (SEK/m^2 catchment area)	Low - high
	Operation & maintenance cost	Calculation of costs	Quantitative (SEK/(year, impervious catchment area))	Low- high
Technical-environmental	Climate change impact	Greenhouse gas emissions	Quantitative (per m^2 catchment area)	Low - High
	Biodiversity	Number of plant species	Quantitative (plant species richness)	High – low
	Robustness	Expert judgement	Qualitative (low/medium/high)	High- Low
	P removal	Treatment efficiency	Quantitative (%)	High – low
	N removal	Treatment efficiency	Quantitative (%)	High – low
	Cu removal	Treatment efficiency	Quantitative (%)	High – low
	Zn removal	Treatment efficiency	Quantitative (%)	High - low
	Runoff retention	Maximum average return interval (ARI)	Quantitative (years)	High - low

for comparison purposes. This was done for the human toxicity impact; construction cost; operation and maintenance cost; and climate change impact sub-criteria. For the other sub-criteria (the treatment efficiencies, biodiversity, robustness, and runoff retention) the relation of impact to catchment area for each system was either included in the calculations/evaluations or deemed not applicable, and hence, the results in terms of these sub-criteria were not normalised with the catchment area.

2.1.1. Social criterion

For the social criteria, *amenity* and *human toxicity* were selected as the sub-criteria as explained below. The indicators used for their representation encompassed the vegetation type in each bioretention system and the Comparative Toxic Unit for humans (CTUh) as a result of the construction of the systems.

2.1.1.1. Amenity. According to e.g., Horton et al. (2019), amenity is a measure of the attractiveness and desirability of an area. Amenity benefits can accrue in new build, retrofit, or redevelopment situations and often relate to the pleasure derived from or the use of components provided. Furthermore, amenities can be measured at different levels. For the assessment of bioretention systems in this study, amenity from street improvements including the planting of trees and green verges was used (Horton et al., 2019). Mell et al. (2013) assessed the willingness to pay (WTP) for small and large trees with or without lower vegetation (e.g., grass, perennial plants), respectively, and this approach has been used for the qualitative assessment of amenity in this study. Depending on the vegetation in the bioretention systems and the results in Mell et al. (2013), the amenity was assessed as low (small or no trees and grass), medium (small trees, bushes, and grass), or high (large trees, bushes, and grass).

2.1.1.2. Human toxicity. Human toxicity (assessed as cancer effects) was modelled and evaluated using a life cycle assessment (LCA), as described in Öhrn Sagrelius et al. (2022), for the construction phase of each bioretention system (i.e., during the production, transportation, and installation of the systems). As mentioned in the human toxicity sub-criteria, Since the LCA (Öhrn Sagrelius, 2022) focused on various bioretention designs specifically, impacts associated with life cycle stages that were assumed to incur relatively equal impacts independent of design configurations (during operation and decommission) were assumed to be comparable for all 12 bioretention systems, and hence, not included. The toxicological response of chemical emissions incurred by the bioretention systems (both likelihood of effects and severity) was used for the calculations as described in the ILCD handbook (EC-JRC, 2012). The human toxicity effect in CTUh was normalised by using the per-person factor set developed by EC-JRC (2014). For comparison reasons, the normalised human toxicity effects were divided by the corresponding impervious catchment area of each bioretention system, also described by Öhrn Sagrelius et al. (2022).

2.1.2. Economic criterion

For the economic criteria, the *construction cost* and *operation and maintenance cost* were used as the sub-criteria as explained below. These sub-criteria were calculated based on the bioretention specifications and services needed to implement and maintain the systems. The technical lifetime of the systems was assumed to be 30 years.

2.1.2.1. Construction cost. The construction cost was calculated based on the bioretention components and services needed to implement each bioretention system. The prices of the components and services were estimated based on current (August 2022) Swedish price levels in Swedish kronor (SEK). The construction costs were normalised by dividing the costs by each systems' impervious catchment area (see Table 1). A complete list with a detailed inventory of costs for each system can be found in the Supplementary material.

2.1.2.2. Operation & maintenance cost. The annual cost of operation and maintenance (O&M) was estimated based on the activities required to maintain sustained functioning over the assumed system lifetime (30 years). The O&M cost for each bioretention option was estimated for the inventory and staff costs to remove sediment at inflow points by flushing, an inspection of the basin including garbage collection and disposal, and resetting of the system. The occurrence of these activities was assumed to vary depending on what design features and filter material mixtures were used in the bioretention systems. The O&M costs were normalised by dividing the annual costs by each system impervious catchment area (see Table 1). Full calculations of the O&M costs are included in the Supplementary material, Table S2.

2.1.3. Technical-environmental criterion

The following sub-criteria were defined for the technical-environmental criterion: *climate change impact, biodiversity, robustness, phosphorus (P) removal, nitrogen (N) removal, copper (Cu) removal, zinc (Zn) removal,* and *runoff retention*. Methodology descriptions regarding the sub-criteria are presented individually in the following sections.

