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Valuing structured alternatives for retrofitting blue-green infrastructure at a catchment scale using the Benefit Estimation Tool (B£ST)

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ABSTRACT

Blue-green infrastructure (BGI) options are considered to be more sustainable practices for water management and bring a range of benefits over and above water management. Davidshall in Malmö, Sweden, has been used as a case area to assess the multiple benefits of implementing BGI, considering seven alternative BGI schemes systematically developed along two scales: naturalness (i.e. more/less engineered/complex) and spatial distribution (e.g. decentral vs. end-of-pipe). The baseline alternative was the existing situation. The Benefit Estimation Tool (B£ST) was used to carry out a socio-economic assessment. The overall benefits varied significantly (two orders of magnitude), depending on the BGI scheme implemented: the greatest values were associated with natural decentral, natural decentral/end-of-pipe, and engineered decentral/end-of-pipe alternatives, those including sub-surface and open dry detention, stormwater tree pits, and rain gardens. The three B£ST categories providing the greatest benefits were enhancing amenity, benefiting health, and reducing flooding. Cultural ecosystem services were provided by all alternatives, and two alternatives (natural decentral and natural decentral/end-of-pipe) also provided regulating ecosystem services. The study showed that amenity and health were the most significant benefits of BGI implementation, contrasting with the main aim of BGI implementation, which was stormwater management (water quality and flood protection).

Key words: Benefit Estimation Tool, blue-green infrastructure, catchment scale, naturalness scale, social benefits, spatial scale

HIGHLIGHTS

- Social benefits can be monetised and assessed for the decision-making process.
- Selection of the appropriate BGI alternative should correspond to the primary aim of a project.
- Who pays for BGI projects, and who receives the benefits?
- How to select BGI alternatives and what should be considered?
- There is not one single, or type of, BGI system that can provide the greatest overall benefits.

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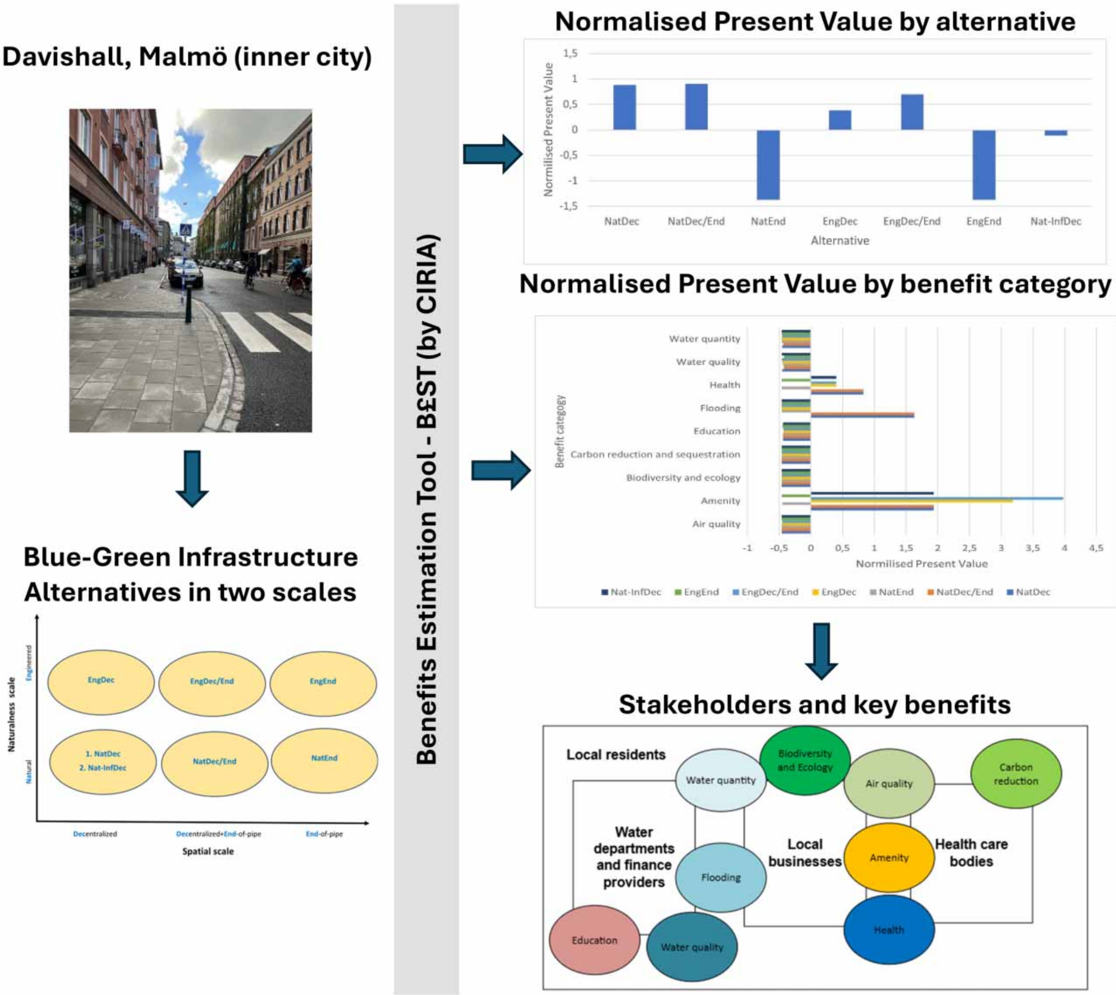
GRAPHICAL ABSTRACT



INTRODUCTION

Since the last century, people have increasingly chosen to live in cities and towns. In 1950, 30% of the world's population was urban; by 2028, this will rise to 55% and is projected to be 68% by 2050 (United Nations 2019). Cities have struggled to adapt to such rapid increases in population, and their existing buried grey infrastructure limits their capacity to adapt to the consequences of climate change, such as increased stormwater volumes and higher temperatures. The grey infrastructure of significance here is the buried piped drainage systems installed in industrialised countries over the last centuries. Modifying this existing asset base to cope with increasing inputs due to population and climate pressures is costly and may miss opportunities for treating stormwater as an opportunity rather than a problem (Ashley *et al.* 2024).

Stormwater is traditionally seen as problematic in terms of both quantity and quality. Large volumes of stormwater, resulting from increasingly intense rainfall events, and increases in impervious urban surfaces cause flooding and/or erosive flows in receiving water. Pollutants that are discharged with traditional stormwater systems lead to deteriorating water quality in receiving water bodies (Müller *et al.* 2020). Dealing with these problems requires better urban infrastructure and an opportunity-led perspective. One approach is to utilise green and blue systems (e.g. wetlands, ditches, and ponds) for managing and treating stormwater, in place of grey infrastructure (pipes and tanks) (e.g. Eckart *et al.* 2017).

In 2013, a green infrastructure (GI) strategy was adopted by the European Commission 'to promote the deployment of green infrastructure in the EU in urban and rural areas' (European Commission 2013). Within the 2030 Agenda for Sustainable Development (United Nations 2015), Sustainable Development Goal 11.3 (inclusive and sustainable urbanisation) also refers to GI, noting that investment in GI should result in smarter, greener cities as well as communication among all stakeholders for sustainable human settlement planning and management.

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Because of this, GI is currently integrated into many city development plans and sustainable urban development in Europe and beyond (Wong & Montalto 2020).

GI solutions involving urban water management are often referred to as blue-green infrastructure (BGI). BGI may refer to nature-based solutions (NBS) and can include concepts such as sustainable urban drainage or water sensitive urban design. BGI facilities vary in type, from parks and green resort areas to constructed sites such as green roofs, ponds, and bioretention wetlands (Pochodyła *et al.* 2021). These are holistic, multifunctional approaches that combine nature-based engineered processes for (storm-)water retention and water quality treatment with socioeconomic and other benefits (Fletcher *et al.* 2015). On BGI sites, soil, vegetation, and natural processes are used to utilise or retain and infiltrate stormwater, mitigating flooding and improving water quality in receiving water bodies. This means that BGI can be considered effective for water management in urban areas (Charlesworth & Warwick 2020; Cheshmehzang *et al.* 2021; Pochodyła *et al.* 2021). Furthermore, by improving the environmental conditions, BGI sites can yield additional benefits for local populations, including improved air quality, urban heat island control, amenity value, recreation opportunities, and aesthetic attractiveness (Jose *et al.* 2015; Ossa-Moreno *et al.* 2017; Khoshnava *et al.* 2020). This, in turn, contributes to improving the local population's quality of life and health. BGI can provide numerous ecosystem services (i.e. direct and indirect benefits that humans receive from ecosystems) to local populations, comprising four groups: 1. Provisioning services – goods or products that people consume or are used in the production of other goods; 2. Regulating services – benefits derived as a result of an ecosystem control of natural processes such as water quality and flows; 3. Cultural services – non-material benefits such as recreation and aesthetic enjoyment; 4. Supporting services – natural processes that maintain the production of all other ecosystem services such as habitat provision and water cycling. Many of these benefits can be provided by natural systems, including BGI (e.g. Kopp *et al.* 2021). Thus, BGI is a promising NBS to address a variety of problems in cities and to exploit opportunities. If planned strategically, BGI sites can support the green economy, reduce dependence on grey infrastructure, and protect biodiversity.

Increasingly, the substantial investments in BGI are being justified by valuing all the benefits they bring, i.e. not just for their technical/environmental functions but for their multi-functionality. BGI is often seen primarily as a water management solution and is, thus, usually exclusively financed by the water sector. However, particularly where BGI is retrofitted to the existing areas, the main beneficiaries may be others, such as homeowners, public health services, insurance companies, and the wider public (Ashley *et al.* 2018a). These benefits can accrue to a variety of different stakeholders, institutions, or responsible authorities, as well as individuals, depending on the local arrangements for managing urban drainage.

It is often necessary to undertake a socio-economic assessment before making a decision on what type of BGI facility (alternative) to select, especially for the justification of investments. Several assessments of the value of benefits of BGI have been conducted, using a variety of tools. These include the Economics of Ecosystems and Biodiversity – TEEB (TEEB 2010), Multicriteria Analysis (Loc *et al.* 2017), a contingent valuation method for the assessment of BGI (Viti *et al.* 2023), the Investment Framework for Economics of Water Sensitive Cities – INFFEWS (Pannell 2020; Iftekhar & Pannell 2022), Decision-making trial and evaluation laboratory – DEMATEL (Khoshnava *et al.* 2020), and the Benefits Estimation Tool – B£ST (Horton *et al.* 2019). These generate outputs that can support decision-makers in selecting what type, appropriate locations, and scales of the BGI facility to establish.

In this study, the B£ST tool has been used as it was developed specifically for BGI; the data inventory and logic behind the tool are mostly from scientific literature; it is user-friendly and can include additional benefits identified by the user. B£ST, which originated in the UK, was developed by the Construction Industry Research and Information Association (CIRIA 2024). This is a structured approach for assessing the various benefits of BGI based on the impact pathway approach, which includes the following: BGI scheme → Impact on ecosystem → Changes in ecosystem services → Impacts on human welfare → Economic value of changes in welfare. It includes both monetised and non-monetised benefit categories, enabling alternative BGI options to be assessed in terms of their long-term value. Although B£ST does not provide an optimisation tool, it can be used to support decision-makers by providing information for selecting the BGI facilities, taking into consideration the economic, environmental, and social benefits. Thus, the tool can help to contribute to sustainable development.

Contemporary urban planning poses an array of complex challenges, including climate change, biodiversity loss, and increased demands on GI as a solution to these challenges. In a municipal context, practitioners constantly need to identify and prioritise strategic actions – be it for education, social care, or green space

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management – while working under increasing demands to act holistically and systematically to address issues in a synergistic way (e.g. Sunding *et al.* 2024). Today, one of the key questions in urban planning has been expressed as 'to what extent do urban policies, together with the triad 'environmental, social, and governance' articulate and promote a sustainable production of urban spaces?' (Teixeira Dias *et al.* 2023), and this applies to stormwater management as much as other aspects of urban planning.

Nowadays, BGI facilities include a wide variety of components where natural processes play the main role. However, BGI facilities are basic technologically, when just a simple construction is required (e.g. digging a hole and making a drainage layer) with nature providing the processes. Decisions on selection and construction have to be based on understanding and weighing multiple function(s) on a system scale. Studies of various types of BGI facilities typically target a single aim and often focus on a single BGI technique or a specific case study (Al-Rubaei *et al.* 2016). A valuable next step would be to deepen the understanding of complex, multifunctional BGI systems as alternative options in larger urban areas (Sunding *et al.* 2024). Such alternatives may involve different combinations of BGI at the urban catchment scale. Thus, rather than studying *single* BGI facilities or schemes separately (as is often done), the analysis should include alternatives of BGI facilities or schemes on an (urban) catchment scale, implemented at different spatial and complexity scales. Still, most studies usually describe single BGI implementation schemes. Given the large number of different BGI technologies, comprehensive studies must include different combinations and alternatives of BGI in a catchment, as done here using seven alternatives systematically developed for two scales. In this context, here a 'naturalness' scale has been used to classify the variety of types of BGI facilities considered, i.e. alternatives may comprise more or fewer engineered technologies related to a 'complexity' scale, which pertains to the utilisation of more or fewer complex processes by the option. The spatial scale relates to whether or not the alternative includes centralised or more decentralised implementation across a catchment, i.e. a single large facility or, alternatively, a number of dispersed smaller BGI facilities that provide the same degree of control of stormwater. Time scale is also important and relates to long-term functionality, bearing in mind the predicted or unforeseen new challenges related to maintenance, climate change, and including changes in societal expectations or needs.