However, for the pollution treatment indicators (assessed by P, N, Cu, and Zn removal rates) several methodological aspects were relevant for each of these sub-criteria. These generic assumptions considered that the treatment of pollution in bioretention systems is affected by several design parameters such as plant selection, filter material composition, and other design features such as submerged water zones or sediment pre-treatment. Søberg (2019) reviewed the treatment efficiency of several filter material mixtures and the findings, summarized in the Supplementary material (Tables S3a–c), served as the foundation for the treatment rate assumptions in the following sections. The pollutant removal rates were based on the treatment efficiency of a conventional filter material mixture commonly consisting of sand fractions mixed with soil and/or gravel. By reviewing relevant literature, the effects of adding/replacing other materials e.g., compost, biochar or pumice to/with this conventional mixture were evaluated. The total concentrations of the P, N, Cu, and Zn treatment efficiency rates were used.

2.1.3.1. Phosphorus removal. Based on Søberg's (2019) literature review, the P removal by the conventional filter material mixture was assumed to be 70%. With a higher ratio of finer fractions and/or organic matter in the filter material, P removal was shown to be less efficient or even negative (i.e. leaching occurred) due to the leaching of fine particles and/or organic matter (Li and Davis, 2009). Other evaluations have shown that fertilizer application (Chahal et al., 2016), organic materials (Clark and Pitt, 2012), and the use of compost (Cording et al., 2018) often cause low or negative nutrient P removal due to nutrient leaching. Consequently, the treatment efficiency was assumed to be −150% to −200% if filter materials with these features were used in the filters evaluated in this study. Mohanty et al. (2018) concluded that biochar can have both positive and negative impacts on P removal rates and hence, the P removal rate was assumed to be unaffected by biochar. When pumice was used as a component in the filter material, the P removal was enhanced (Cheng et al., 2017).

2.1.3.2. Nitrogen removal. For the conventional filter material mixture including sand, soil, and gravel, the N removal rate was assumed to be 50% based on the results shown in the review by Søberg (2019). In association with the P removal, fertilizing, organic materials, and compost reduced the N removal rates due to leaching, and 0% treatment was assumed for filter material mixtures that included these components. Tian et al. (2019) found that biochar improved N removal and hence, the total N removal was assumed to be 80% when biochar was used in the filter material. Furthermore, by including a submerged water zone, the N removal was enhanced (Zinger et al., 2013). For the system with a submerged water zone, the N removal was assumed to be 80%.

2.1.3.3. Copper removal. Based on Søberg's (2019) review, the baseline of the Cu removal for the conventional filter material mixture was assumed to be 80%. However, studies have shown a risk of impeded Cu treatment if compost was added to the filter material (Cording et al., 2018). Hence, in the bioretention systems where compost was added the removal efficiency was assumed to be 70%. Biochar and pumice have not been studied to the same extent and hence, the assumption was that these substrates had no or little effect on Cu removal rates.

2.1.3.4. Zinc removal. The total Zn removal for the conventional filter media mixture was assumed to be 90% based on the review by Søberg (2019). The removal rate when compost was used was estimated to be 80%, due to the risk of impeded treatment as shown by Cording et al. (2018). Biochar and pumice have not been studied to the same extent and hence, the assumption was that these substrates had no or little effect on Zn removal rates.

2.1.3.5. Runoff retention. The hydraulic effectiveness of the bioretention systems was assessed as the runoff volume reduction. The reduction rate is influenced by design factors especially the infiltration capacity of the filter material and the ponding volume. The infiltration capacities of the filter material mixtures were evaluated based on previous measurements with an infiltrometer and expert judgements of the expected capacities. The ponding volumes were calculated from construction drawings. Swedish design rainfall (based on the Dahlström equation (Dahlström, 2010)) was used to determine the average return interval (ARI) of the largest runoff volume that each system could retain in its storage volume without there being an overflow, which was used to estimate the retention performance of each bioretention system. The return period in years of this event was used as the retention indicator.

2.1.3.6. Climate change. LCA results for the greenhouse gas emissions (in kg CO_2 eq.) of the construction phase (i.e., during production, transportation, and installation) of each bioretention option were used for the climate change sub-criterion, as described in Öhrn Sagrelius et al. (2022). As mentioned regarding the *human toxicity* sub-criteria, climate change impacts associated with the operational and decommissioning phases were not included in the earlier LCA (Öhrn Sagrelius, 2022). For comparison reasons, the results were normalised using the per-person factor set of greenhouse gas emissions developed by the European Commission (ER-JRC, 2014). The normalised results were also divided by the corresponding impervious catchment area of each bioretention system.

2.1.3.7. Biodiversity. Plant species richness was used as a measure of the variety of plant species in each bioretention system for this sub-criterion. There are numerous methods used as biodiversity indices (Fedor and Zvaríková, 2019). The species richness measure is a relatively simple method that has frequently been used in literature. The number of plant species was counted from the planting plans of each bioretention system and used as the biodiversity indicator.

2.1.3.8. Robustness. Robustness was qualitatively rated (low/medium/high) based on professional assessments by persons involved in the implementation process of the systems and by researchers with a focus on bioretention systems. This was to assess how different design elements affected the bioretention system functionality and resilience over time, as well as how each system met the design objectives and construction plans both during and after implementation. The results of Beryani et al. (2021), who assessed the operational status of bioretention facilities in Sweden, were used for the robustness rating. In addition to the results of Beryani et al. (2021), the expected robustness performance was estimated based on the following: 'low' performance was characterized by a high risk of clogging due to discarded sediment pre-treatment and/or finer filter materials; 'medium' performance was assigned if systems had a medium risk of clogging, and 'high' performance was associated with sediment pre-treatment and a filter material mixture with lower risk of clogging.