In this context, the aim of the study is to compare alternatives as well as separate benefits for implementing BGI in an urban catchment using the B£ST tool. Seven BGI alternatives (detailed information is presented in Table 2) have been compared for the catchment of Davidshall (Malmö), classified using the two scales (naturalness and spatial) to identify which alternatives are more or less preferable for various stakeholders. This will enable strategies for BGI implementation to be more evidence-based at the catchment scale and ensure potentially better acceptance of BGI by local populations. The key focus of the research is to compare alternatives and benefit categories for the various options. As the B£ST tool was developed for a UK context, it is used here to compare alternatives based on a normalised version of the monetary assessment. The results provide support to decision-makers concerning: (i) the benefits provided by different BGI alternatives; and (ii) comparisons between the alternatives.

METHODS

The methodology used here comprised the following: (1) identification of stakeholders and potential benefits; (2) developing alternatives for BGI for the site; (3) data collection for applying B£ST; (4) using B£ST to identify and compare the value of the socio-economic benefits for all alternatives; and (5) comparing and discussing the results.

Identification of stakeholders and potential benefits

BGI provides a wide range of benefits and beneficiaries of the Davidshall project, including various key stakeholders, presented in Table 1. They would each receive some potential benefits from the implementation of BGI. Some of them receive benefits but do not participate in the decision-making process and do not provide funds for BGI construction and/or maintenance.

Description of the urban catchment case

Davidshall is a 6.25 ha district in the western inner city of Malmö, Sweden. It is densely populated (population c. 2,000) with the receiving water channel *Rörsjökanalen* running along the western border of the catchment. Buildings in Davidshall are mostly 3–4 storey residential buildings with small businesses (e.g. shops, cafes, and hairdressers) on the ground floor. Many buildings have basements. The photographs in Supplementary

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Table 1 | Stakeholders of BGI

Stakeholder group	Role	Provides funds for construction and/or maintenance of BGI facilities (Y/N)	What potential benefits can receive?
Local residents	End-users and adjacency of BGI	Y (indirect – through taxes)	More attractive area, better air quality, better biodiversity, lower air temperature on streets in summer, less noise, better health, higher value for property (for house owners)
Water departments (municipalities) and finance providers	Responsible for construction and maintenance of BGI, responsible for stormwater management	Y	Flood mitigation, better water quality in receiving waters, field site for education and training (e.g. for communities, employees, or students)
Local businesses	Owners of shops, cafes, insurance companies	N	Better business, more clients, lower payments for insurance in case of damaged property due to flooding
Health care bodies	Hospitals	N	Mental and physically healthier population with fewer referrals/ appointments for care

Figure S1 illustrate the catchment. The site represents conditions typical of urban catchments in Sweden, with relatively little space, flooding problems after intense rainfall, inadequate grey stormwater infrastructure, and a lack of green space. Thus, retrofitting multifunctional BGI could both solve these stormwater-related problems and enhance the living environment by introducing more GI, i.e. the main drivers for BGI implementation in the area are (Blecken *et al.* 2015; Eckart *et al.* 2017; Charlesworth & Warwick 2020; Khoshnava *et al.* 2020):

– Flood mitigation (reduction of water quantity in the existing water systems).
– Stormwater treatment to enhance water quality in receiving water bodies.
– Greener environment: improved amenity which results in better human well-being and greater attractiveness of the area.
– Improved biodiversity.

Description of alternatives

The existing green areas comprise 0.383 ha (or 6.1%) of the catchment. The baseline alternative is the existing grey stormwater infrastructure. The two scales below were taken into consideration in devising the seven BGI alternatives to be considered in detail (detailed information about scales is in Adhikari *et al.* 2024):

- *Naturalness scale*: BGI facilities have been classified using construction/engineering requirements (e.g. use of concrete and interconnecting pipes vs natural spaces). Hence, simpler, cheaper, low-technology, more natural BGI (e.g. open dry detention) vs engineered, more expensive, NBSs (e.g. rain garden and bioretention). This is expressed using two categories: *Natural* (Nat) and *Engineered* (Eng).
- *Spatial scale*: decentralised facilities (e.g. facilities spread out across the catchment) are considered vs an end-of-pipe approach (one central facility located before the receiving water) and combinations of these (decentralised retention facilities spread out across the catchment together with end-of-pipe quality treatment). This is also expressed in terms of three categories: *Decentralised* (Dec), *Decentralised plus End-of-pipe* (Dec/End), and *End-of-pipe* (End).

The combinations of the two BGI classification categories are illustrated in Figure 1. For each of the alternatives, BGI facilities that could be implemented on the site and are known to be effective for stormwater management in terms of water quality and water quantity were chosen. As a separate alternative, a seventh alternative (Nat-InfDec) decentralised across the catchment area has been used that includes a combination of facilities, utilising *Infiltration*, e.g. infiltration trenches. For the calculation of the area for each alternative, runoff from each sub-catchment was taken into consideration while designing the BGI facility. As a result, the

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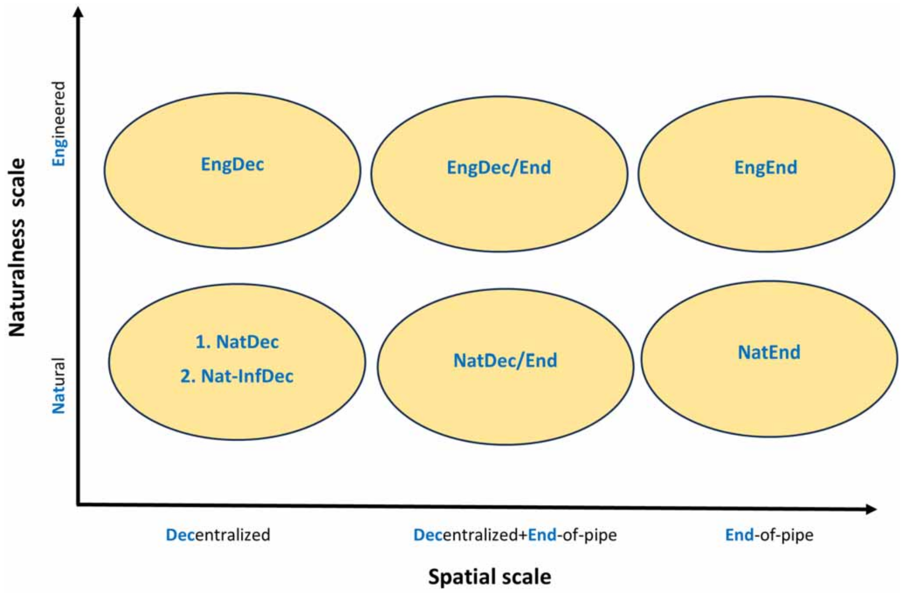

Figure 1 | Degree of naturalness and complexity of alternative options.

same BGI facility has been implemented in different areas depending on the runoff volume received from the catchment. However, in some cases, the BGI facility was implemented with the maximum possible surface area when the available surface area in the sub-catchment was limited. The detailed alternatives are presented in Table 2. Supplementary Figure S2 illustrates the alternatives.

Description of B£ST

B£ST – Benefit Estimation Tool (BEST 2019) has been used to carry out a monetary assessment of the BGI alternatives. This tool (version 2019) was specifically developed to assess the benefits of BGI and has been regularly used in case studies, both in the UK and other countries (Ashley *et al*. 2018a, 2018b; Hamann *et al*. 2020). Given that most in-data in B£ST is from UK databases, readily implementing the monetized values in other countries is limited (though feasible as discussed by Hamann *et al*. 2020). However, it can be useful for *comparing* different BGI alternatives and benefit categories using normalized values, as done in this study.

The current version, updated since the earlier 2015 version, includes Natural Flood Management and other elements of BGI. The B£ST model provides a structured approach to evaluating a range of financial or economic benefits, for the system selected. It follows a simple structure, commencing with a screening and qualitative assessment to identify the potential benefits for each specific case before evaluating these in detail. B£ST was originally an Excel-based tool that required data from various open sources, local studies, and assumptions. Support is provided in guidance and from the B£ST software library, helping the user to quantify and monetise a benefit (Horton *et al*. 2019). Here, 14 monetised benefit categories (air quality, amenity, asset performance, biodiversity and ecology, building temperature, carbon reduction and sequestration, education, enabling development, flooding, health, noise, recreation, water quality, and water quantity) and four non-monetised categories (crime, economic growth, tourism, and traffic calming) are provided. Users can create their own benefit categories, which can then be included in the value assessment.

An impact pathway approach is used in B£ST to assess the value of the benefits in terms of monetised (presented as the present value of the benefits) and qualitative (non-monetised impacts having subjective scores) outputs. These collectively provide an identified value for each of the regulating, cultural, provisioning, and supporting ecosystem services.

The assessment is performed in two steps and ultimately yields figures that show the value generated for each type of benefit (net present value (NPV)), calculated in UK pounds (£). B£ST requires a user-specified timescale and a financial discount rate that makes it possible to match the value of future benefits to today's prices. Calculations for a 30-year period are recommended. User input cost data allow B£ST to estimate the NPV of an option. The most recent version of B£ST is presented on an online platform using Geo-Information System (GIS) mapping, but this is linked to UK databases and is, therefore, not suitable for non-UK applications.

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Table 2 | Characteristics of the seven alternatives assessed

Name	Brief description	The main characteristics of alternatives
Baseline	Existing pipe-based infrastructure	Underground pipe system Asphalt on streets
Alternative 1 - NatDec – Sub-surface detention and open dry detention	Naturalness scale: Natural Spatial scale: Decentralised	BGI decentralised: Sub-surface detention and open dry detention for water retention and basic quality treatment. Area and type: • sub-surface macadam detention: 948 m^2; • open dry detention (grass and bushes): 1,660 m^2. Additional number of residents living on green streets: 593
Alternative 2 – NatDec/End – Sub-surface detention, open dry detention, and floating sedimentation	Naturalness scale: Natural Spatial scale: Decentralised/End-of-pipe	BGI decentralised: Sub-surface detention, open dry detention, and floating sedimentation for water retention and basic quality treatment. BGI end-of-pipe: floating sedimentation basin (or floating curtain) for water quality treatment. Area and type: • sub-surface detention – 949 m^2 • open dry detention (grass and bushes)– 1,660 m^2 • floating sedimentation -in the receiving water Additional number of residents living on green streets: 593
Alternative 3 – NatEnd – Sub-surface detention and floating sedimentation	Naturalness scale: Natural Spatial scale: End-of-pipe	BGI end-of-pipe: sub-surface detention storage for water retention, with basic quality treatment using floating sedimentation (or floating curtain) for water quality treatment. Area and type: • sub-surface detention (gravel) – 141 m^2 • floating sedimentation -in the receiving water Additional number of residents, living on green streets: 0
Alternative 4 – EngDec - Bioretention	Naturalness scale: Engineered Spatial scale: Decentralised	BGI decentralised: Bioretention (sub-surface biofilter) for stormwater quality treatment. Area and type: • Bioretention – 400 m^2 Additional number of residents living on green streets: 593
Alternative 5 – EngDec/End – RainGarden and stormwater tree pit	Naturalness scale: Engineered Spatial scale: Decentralised/End-of-pipe	BGI decentralised: Stormwater tree pits to maximise the stormwater capture potential of trees. BGI end-of-pipe: rain gardens for stormwater retention. Area and type: • Stormwater tree pits (tree planters with structural soils or the so-called 'Stockholm solution') – 1,280 m^2 (33 trees) • Rain garden (shrubs and grass) – 140 m^2 Additional number of residents living on green streets: 790
Alternative 6 – EngEnd – Precast treatment facility	Naturalness scale: Engineered Spatial scale: End-of-pipe	BGI end-of-pipe: Precast treatment facility (sub-surface detention facility) for stormwater quality treatment. Area and type: • Sub-surface detention facility/filter facility (underground facility) – 13 m^2 Additional number of residents living on green streets: 0

(*Continued*.)

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Table 2 | Continued

Name	Brief description	The main characteristics of alternatives
Alternative 7 – Nat-InfDec – Infiltration facilities	Naturalness scale: Natural Spatial scale: Decentralised	BGI decentralised: facilities targeting infiltration, i.e. infiltration trench and basin for quality treatment and permeable pavement. Area and type: • infiltration trench (gravel) – 1,320 m^2 • infiltration basin (grass and bushes) – 930 m^2 • permeable pavement (grass (50%) and asphalt (50%)) – 175 m^2 Additional number of residents living on green streets: 593

Input data for B£ST

The input data required by B£ST and relevant information sources are summarised in Supplementary Table S1. Use of the tool requires a mix of statistical data (e.g. number of inhabitants; Statistical database for the year 2021), modelling results (e.g. number of properties at risk of flooding and groundwater infiltration), and data based on expert judgements (e.g. number of trees which will be planted). There is also a library of data already incorporated into the software: for example, the value of carbon sequestration is based on both the traded price of carbon and the nontraded price as set by the UK government (Horton *et al.* 2019).

The US-EPA Storm Water Management Model (SWMM) was used here to generate input data on those categories related to water quantity and quality in the catchment area (Rossman & Huber 2016). Modelling used block rainfall with a 30-year return interval and 20 min duration using Swedish design recommendations (78.1 mm/h, 6 h simulation, Svensk Vatten 2019). As the nearest water body is an artificial canal, Water Framework Directive (WFD) classifications for the existing and future water quality (Vatteninformationssystem Sverige 2022) were not relevant. Thus, for the purposes of the study, the nearest water body (*Sege å*) has been used as the background water body for comparing any change in the WFD status (Vatteninformationssystem Sverige 2022). Based on this, total concentrations of P and N were identified as the most relevant pollutants for water quality status. The key modelling results are presented in Table 3.