2.2. Scores

Linear value functions were used to score the options based on the bioretention system performance for each sub-criterion. Each bioretention option was allotted a value score between 0 and 100 points for all sub-criteria except for the P removal sub-criterion. For this sub-criterion, scores between −100 and 100 points were used to include the occurrence of P leaching. In each sub-criterion, the bioretention option with the best performance (in relation to the aim in Table 2) was assigned 100 points and the option with the worst performance, 0 points (−100 points in the P removal sub-criterion). Additionally, a linear value function from 0 points for 0% treatment to 100 points for the highest treatment efficiency was used to better represent the pollution treatment performance measured as treatment efficiency (%). The results for each sub-criteria of the technical-environmental criteria were combined and analysed, with the mean pollution treatment accounting for the mean removal rate of P, N, Cu, and Zn treatment (in %). Assessments were also made of the removal rates of P, N, Cu, and Zn separately.

Using the value scores for each sub-criterion, a mean score was also calculated at the criteria level considering social, economic, and technical-environmental criteria. The value scores at the criteria level were calculated by adding the points of all sub-criteria in the social, economic, and technical-environmental criteria respectively, and dividing that sum by the number of sub-criteria in each criterion.

3. Results

In Table 3, the performance of each bioretention option is presented in terms of the sub-criteria included in this study. The performance data in Table 3 were used to score each bioretention option to further analyse and compare the differences that various designs, construction components, filter material, and vegetation incurred.

The value score results are presented in Figs. 2 and 3. Higher value scores indicate better performance or lower costs. Since the value scores were based on the highest/lowest performance of the systems, comparisons and conclusions should be drawn accordingly, i.e., the value scores should only be used for comparisons of the bioretention options in this study.

Fig. 2a shows the results of the amenity and human toxicity scores (representing the social criteria). In Fig. 2b, the cost scores of bioretention construction and O&M are presented (economic criteria). High scores in Fig. 2b represent low costs and vice versa. The sub-criteria scores in Fig. 2c and d represent the results in the technical-environmental criteria. In Fig. 2c, runoff retention and pollution control scores are presented. The pollution control scores include mean P, N, Cu, and Zn removal scores. In Fig. 2d, the climate change, biodiversity, and robustness scores are presented.

In Fig. 2, the results have been presented at the sub-criteria level. In Fig. 3, an overview of the performance at the criteria level is presented. Fig. 3 shows the scores for the social, economic, and technical-environmental criteria of each bioretention option.

4. Discussion

The approach in this study was to theoretically assess the impacts of various bioretention designs, dependent on site specific requirements and the size of the systems. Therefore, there are a number of study limitations that impact the comparability and use of the results. However, since the design of bioretention systems to manage urban runoff is

Table 3
Bioretention performance in all the analysed sub-criteria.

Criteria	Social		Economic		Technical-environmental							
Sub-criteria	Amenity	Human toxicity	Construction cost	O&M cost	Climate change	Biodiversity	Robustness	P removal	N removal	Cu removal	Zn removal	Runoff retention
Indicator	Vegetation type	CTUh/m² catchment area	SEK/m² catchment area	SEK/(year, m² catchment area)	CO_2 eq./m² catchment area	Number of plant species	Expert judgement	%	%	%	%	Max ARI (years)
Biore-tention system												
A1	mid	0.062	1610	72	0.0047	14	high	70	0	80	90	50
A2	mid	0.062	1600	72	0.0047	9	high	70	50	80	90	16
A3	mid	0.040	1580	71	0.0016	20	high	70	50	80	90	50
A3-S	mid	0.040	1580	71	0.0016	20	high	70	80	80	90	50
A4	mid	0.035	1580	72	0.0014	23	high	−200	0	80	90	4
A5	mid	0.039	1550	71	0.0018	23	high	−200	0	70	80	9
B6	high	0.009	970	48	0.0008	14	low	−200	0	70	80	250
B7	high	0.009	1040	49	0.0006	14	low	−150	25	80	90	200
C8	low	0.005	310	11	0.0003	8	mid	70	50	80	90	50
C9	low	0.005	330	12	0.0003	8	mid	70	80	80	90	25
D10	mid	0.004	510	37	0.0002	8	low	−200	0	70	80	1
D11	mid	0.002	440	23	0.0002	10	low	−200	0	70	80	1

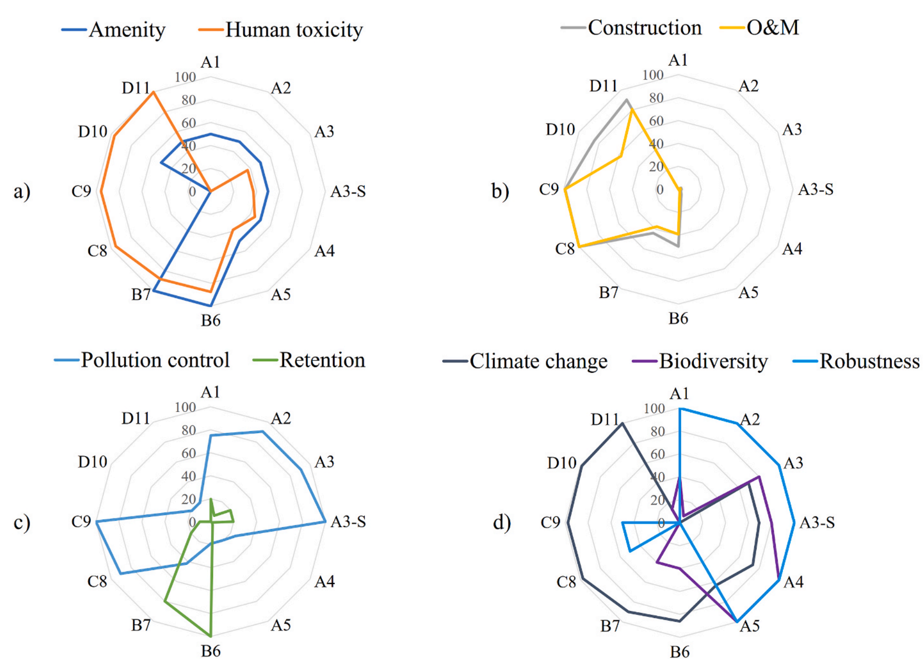

Fig. 2. **a)** The amenity and human toxicity scores, **b)** construction cost and O&M cost scores, **c)** pollution control and retention scores, and **d)** climate change, biodiversity, and robustness scores of all the studied bioretention options. High scores indicate better performance in Fig. 2a, c, and 2d or lower costs in Fig. 2b.

in many cases throughout the world based on similar assumptions concerning choice of filter material, construction materials and methods, vegetation, etc. (as described in the method section), the following findings have wide applicability despite these study limitations and assumptions, such as the geographical location of the systems and differences in costs of materials. The overall result shows that different design choices have varying degrees of impact on the environmental. It indicates that the selection of filter material mixture, construction components, plants, and other design features should be carefully considered when designing bioretention systems. The aim of bioretention stormwater quality treatment is to reduce the environmental impact of urban runoff on receiving water bodies. Furthermore, runoff retention, ecosystem service delivery, and so on may be required. At the same time the construction creates impacts due to material use and transport. The potential positive and negative consequences must be balanced. The design of each facility is also determined by the site-specific prioritization of various goals. Although often different aims complete each other, partly they can also be conflictive, e.g., compost amendment supports vegetation growth but reduces P removal. The implications of the findings of the MCA for the design of bioretention systems to manage urban runoff are discussed in more detail in the following sections.

4.1. Pollution treatment and hydraulic control

The impacts of different design elements of the bioretention options have been evaluated by analysing the value scores in Figs. 2 and 3. Fig. 2b shows that bioretention A3-S and C9 performed best in terms of pollution control (maximum 100 points in the P, N, Cu, and Zn removal sub-criteria). A3-S has a saturated water zone that increases the total N removal compared with the other systems. In the filter material of C9, biochar was used which has also been found to increase N removal (Tian

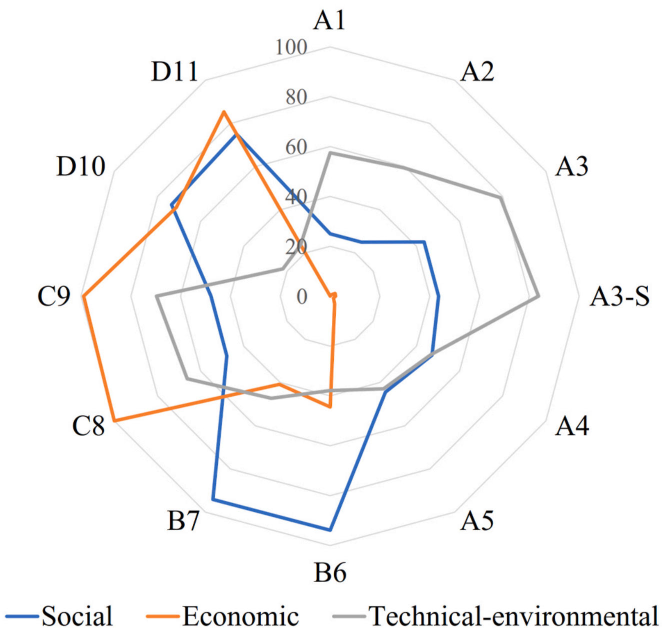

Fig. 3. Value scores for the bioretention systems at the criteria level.

et al., 2019). P leaching (indicated by a negative score in Table 3) was a consequence of using compost in the filter material (see bioretention A4, A5, B6, D10, and D11). Furthermore, all bioretention systems indicated high Cu and Zn removal scores (88–100 points). In Fig. 2c, the type B systems showed the highest scores in the retention sub-criteria (B6 100 points; B7 80 points), indicating that these systems performed best regarding hydraulic control compared with the other systems that all scored less than 20 points. These results of pollution treatment scores and hydraulic control support the general perception that bioretention systems primarily serve as treatment facilities rather than runoff retention. However, the type B systems indicate that bioretention systems can act as hydraulic control measures if designed accordingly with a large ratio of bioretention area to catchment area.

4.2. Amenity and human toxicity impacts

For the amenity sub-criterion, the type B systems scored 100 points and outperformed the other systems. This is the result of larger trees being used, which Mell et al. (2013) showed was more beneficial for urban amenity compared with lower ground plants when the WTP was considered. However, while amenity may benefit some residents, it may also harm less affluent residents who may be displaced if e.g., property values rise. Consequently, this impact requires more attention in future research to gain a better understanding of how bioretention implementation affects residents beyond WTP indicators.