The B£ST methodology library contains values for various interventions, based on vegetation type (19 key types are provided), and these were used to calculate biodiversity benefit. As none of these matched the vegetation in this catchment, it was assumed that infiltration basins, open dry detention, and permeable pavement/grass correspond to 'Low dry acid grass values', and that bioretention, rain garden, and stormwater tree pits correspond to 'Improved grassland' values. This assumption is based on vegetation type and potential change in the biodiversity level.

Statistical data from a Swedish insurance company (Svensk Försäkring 2022) have been used to calculate costs for damaged properties: the average payment for damaged property is approximately 138,000 SEK for a commercial property and 13,000 SEK for a private property (about 12,000 and 1,100 EUR, respectively).

Z-score normalisation of generated monetary value

In the analysis, it was considered more robust to compare benefit categories and relative impacts rather than the UK-based monetary value. Therefore, a *z*-score normalisation has been used (Han *et al.* 2012). This normalisation process was selected because it is characterised by outlier robustness and meaningful comparison of values; moreover, it highlights the variability among the values. The *z*-score algorithm normalizes the values by dividing them by their standard deviation, resulting in values with a mean of 0. The normalised value represents the number of standard deviations that the original value is from the mean, i.e. if the normalised value is positive, it is above the mean, and if negative, below the mean. The following formula is applied:

$$x' = (x - \mu)/\delta,$$

where x' is the normalised value, x is the original value, μ is the mean of values, and δ is the standard deviation of values.

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Table 3 | Input data for B£ST produced through SWMM modelling

Alternative	Additional groundwater recharge, m^3	Flooding volume, m^3	Number of flooded properties	Total P concentration, mg/L	Total N concentration, mg/L
Baseline	N/A	90	5	0.09	1.73
NatDec	64	0	0	0.08	1.16
NatDec/End	64	0	0	0.04	0.70
NatEnd	0	90	5	0.04	1.02
EngDec	8	32	5	0.08	1.61
EngDec/End	87	19	5	0.10	2.36
EngEnd	0	90	5	0.03	1.31
Nat-InfDec	53	22	5	0.09	1.30

Uncertainty

As with all models, this B£ST simulation involves uncertainties and the results should be understood accordingly. Calculations were made for facilities that are planned (i.e. from the modelling using the non-calibrated SWMM model of the proposed alternatives as no extant examples were available for comparisons), using expert judgements and assumptions as input data. Flooding volume also varied between alternatives, although this did not affect the final results because only the number of properties flooded is used in B£ST. This may explain why, in this study, the results proved relatively insensitive to changes in flooding.

Calculations cover a design life of 30 years using rainfall with a 30-year return interval. However, due to climate change in the next 30 years, there could be more rainfall (thus, greater flooding) or longer dry periods. This creates additional uncertainties.

Furthermore, B£ST was developed for UK conditions and includes a data library specifically defined for the UK conditions and standards (e.g. traded price for carbon, type of vegetation, and property price). However, the Swedish context differs. Consequently, the B£ST methodology has been used for the comparison of benefits from alternatives and not for a detailed monetary assessment. However, this creates additional uncertainty. A facility of the B£ST tool allows the user to select a level of confidence to take data uncertainties into account. In this study, we used the confidence scores recommended in the Guidelines (BEST 2019) for every benefit category. The inclusion of specific uncertainties in this way is a benefit of the methodology.

The results from the B£ST application were primarily used to compare the different alternatives, which were all based on similar assumptions and/or data. These alternative comparisons should be more robust than e.g. any direct comparison with other studies that use B£ST but are based on non-UK data. Each alternative, however, differs in hydraulic and water quality performances, albeit each fulfils the required aims. No further discussion is given regarding these differences; instead, the relative economic benefits are considered in more detail.

RESULTS

Screening questions and potential impacts identified

Nine impacts were identified as having medium or high potential significance for at least one of the BGI alternatives in the initial screening (summarised in Supplementary Information – Table S2). These potential benefits were then investigated in detail.

The most important impacts (including both medium and high) were found to be associated with improved amenities, educational benefits, flood risk reduction, and increased groundwater recharge. Screening questions show that benefits from improved air quality or carbon reduction and sequestration were only found to be provided by one alternative – EngDec/End, as this utilises trees and shrubs. The two natural, less complex (NatDec and NatDec/End), and engineered (EngDec and EngDec/End) alternatives using decentralised BGI provide the greatest number of potential benefits for the local population, while EngEnd provides only three potential impacts, the fewest.

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Detailed assessment of identified impact categories

In this section, results are presented focusing on: (i) the present value after confidence applied for each alternative, which brings the greatest value; (ii) the number of benefits – which alternatives provide the most benefits; (iii) the proportion of benefits – which benefits contribute most to the total present value; and (iv) a comparison of the present value of various types of benefits – which types of benefits bring the greatest value.

As described in the 'Method' section, the main focus is on comparing benefit categories and relative impacts. The calculated present values for all developed alternatives (normalised values) are shown in Figure 2, illustrating which alternatives produce the greatest value.

Figure 2 shows that the present value varies by an order of magnitude; the lowest is for EngEnd (1.37 standard deviations below the mean) and the highest for NatDec/End (0.9 standard deviations above the mean). This variation depends mostly on the type of BGI: the highest value is associated with (green) dry detention, bioretention/rain gardens, and the Stockholm System tree planters. This is because B£ST presumes green environments benefit people's well-being and activity levels (Horton *et al.* 2019).

Overall, it is possible to categorise the seven alternatives into three groups based on the normalised scores:

- Group 1: NatDec, NatDec/End, and EngDec/End provide the greatest value (>0.5 standard deviations above the mean);
- Group 2: EngDec and Nat-InfDec provide an average value (between 0.5 standard deviations above the mean and 0.5 standard deviations below the mean);
- Group 3: NatEnd and EngEnd provide the lowest value (>0.5 standard deviations below the mean).

Group 1 – NatDec, NatDec/End, and EngDec/End alternatives provide the most and greatest benefits (in terms of the total present value – 0.7–0.9 standard deviations above the mean). It is apparent that Group 3 (NatEnd and EngEnd) options will not provide significant social benefits because they have a very low total present value (around 1.4 standard deviations below the mean). This may be because the infrastructure is aquatic (e.g. floating sedimentation/curtain) or underground (sub-surface detention facility), invisible to local people. These do not provide the benefits associated with surface-based or green areas, in a similar way to buried piped systems.

In addition to the total value, the number of individual benefits contributing to this is important, especially for future flexibility and resilience (Ashley *et al.* 2018a). Table 4 shows the distribution of benefits contributing to the value of each alternative.

The range of benefit categories can show how diverse the benefits provided by each alternative are. The alternatives comprising decentralised BGI provide a wider range of economic benefits (6–7 types), while the end-of-pipe alternatives provide comparatively few benefits (only 2–3 types). The infiltration alternative Nat-InfDec also provides a considerable range of benefits (5 types). The more natural alternatives (NatDec and NatDec/End) provide value in three categories (health, amenity, and flooding); i.e. these provide a more multifunctional value than EngDec, EngDec/End, and InfDec, which provide value in just two categories (health and amenity).