In the human toxicity sub-criterion, the bioretention structures with a lot of concrete were associated with the lowest performance (type A systems: 0–44 points). As Öhrn Sagrelius et al. (2022) concluded, the high use of concrete in the bioretention structure in combination with pumice in the filter material mixture, which was associated with long transportation distances, incurred high environmental impacts, which in this study was represented by 0 points for bioretention A1 and A2 in both the human toxicity and the climate change impact sub-criteria.

4.3. Biodiversity

In the biodiversity sub-criterion in Fig. 2d, systems A4 and A5 scored 100 points, indicating that these systems best provide urban biodiversity. The biodiversity performance was based on the initial state of plant species richness in the bioretention systems as described in each system planting plan. However, the results should be viewed as an indication of the biodiversity since this initial state of planting could be changed during the lifetime of system. Over time, plant species can be outcompeted or eradicated within the system by e.g., other plants, a poor plant environment, a demanding climate, or vandalism. Hence, species richness could potentially change over time. The results should be used as an indication of how well the systems perform in the biodiversity sub-criterion and conclusions should be complemented with long-term evaluations of other biodiversity indices, as described by e.g., Winfrey et al. (2018). The systems with 0 points in the biodiversity sub-criteria were C8, C9, and D10.

4.4. Robustness and costs

The results in Fig. 2d indicate that the type A systems perform best (100 points) in the robustness sub-criterion, indicating that the design of these systems could be favourable if long-term functionality, resistance to extreme conditions, and meeting design objectives were included in the evaluation. For the type B and type D systems the robustness scores were lower, which can be explained by difficulties to meet the design objectives during construction, which was experienced during implementation of those systems, or finer particles being used in the filter material increasing the risk of clogging. However, the construction costs (Fig. 2b) of type B and type D systems were lower resulting in higher value scores ranging from 44 to 90 points compared with the type A systems (0–5 points) indicating that there is a compromise between costs and robustness when implementing these systems. The high construction cost for type A systems is related to high O&M costs (0–5 points for the type A systems). These findings suggest that initially high construction costs also imply high operating and maintenance expenses over time, mainly due to the high resetting cost. According to the value scores that represent the expenses of O&M (Fig. 2b), the type C systems perform the best. Type C systems show high construction cost scores (99–100 points) as well as O&M cost scores (99–100 points) combined with a value score of 50 points in the robustness sub-criterion (Fig. 2d) indicating that relatively high scores in these three categories are possible.

4.5. Multifunctionality of bioretention and trade-offs

It is important to draw attention to other trade-offs connected to the multifunctionality of bioretention systems. For instance, the use of compost in the filter material, which promotes plant growth and sustains the plant environment but increases the risk of nutrient leaching, is an example of how aesthetic values and runoff treatment performance can be in conflict. To manage these kinds of trade-offs, the objective and scope definition for each planned bioretention implementation must be carefully considered. Then, it would be possible to manage the difficulties caused by conflicting interests in the decision-making and implementation processes of these systems, i.e., by analysing stakeholder perspectives, allocating weights to each sub-criterion, and identifying the primary functions that the system should perform in each particular case. This approach would make it feasible to design fit-for-purpose bioretention systems for any given situation.

However, prioritization should also be addressed. For example, high amenity values are associated with low economic and technical-environmental scores (see type B systems in Fig. 2a, b, and 2c). High pollution treatment scores for type A systems are associated with poor economic performance. This is, however, not caused by specific adaptation to runoff pollution treatment but due to the relatively costly concrete construction and/or pumice in the filter material. The type C systems with a similar filter material and, thus, similarly high treatment performance use a simpler construction (minimising the use of concrete) which is more cost-efficient and has higher scores concerning climate change impact and human toxicity (due to lower emissions from cement production and shorter transport of construction material). Still, the overarching question is whether there is a truly multifunctional bioretention system design that addresses all issues associated with urban drainage and the benefits of BGI, or whether specific functions must be prioritized during implementation. The multi-functionality of the evaluated system designs varies, but the results underline that multi-functionality is not achieved per se when implementing BGI.

4.6. Relative sustainability performance at the criteria level

Other evaluation methods have been employed to assess BGI including e.g. cost-benefit analysis (Hamann et al., 2020) and a conceptual and spatial benefit assessment (Hoang et al., 2016). In these assessments, the focus was on the benefit evaluation of BGI rather than highlighting the differences in impacts incurred by various design choices. The results at the criteria level, in Fig. 3, show how the design components affect social, economic, and technical-environmental performance on a more generic level. The findings at the criteria level confirm the results at the sub-criteria level: design components of bioretention systems affect social, economic, and technical-environmental performance to varying degrees. The main outcome is that an optimal bioretention design with high performance in the social, economic, and technical-environmental criteria of the bioretention systems A1-D11 could not be identified.

4.7. Implementation scenarios

The findings indicate that the selection of construction components, filter material, plants, and other design elements are important when bioretention systems are planned. However, in the case of decision-making for bioretention systems, many stakeholders (city planners, landscape architects, stormwater managers, public and private actors, etc) are usually involved and the requirements of these parties may differ. As Ashley et al. (2022) discussed, there are many perspectives on the value of nature-based infrastructure, and thus these issues must be addressed early in the planning process. The context in which bioretention systems are planned varies depending on factors such as the existing blue-green spaces, socioeconomic preferences, traffic intensity on the street where the bioretention is planned, etc. Hence, the findings of this study could be combined with stakeholder perspectives and weighing the scores of the criteria and sub-criteria to determine the optimal bioretention design for each particular situation, including aspects like the location, need, application, and other requirements.