Amenity is the benefit that provides the greatest value for all alternatives (except EngEnd). NatDec and NatDec/End are alternatives with a relatively high present value (Figure 2), for which amenity accounts for more than 40% of the total. While for EngDec/End, which has a comparable present value, amenity benefits are around 80% of the overall total, i.e. twice as much. This is primarily due to EngDec/End having greater

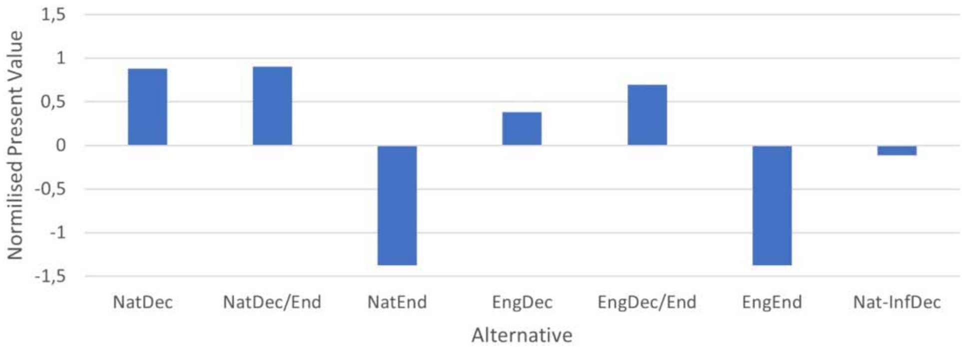

Figure 2 | Present value after confidence applied: normalised results of the detailed assessment using B£ST.

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Table 4 | Distribution of the individual benefits for alternatives (proportion of total benefits for option, %)

	Present value after confidence applied (%)						
Benefit category	**NatDec**	**NatDec/End**	**NatEnd**	**EngDec**	**EngDec/End**	**EngEnd**	**Nat-InfDec**
Air quality	0	0	0	0	0.05	0	0
Amenity	41.27	40.99	18.74	80.27	83.08	0	73.05
Biodiversity and ecology	0.01	0.01	0	0.01	0.01	0	0
Carbon reduction and sequestration	0	0	0	0	0.02	0	0
Education	0.34	0.34	41.08	0.59	0.47	18.52	0.54
Flooding	36.04	35.50	0	0	0	0	0
Health	22.19	22.08	0	18.98	16.26	0	26.30
Water quality	0.08	0.67	40.18	0.10	0	81.48	0
Water quantity	0.07	0.41	0	0.05	0.11	0	0.11
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

visual attractiveness. The benefits of NatDec and NatDec/End are similar, with some 40% for amenity, 35% for flooding, and 22% for health, suggesting that these alternatives would be attractive to local people, the economy, and healthcare stakeholders. Water quality benefits represent 81% of the total for EngEnd, due to the underground location of a precast treatment facility (e.g. Ecovault® or UponorVault®).

Amenity is defined in B£ST as 'attractiveness or desirability of a place'. However, valuation is a function of the number of households or businesses that may potentially benefit. Benefits include improved views as well as neighbourhoods and the dominant financial value for this benefit is often property value increases (e.g. Gensler & ULI 2011). In most published studies assessing the value provided by BGI, property value increase dominates the overall results, raising significant concerns about who pays and who benefits (Ashley *et al*. 2024). In this study, the potential for increases in property prices (typically +3% for business properties) has been ignored as these benefits were deemed too uncertain to include. However, the consequence is that the increase in amenity value due to the various alternatives may be underestimated.

Figure 3 shows the normalised monetary value of all benefit categories. This illustrates that the initial B£ST screening assessment identified the irrelevant benefit categories as most of the alternatives have no or little impact on air quality, biodiversity and ecology, carbon reduction and sequestration, or flooding. This is because of the small extent and limited biodiversity of the BGI alternatives selected. The less-engineered alternatives NatDec and NatDec/End produce numerous social benefits with broadly similar values (from 22 to 41% per

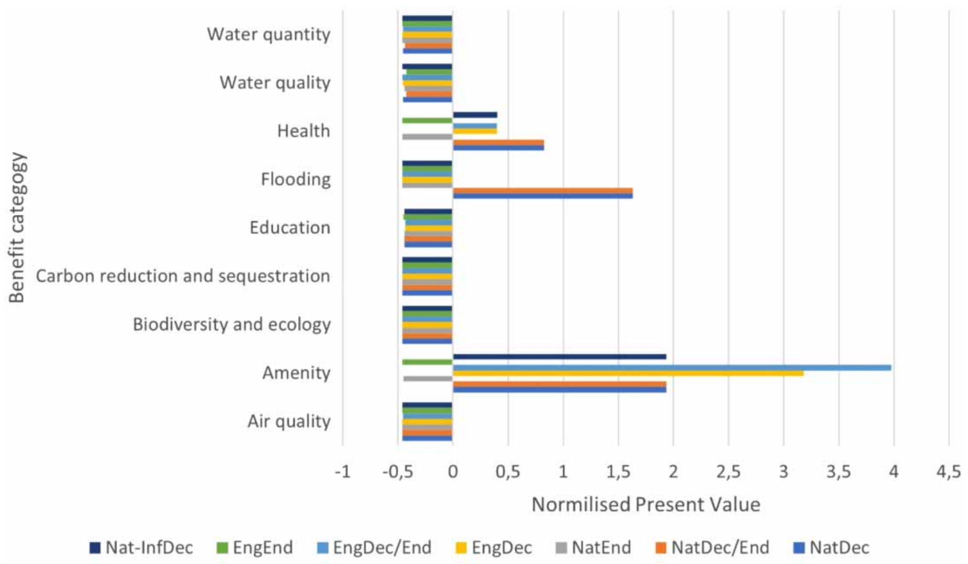

Figure 3 | Results of the detailed assessment by benefit category.

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category – see Table 4). Estimates for flooding benefits are based only on the number of flooded properties. In the Baseline, NatEnd, EngDec, EngDec/End, EngEnd, and Nat-InfDec alternatives, five properties are flooded, while in NatDec and NatDec/End, there are no flooded properties. Thus, only the latter two alternatives provide value by reducing damage, and all other alternatives bring no value in terms of flooding benefits. Although the number of properties potentially affected by flooding is quite small (five), the value for this benefit category is substantial (almost 36% of the present value – see Table 4).

Overall, the three categories that provide the greatest benefits for the alternatives are amenity (the highest is for EngDec/End – around 4 standard deviations above the mean), health (the highest is for NatDec and NatDec/End – 0.8 standard deviations above the mean), and flooding (but for NatDec and NatDec/End only – 1.6 standard deviations above the mean), while few benefits accrue due to improvements in air quality, biodiversity and ecology, and carbon reduction and sequestration. Education benefits are significant for all seven alternatives (Figure 3) and are almost identical (around 4.4 standard deviations below the mean), apart from EngEnd (4.6 standard deviations below the mean), due to the nature of the BGI facilities used. Water quality and water quantity benefits are greater than biodiversity, carbon reduction and sequestration, and air quality benefits for NatDec, NatDec/End, EngDec, and Nat-InfDec.

Ecosystem services

Each benefit can be classified in terms of ecosystem services (i.e. services provided by nature to humans). Figure 4 shows the results in terms of ecosystem service provision. In this study, significant cultural ecosystem services (amenity, education, and health) are provided by five alternatives (the highest value is for EngDec/End – 1.8 standard deviations above the mean), and two alternatives (NatDec and NatDec/End) also provide regulating ecosystem services (air quality, carbon reduction and sequestration, flooding, water quality) at 0.3 standard deviations below the mean. For NatEnd and EngEnd alternatives, the benefits comprising all four types of ecosystem services are around 0.6 standard deviations below the mean. Provisioning (water quantity) and supporting (biodiversity and ecology) ecosystem services are low for all seven alternatives.

Comparison of alternatives

B£ST was developed for UK conditions; hence, it has been used here only for the comparison of BGI alternatives and not to assess monetary value, as in an earlier Swedish study (Hamann *et al.* 2020).

A comparison of the relative benefits of using the various BGI options (Figure 3 and Table 4) can help to identify which one provides the most value. Group 1 has the three alternatives that provide the greatest value: NatDec, NatDec/End, and EngDec/End; moreover, each provides seven social benefits. Overall, the three alternatives bring broadly similar benefits, but from different benefit categories: for the NatDec and NatDec/End alternatives, the greatest value is from amenity enhancements (40–41%); flooding (36%); and health (22%). For EngDec/End, the main benefits are from amenity (83%) and health (16%) enhancements. Overall, the most valuable benefit category for all three alternatives is amenity. Thus, should only Group 1 alternatives or alternatives having many types of benefits be considered for application as amenity is the most important benefit category? What does this mean for decision-making processes?

The primary objectives of any scheme using GI to manage urban water quantity and quality need to be clearly defined (Ashley *et al.* 2023). However, urban planning processes should take the differences in the objectives of the various stakeholders into account.

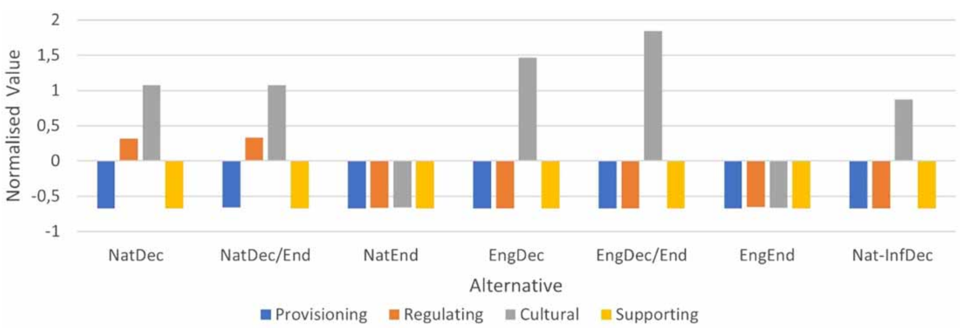

Figure 4 | Ecosystem service summary.

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Table 1 shows the four stakeholder groups identified as having the most significance in this study area, each having particular priorities regarding the importance of the types of benefits provided by BGI. (i) For *the local population*, the visibility and access to green areas are the most significant factors in valuing BGI. New facilities make the area more attractive, and people enjoy having green views from their windows and plants near their homes, which may also encourage them to spend more free time outside. In most studies, it is the increase in property value that dominates the benefits in the amenity category. Amenity benefit is also reflected in other categories such as health, although there is a danger of double counting of benefit value across amenity and these other categories. The local population would be expected to find NatDec and NatDec/End the most preferable in terms of these values. (ii) For *water departments (e.g. municipalities)*, water quality in the receiving water body is the priority, which explains why they are interested in types of BGI that are invisible (e.g. floating sedimentation and a precast treatment facility, Ecovault® or UponorVault®, located underground) but effective for water treatment (NatEnd and EngEnd). If the finance provider is a bank, then issues related to compliance with internal policy are usually the priority. (iii) *Healthcare bodies* are interested in better population health and reduced demand for their services, so they may be more interested in natural/simple and visible solutions (NatDec and NatDec/End) that bring the greatest health and welfare benefits. (iv) *Local businesses* are more interested in a more attractive environment and a greater number of clients in the area (e.g. restaurants and cafes) and eliminating flooding (e.g. insurance companies will pay less for damaged properties); hence; NatDec, NatDec/End, EngDec, EngDec/End, and Nat-InfDec are likely to be seen as more valuable.

Comparison with other studies

Because Davidshall is an urbanised area, it comprises many existing buildings and relatively little open space; hence, the area potentially available for retrofitting BGI is limited. This was taken into account in developing the alternatives. Two features of the study are particularly significant: (i) a large number of alternatives are considered – seven; and (ii) the alternatives include several types of BGI, which vary on two scales: naturalness and the spatial scale.

Numerous studies valuing the benefits of BGI have mostly considered flood risk reduction (e.g. Alyaseri *et al.* 2023) or better microclimate (Probst *et al.* 2022). Moreover, the main intention behind BGI implementation is stormwater management (quality treatment and flood protection). By contrast, the present study is focused on social benefits, both direct (e.g. health and education) and indirect (e.g. amenity, carbon reduction, and sequestration). The results confirm the importance of flood mitigation; in addition, they align with a previous study in Sweden (Hamann *et al.* 2020) in identifying that health and amenity are the most significant benefits of BGI implementation in urban areas. Moreover, amenity benefits provide the highest present value because of an aesthetic landscape and opportunities to spend free time outside in more attractive environments. This is aligned with the previous studies where amenity also has a high value because a greener environment makes an area more attractive, and property values increase as a consequence (Ashley *et al.* 2023). In this study, the potential for a higher property value due to BGI implementation has not been included. This omission is potentially important, as demonstrated in numerous previous studies. Moreover, this aspect is a selling point for the local implementation of BGI, as a higher property value is a benefit for the local population who own properties; however, it can be a disadvantage for people who are planning to buy a property, move to the area, start a business, and rent premises, or for potential investors.

DISCUSSION

The results here confirm that consideration of social benefits should be essential during the decision-making process, and city planners should engage with a wide range of stakeholders to reach a consensus as to the preferred BGI to retrofit (Bohman *et al.* 2020; McNabb *et al.* 2024; Sun *et al.* 2024). B£ST results can inform the decision-making process. Albeit, a final decision as to the BGI selected needs to fulfil the primary objectives for the development plan for the area and address any required business plans for the various funders (e.g. BEGIN 2024).

Recommendations and questions for future discussion and research

As a result of this study, some general recommendations can be made as follows.