Some examples can be given to demonstrate how bioretention designs should consider the implementation requirements in various situations. A water-saturated zone (A3-S), for example, could be implemented if a bioretention system is planned in an area where N removal is prioritized. If P removal is the most important consideration, finer particles and/or high organic matter/nutrient content in the filter material (as in systems A4, A5, B6, B7, D10, and D11) should be avoided and organic matter-poor materials should be used (e.g., A1, A2, C8, and C9) despite a lower number of adapted plant species, which e.g., affects biodiversity. Nutrients in the influent stormwater can support plant growth in the bioretention systems, despite using filter substrates with low organic matter content. This nutrient load must be considered as part of the total nutrient balance when designing bioretention systems. Thus, if urban amenity is the most important aspect when designing a bioretention system for urban runoff, the selection of vegetation should be prioritized, but this may compromise P removal (or even P leaching). Furthermore, too much concrete and pumice (A1 and A2) should be avoided if the bioretention system is designed to have as small a carbon footprint as possible.

When the context, exemplified above, is considered, multifunctional bioretention systems have the potential to offer advantages beyond runoff pollution treatment and hydraulic control. Although the bioretention systems analysed in this study were only in Sweden, the similarities in bioretention designs indicate that the results of this study can support specific decisions regarding design differences and considerations of bioretention systems that BGI practitioners often face, also beyond Sweden.

5. Conclusion

Bioretention systems are becoming more common in urban drainage and stormwater management. It is therefore important to understand how different design elements, construction components, filter material mixtures, and plants affect the social, technical-environmental, and economic performance, i.e., the sustainability of these systems. The environmental performance of 12 different bioretention systems (A, B, C, and D, Table 1) have been analysed using a multicriteria analysis. This shows that the social, technical-environmental, and economic performance of the different bioretention systems varies depending on various design parameters. When all criteria are considered, the overall conclusion is that among the systems studied, one preferred system design could not be found to maximise the performance and/or minimise the impact for each criterion. If cost minimisation is the main objective, type C systems are preferred. Maximisation of social benefits are attained from type B systems. The best technical-environmental performance is associated with systems A3 and A3-S. These findings suggest that to fully incorporate design parameters that meet the objective - the most sustainable bioretention system - planning and implementation should include a clear goal definition that sets the scope in which the systems are built. BGI practitioners can then use the results from this study to design the most appropriate bioretention system for a particular context. In further work, the findings of this study should be combined with the perspectives of stakeholders to weigh the criteria and sub-criteria and thereby, find the most sustainable bioretention design for specific cases.

Author contribution

Pär Öhrn Sagrelius: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Writing – original draft, and Visualization. Godecke Blecken: Conceptualisation, Methodology, Writing – review & editing, Visualization, and supervision, Project administration, and funding acquisition. Annelie Hedström: Conceptualisation, Methodology, Writing – review & editing. project administration, and funding acquisition. Richard Ashley: Conceptualisation, Methodology, Writing – review & editing, and Supervision. Maria Viklander: Conceptualisation, Methodology, Writing – review & editing, Supervision, Project administration, and funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study was supported by the Swedish Research Council Formas (grant nr 2021-01963). It was conducted within the frame of the research centre DRIZZLE (Vinnova grant 2016-05176). The authors thank Johan Kjellin and David Hagerberg at Tyréns AB for their contribution and discussions during the entire process of this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.jenvman.2023.117949.

References

Ashley, R.M., Horton, B., Walker, L., Digman, C., Shaffer, P., Herk, S. van, 2022. The benefits of nature-based systems in a changing and uncertain world. In: Proceedings of the Institution of Civil Engineers - Engineering Sustainability. Thomas Telford Ltd, pp. 1–11. https://doi.org/10.1680/jensu.21.00102.

Beryani, A., Goldstein, A., Al-Rubaei, A.M., Viklander, M., Hunt III, W.F., Blecken, G.-T., 2021. Survey of the operational status of twenty-six urban stormwater biofilter facilities in Sweden. In: Journal of Environmental Management, vol. 297. Elsevier BV, 113375. https://doi.org/10.1016/j.jenvman.2021.113375.

Bhatt, A., Bradford, A., Abbassi, B.E., 2019. Cradle-to-grave life cycle assessment (LCA) of low-impact-development (LID) technologies in southern Ontario. In: Journal of Environmental Management, vol. 231. Elsevier BV, pp. 98–109. https://doi.org/10.1016/j.jenvman.2018.10.033.

Blecken, G.-T., Zinger, Y., Deletić, A., Fletcher, T.D., Viklander, M., 2009. Impact of a submerged zone and a carbon source on heavy metal removal in stormwater biofilters. In: Ecological Engineering, vol. 35. Elsevier BV, pp. 769–778. https://doi.org/10.1016/j.ecoleng.2008.12.009. Issue 5.

Cettner, A., Söderholm, K., Viklander, M., 2012. An adaptive stormwater culture? Historical perspectives on the status of stormwater within the Swedish urban water system. J. Urban Technol. 19 (3), 25–40. https://doi.org/10.1080/10630732.2012.673058.

Chahal, M.K., Shi, Z., Flury, M., 2016. Nutrient leaching and copper speciation in compost-amended bioretention systems. In: Sci. Total Environ. Elsevier BV, pp. 302–309. https://doi.org/10.1016/j.scitotenv.2016.02.125. Vol. 556.

Cheng, J., Yuan, Q., Kim, Y., 2017. Long-term operational studies of lab-scale pumice-woodchip packed stormwater biofilters. Environ. Technol. 39 (14), 1765–1775. https://doi.org/10.1080/09593330.2017.1337816.

Clark, S.E., Pitt, R., 2012. Targeting treatment technologies to address specific stormwater pollutants and numeric discharge limits. Water Res. 46 (Issue 20), 6715–6730. https://doi.org/10.1016/j.watres.2012.07.009. Elsevier BV.

Cording, A., Hurley, S., Adair, C., 2018. Influence of critical bioretention design factors and projected increases in precipitation due to climate change on roadside bioretention performance. In: Journal of Environmental Engineering, vol. 144. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)ee.1943-7870.0001411. Issue 9.

Dahlström, B., 2010. Regnintensitet – En Molnfysikalisk Betraktelse [English: Rain Intensity - a Cloud-Physics Contemplation]. Svenskt Vatten Utveckling, Stockholm rapport 2010–05.

Dodgson, J., Spackman, M., Pearman, A., Phillips, L., 2009. Multi-criteria Analysis: A Manual. Department for Communities and Local Government, London.

EC-JRC [European Commission, Joint Research Centre, Institute for Environment and Sustainability], 2012. Characterisation Factors of the ILCD Recommended Life Cycle Impact Assessment Methods. Database and Supporting Information, first ed. Publications Office of the European Union, Luxembourg. EUR 251.

EC-JRC [European Commission. Joint Research Centre. Institute for Environment and Sustainability], 2014. Normalisation Method and Data for Environmental Footprints. EUR 26842, JRC91531. Publications Office of the European Union, Luxembourg.

Fassman, E.A., Simcock, R., Wang, S., 2013. Media Specification for Stormwater Bioretention Devices, Prepared by Auckland UniServices for Auckland Council. Auckland Council technical report. TR2013/011.

FAWB, 2009. Biofiltration Filter Media Guidelines [Version 3.01], Prepared by the Facility for Advancing Water Biofiltration (FAWB). Retrieved from. http://graie.org/SOCOMA/IMG/pdf/FAWB_Filter_media_guidelines_v3_June_2009-2.pdf. (Accessed 22 March 2023). Accessed.

Fedor, P., Zvaríková, M., 2019. Biodiversity indices. In: Encyclopedia of Ecology. Elsevier Amsterdam, Netherlands.

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D., Viklander, M., 2014. SUDS, LID, BMPs, WSUD and more – the evolution and application of terminology surrounding urban drainage. Urban Water J. 12 (7), 525–542. https://doi.org/10.1080/1573062x.2014.916314.

Foxon, T.J., Mcilkenny, G., Gilmour, D., Oltean-Dumbrava, C., Souter, N., Ashley, R., Butler, D., Pearson, P., Jowitt, P., Moir, J., 2002. Sustainability criteria for decision support in the UK water industry. In: Journal of Environmental Planning and Management, vol. 45, pp. 285–301. https://doi.org/10.1080/09640560220116341. Issue 2.

Hamann, F., Blecken, G.-T., Ashley, R.M., Viklander, M., 2020. Valuing the multiple benefits of blue-green infrastructure for a Swedish case study: contrasting the economic assessment tools B£ST and TEEB. In: Journal of Sustainable Water in the Built Environment, vol. 6. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/jswbay.0000919. Issue 4.

Hoang, L., Fenner, R.A., Skenderian, M., 2016. A conceptual approach for evaluating the multiple benefits of urban flood management practices. In: Journal of Flood Risk Management, vol. 11. Wiley. https://doi.org/10.1111/jfr3.12267. Issue S2.

Horton, B., Digman, C.J., Ashley, R.M., McMullan, J., 2019. B£ST Guidance – Guidance to Assess the Benefits of Blue and Green Infrastructure Using B£ST. CIRIA, Griffin Court, 15 Long Lane. London, EC1A 9PN, UK.

Hua, P., Yang, W., Qi, X., Jiang, S., Xie, J., Gu, X., Li, H., Zhang, J., Krebs, P., 2020. Evaluating the effect of urban flooding reduction strategies in response to design rainfall and low impact development. In: Journal of Cleaner Production, vol. 242. Elsevier BV, 118515. https://doi.org/10.1016/j.jclepro.2019.118515.

Jia, H., Yao, H., Tang, Y., Yu, S.L., Zhen, J.X., Lu, Y., 2013. Development of a multi-criteria index ranking system for urban runoff best management practices (BMPs) selection. In: Environmental Monitoring and Assessment, vol. 185. Springer Science and Business Media LLC, pp. 7915–7933. https://doi.org/10.1007/s10661-013-3144-0. Issue 9.

Jose, R., Wade, R., Jefferies, C., 2014. Smart SUDS: recognising the multiple-benefit potential of sustainable surface water management systems. In: Water Science and Technology, vol. 71. IWA Publishing, pp. 245–251. https://doi.org/10.2166/wst.2014.484. Issue 2.

Koc, K., Ekmekcioğlu, Ö., Özger, M., 2021. An integrated framework for the comprehensive evaluation of low impact development strategies. In: Journal of Environmental Management, vol. 294. Elsevier BV, 113023. https://doi.org/10.1016/j.jenvman.2021.113023.