Before starting any project, it is important to identify the key aims (e.g. flood mitigation and greener environment), and ideally, priority should be given to the alternative that provides the higher value in terms of the specific benefits that are important in meeting those aims. However, the determination of value is currently uncertain. As

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yet, there is no 'universal' valuation tool, unlike, e.g. a hydraulic simulation of urban drainage, with extant tools largely set up for national application.

The selection of the most appropriate valuation tool is currently unclear for studies such as this. Results from the usage of tools outside of their development context need to be considered only in terms of indicative comparisons of options, as in this paper.

The relative capital investment involved in constructing a BGI facility is often the most crucial consideration. In this study, no attempt has been made to include construction or other costs. Ideally, these need to be included in the B£ST analysis in order to determine the NPV; i.e. the relative benefit value compared with the cost. Often the alternative with the highest NPV is selected, although frequently, due to cost considerations, the lowest-cost option is selected irrespective of benefits. A clear demonstration of the added benefits from BGI over and above the 'engineering required performance' is now raising challenging questions as to who pays and who benefits, especially where there are potentially large returns in social benefits from marginal increases in investments (e.g. Ashley *et al*. 2023, 2024). In many categories, B£ST estimates the value based on the visibility of BGI and access to green spaces as being important for the local population and businesses, and it is thus preferable to select BGI facilities that include some visible green elements (endorsed by Gensler & ULI 2011).

It is recommended to carry out a detailed cost–benefit analysis (NPV) before making decisions for cases where the social benefits would be higher using traditional engineered solutions.

In addition to construction and maintenance considerations, it is important to consider operational management and responsibilities. The alternatives considered here include various types of BGI facilities, which should be regularly maintained during the design life of 30 years. The differing efforts required for managing and maintaining each of the different alternatives will affect their long-term effectiveness and viability and ensure the longevity of the projected financial benefits. Usually, for more engineered solutions such as bioretention, greater maintenance activities and, thus, costs are necessary to maintain their function over time (Blecken *et al*. 2015). In contrast, less-engineered facilities such as dry detention basins are more robust, have less risk of failure, and require less maintenance. If maintenance is adequate, these systems are more robust to failure. Thus, although more highly engineered systems such as bioretention often have a larger *potential* for stormwater management compared with simpler measures such as dry detention, achieving and sustaining performance require ongoing organisation, resources, and a wider range of stakeholders. Thus, simpler techniques might be a more reliable solution if maintenance cannot be ensured. Over time, it is more important to consider a *real function* instead of the theoretical *potential functioning*. Both ponds/wetlands and bioretention systems are typically sized to have a filter area of approximately 1.5% of the catchment. The 6.25 ha Davidshall catchment could be provided by one single pond (with an area of approximately 950 m^2), owned, operated, and maintained by a single water utility. In contrast, bioretention is often implemented in smaller, decentralised facilities distributed in the catchment; e.g. this could be 47 facilities, each with an area of 20 m^2. However, these would be distributed throughout the catchment, and sustained responsibilities for their operation and maintenance may be dispersed and difficult to guarantee. Controlling, maintaining, and operating such a large number of smaller BGI sites (as in the Dec-alternatives) will require more organisational efforts to ensure sufficient maintenance compared with a single facility or relatively few end-of-pipe sites. Furthermore, while grey infrastructure will provide the design performance from commissioning, most BGIs, incorporating vegetation, will take time to develop and provide the expected benefits.

Stormwater operators allocate finances for the construction and maintenance of BGI facilities, usually targeting water quality and flood protection. As BGI provides benefits to other stakeholders (local people, business, and health care system), the possibility of devising a means as to how these stakeholders could contribute to financing the construction and maintenance of BGI could be explored. This should be included as part of the decision-making process (Ashley *et al*. 2023).

In addition to the benefit categories considered in the analysis here, there are potentially additional social benefits due to, e.g. economic growth. It is likely that in some alternatives, there will be changes in economic activity in Davidshall. For example, new shops, cafes, or restaurants. Therefore, a more detailed economic impact assessment should be carried out for a better understanding and evaluation of these potential benefits. However, such analyses are likely to be speculative and uncertain, as they require estimates of future business activities. Although such analyses are routinely undertaken for town planning purposes, linking the implementation of BGI to business and economic development is a relatively new field of endeavour and, hence, highly speculative.

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CONCLUSIONS

Increasingly, decision-making about stormwater management is identifying BGI as a preferred option. Here, the UK B£ST tool has been used to estimate the socio-economic value accruing under seven retrofit alternatives for BGI implementation for a 6.25 ha densely urbanised area in Davidshall, Malmö, Sweden. Each alternative was classified using a 'naturalness' scale (the degree of how engineered or natural the BGI alternative is) and a spatial scale, characterised as decentralised and/or end-of-pipe.

The results show that increased amenity, improved public health, and reduced flood risk were the three most valuable benefits for almost all alternatives. However, the distribution of value varied. Amenity value is dominated by changes in liveability for the local population where surface-based BGI is used. Three groups of BGI facilities were defined based on the relative added value provided by the BGI. Group 1 had the highest present value and the greatest number of benefit categories (7 out of 9). This included two less-engineered/natural solutions, such as sub-surface detention, open dry detention (NatDec alternative), and their combination with floating sedimentation (NatDec/End alternative), and also included one engineered alternative EngDec/End, with a rain garden and a stormwater tree pit.

The ecosystem services provided by the BGI showed that cultural ecosystem services categories were the highest for five alternatives; the most for EngDec/End. More regulating services were provided by the NatDec and NatDec/End alternatives. Impacts on provisioning and supporting ecosystem services were negligible.

Decision-making when selecting BGI, especially to retrofit in dense urban areas such as Davidshall, should consider the varying interests of the numerous stakeholders and involve each in the planning process. Here, it has been assumed that local governments responsible for property and road maintenance, insurance companies, local businesses, health care departments, and local people would prefer the less-engineered (more, but not exclusively, surface-based) alternatives. BGI facilities that are not visible to local populations have limited social benefits and might best be constructed alongside other BGI solutions that are more effective in this regard. Water departments responsible for water quality and flood mitigation would likely prefer the EngEnd or NatDec/End alternatives, as these would bring the greatest benefits in these categories. Other factors relating to the complexities and responsibilities for long-term maintenance activities, together with the costs and financing sources, should also be taken into account.

Current valuation tools being used in the BGI schemes are in their infancy, and the results from these need to be seen as highly speculative. These tools utilise a wide range of data sources, spanning natural, social, and economic systems, many areas of which are poorly understood. For example, further studies are needed to better understand the long-term functioning of the BGI facilities (e.g. who is responsible and how to ensure proper maintenance), accounting for capital investment and maintenance costs (especially taking a long-term perspective), the increase of prices for properties due to BGI, the better attractiveness of areas, the 'growth' time needed for nature-based infrastructure to provide the expected performance, and for a more effective dialogue with stakeholders, especially affected communities.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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