Li, H., Davis, A.P., 2009. Water quality improvement through reductions of pollutant loads using bioretention. In: Journal of Environmental Engineering, vol. 135. American Society of Civil Engineers (ASCE), pp. 567–576. https://doi.org/10.1061/(asce)ee.1943-7870.0000026, 8.

Li, J., Deng, C., Li, Y., Li, Y., Song, J., 2017. Comprehensive benefit evaluation system for low-impact development of urban stormwater management measures. In: Water Resources Management, vol. 31. Springer Science and Business Media LLC, pp. 4745–4758. https://doi.org/10.1007/s11269-017-1776-5. Issue 15.

Liquete, C., Udias, A., Conte, G., Grizzetti, B., Masi, F., 2016. Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits. In: Ecosystem Services, vol. 22. Elsevier BV, pp. 392–401. https://doi.org/10.1016/j.ecoser.2016.09.011.

Mell, I.C., Henneberry, J., Hehl-Lange, S., Keskin, B., 2013. Promoting urban greening: valuing the development of green infrastructure investments in the urban core of Manchester, UK. In: Urban Forestry & Urban Greening, vol. 12. Elsevier BV, pp. 296–306. https://doi.org/10.1016/j.ufug.2013.04.006. Issue 3.

Mohanty, S.K., Valenca, R., Berger, A.W., Yu, I.K.M., Xiong, X., Saunders, T.M., Tsang, D.C.W., 2018. Plenty of room for carbon on the ground: potential applications of biochar for stormwater treatment. In: Science of the Total Environment, vol. 625. Elsevier BV, pp. 1644–1658. https://doi.org/10.1016/j.scitotenv.2018.01.037.

Öhrn Sagrelius, P., Blecken, G., Hedström, A., Ashley, R., Viklander, M., 2022. Environmental impacts of stormwater bioretention systems with various design and construction components. In: Journal of Cleaner Production, vol. 359. Elsevier BV, 132091. https://doi.org/10.1016/j.jclepro.2022.132091.

O'Sullivan, A.D., Wicke, D., Hengen, T.J., Sieverding, H.L., Stone, J.J., 2015. Life Cycle Assessment modelling of stormwater treatment systems. In: Journal of Environmental Management, vol. 149. Elsevier BV, pp. 236–244. https://doi.org/10.1016/j.jenvman.2014.10.025.

Søberg, L., 2019. Bioretention for Stormwater Quality Treatment: Effects of Design Features and Ambient Conditions. Ph.D. dissertation. Luleå University of Technology. Retrieved from. http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-73669.

Stahre, P., 2008. Blue-green Fingerprints in the City of Malmö. Malmö, Sweden.

Tian, J., Jin, J., Chiu, P.C., Cha, D.K., Guo, M., Imhoff, P.T., 2019. A pilot-scale, bi-layer bioretention system with biochar and zero-valent iron for enhanced nitrate removal from stormwater. In: Water Research, vol. 148. Elsevier BV, pp. 378–387. https://doi.org/10.1016/j.watres.2018.10.030.

Tirpak, R.A., Afrooz, A.N., Winston, R.J., Valenca, R., Schiff, K., Mohanty, S.K., 2021. Conventional and amended bioretention soil media for targeted pollutant treatment: a critical review to guide the state of the practice. In: Water Research, vol. 189. Elsevier BV, 116648. https://doi.org/10.1016/j.watres.2020.116648.

Vineyard, D., Ingwersen, W.W., Hawkins, T.R., Xue, X., Demeke, B., Shuster, W., 2015. Comparing green and grey infrastructure using life cycle cost and environmental impact: a rain garden case study in cincinnati. In: JAWRA Journal of the American Water Resources Association, vol. 51. Wiley, pp. 1342–1360. https://doi.org/10.1111/1752-1688.12320. Issue 5.

Wang, M., Zhang, D., Adhityan, A., Ng, W.J., Dong, J., Tan, S.K., 2016. Assessing cost-effectiveness of bioretention on stormwater in response to climate change and urbanization for future scenarios. In: Journal of Hydrology, vol. 543. Elsevier BV, pp. 423–432. https://doi.org/10.1016/j.jhydrol.2016.10.019.

Wang, Y., Ni, Z., Hu, M., Li, J., Wang, Y., Lu, Z., Chen, S., Xia, B., 2020. Environmental performances and energy efficiencies of various urban green infrastructures: a life-cycle assessment. In: Journal of Cleaner Production, vol. 248. Elsevier BV, 119244. https://doi.org/10.1016/j.jclepro.2019.119244.

Winfrey, B.K., Hatt, B.E., Ambrose, R.F., 2018. Biodiversity and functional diversity of Australian stormwater biofilter plant communities. In: Landscape and Urban Planning, vol. 170. Elsevier BV, pp. 112–137. https://doi.org/10.1016/j.landurbplan.2017.11.002.

Zinger, Y., Blecken, G.-T., Fletcher, T.D., Viklander, M., Deletić, A., 2013. Optimising nitrogen removal in existing stormwater biofilters: benefits and tradeoffs of a retrofitted saturated zone. In: Ecological Engineering, vol. 51. Elsevier BV, pp. 75–82. https://doi.org/10.1016/j.ecoleng.2012.12.007.