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Blue-green infrastructure for climate adaptation: a socio-economic assessment of decentralised rain-water management measures in the urban environment

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Abstract. This study assesses decentralised blue-green infrastructure measures for urban climate adaptation in Berlin and Cologne using a dual approach that combines multi-criteria analysis and cost–benefit analysis. Twenty sustainable urban drainage system variants, including swales, trenches, tree pits, green roofs, and cisterns, are evaluated with respect to economic, social, environmental, and hydrological performance. Results show that vegetated measures, particularly swales and tree-based systems, achieve the highest overall scores and positive net-benefit values, while predominantly underground systems perform less well. The integrated assessment highlights important co-benefits and trade-offs of blue-green infrastructure and provides decision support for prioritising nature-based solutions in urban rainwater management.

1 Introduction

Extreme weather events such as flooding and heatwaves are expected to intensify as a result of climate change (Seneviratne et al., 2021). The urban heat island effect and prolonged periods of heat exacerbate droughts and impose stress on both urban ecosystems and humans. In Germany, an average of approximately 3,000 heat-related deaths per year was recorded between 2020 and 2025, subject to annual fluctuation (Robert Koch Institute, 2025). On the other hand, urban areas are also particularly vulnerable to extreme rainfall events. They face significant challenges in rainwater management due to extensive surface sealing and overloaded sewer systems that are no longer capable of coping with extreme rainfall events (Liu & Zhang, 2025). This can result in pluvial flooding, leading to substantial damages to infrastructure and considerable economic losses resulting from the high concentration of tangible assets in urban areas. Traditionally, these issues have been addressed through conventional, centralised grey infrastructure solutions that collect and channel stormwater outside of cities to treatment facilities (Fletcher et al., 2015; Neumann et al., 2024). However, *decentralised* rainwater management systems like blue-green infrastructure (BGI), also called sustainable urban drainage systems (SUDS), offer an alternative approach that provide a range of additional socio-economic and environmental benefits. Multiple studies and projects have explored these benefits, e.g. through conducting a multi-criteria analysis (MCA). An MCA is a methodology designed to solve complex decision-making problems that require multiple aims and criteria that need to be taken into account. It enables the systematic evaluation and

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comparison of different options or measures based on these criteria. The objective is to determine the alternative, or order of alternatives, that that are most suitable to reach specified objectives. One advantage of an MCA is that it can combine quantitative and qualitative assessments and thereby integrate factors measured in different units (Geneletti, 2019).

Several studies employ multi-criteria approaches to assess different aspects of SUDS or wider sets of adaptation measures. In 2004 Ellis et al. developed an MCA framework to support the selection of SUDS for the treatment of urban and highway runoff, integrating technical, environmental, social, and economic sustainability criteria and applying the method to a French case study. Kimic and Ostrysz (2021) conducted an MCA for 19 BGI solutions, using a scoring method, to assess and rank their potential value across spatial/functional, environmental, and social aspects in urban spaces. Garcia et al. (2023) assess different conventional and sustainable urban drainage systems in the city of Bauru (Brazil), focusing on technical-environmental criteria but not including social or implementation related aspects. For New York City, Axelsson et al. (2021) also apply a multi-criteria approach, focusing on broad policy choices rather than specific infrastructure elements and stakeholder preferences for different strategies like public vs. private green infrastructure or a grey infrastructure renewal. Ruangpan et al. (2021) apply a multi-criteria framework in the planning of large-scale Nature-Based Solution (NBS) in river basins in Taiwan and Serbia, yet their focus is not on small-scale urban BGI. With a specific focus on urban adaptation, Wójcik-Madej et al. (2025) apply a multi-criteria evaluation to identify the most suitable NBS types, using Lublin (Poland) as a case study and assessing social, political, economic, spatial, and long-term criteria. Similarly, De Bruin et al. (2009) identify, inventories, and rank 96 climate change adaptation options for the Netherlands using an MCA to prioritise alternatives based on criteria like importance, urgency, no-regret characteristics and co-benefits.

As this literature illustrates, an MCA provides a suitable framework to evaluate different BGI measures that pursue various objectives or exhibit distinct implementation characteristics. Within the German context however, there are few studies conducting an MCA with a focus on BGI for adaptation to pluvial flooding and drought. Additionally, municipal investment decisions are often guided by economic efficiency and cost considerations as many German municipalities are under increasing financial pressure (Brand & Salzgeber, 2024). Yet the various additional benefits BGI solutions provide, like health or wellbeing gains for residents through cleaner air and greener and cooler urban environments, are not accounted for in investment decision.

To capture such benefits in economic evaluations of municipal projects a CBA can be undertaken. In a CBA, the costs and benefits of the SUDS, including external benefits, are quantified and expressed in monetary terms, allowing comparison with a baseline scenario and in between measures. By also monetising social and ecological benefits accruing to communities and ecosystems, the analysis provides a common value scale for directly comparing costs and benefits (Bonner, 2022; OECD, 2018).

Several studies employ CBAs to assess the economic efficiency and co-benefits of BGI and related adaptation measures. Berglund (2018) applies a CBA framework in Gothenburg to monetarily compare BGI alternatives with conventional stormwater systems and Wilbers et al. (2022) conduct a CBA to determine economically efficient BGI for green and grey infrastructure for flood protection in Oslo. Looking at green roofs, Macháček et al. (2016) assess private and social returns

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from green roof implementation in Prague, and Carter and Keeler analyse (2008) the life-cycle costs and benefits of green roofs in Athens (Georgia, U.S.). In the German context, Dehnhardt et al. (2020) and Welling et al. (2020) apply a CBA to monetise ecological and societal benefits of urban greening in Bremen. Collectively, these studies demonstrate that CBAs provide an effective framework to monetise and compare the diverse costs and benefits of BGI, though their application and scope vary substantially across spatial scales and benefit categories. While they provide insights into the evaluation of BGI, they largely focus on conventional SUDS measures. However, limited research has a focus on German geographies and addresses more innovative system configurations and SUDS that especially address the retention of extreme rainfall events drought periods. Against this background, the study poses the research question: Which SUDS should be prioritised for implementation in urban areas based on their performance across multiple evaluation criteria and their net-benefit value?

2 Methodology

The following sections outline the measures, methodologies and analytical steps applied.

2.1 Selection of measures

This study examines advanced SUDS variants that integrate adaptation to pluvial flooding and drought prevention including swales, infiltration trenches, swale-trench elements, tree pits, tree trenches, extensive, intensive, and retention roofs, (smart) cisterns, and combinations thereof. For each SUDS type, three design variants were evaluated: a conventional version (SUDS) dimensioned to fully retain rainfall events with a return period of 5 years (T = 5 a), an enhanced version optimised for extreme rainfall (SUDS+, dimensioned for a return period of 100 years, T = 100 a), and a water storage-and use version (SUDS-U) that enables irrigation during prolonged droughts so as to provide irrigation for defined green spaces such that potable water replenishment of cisterns is required only once in ten years. For an overview of the analysed SUDS see Fig. 1 and Table 1.

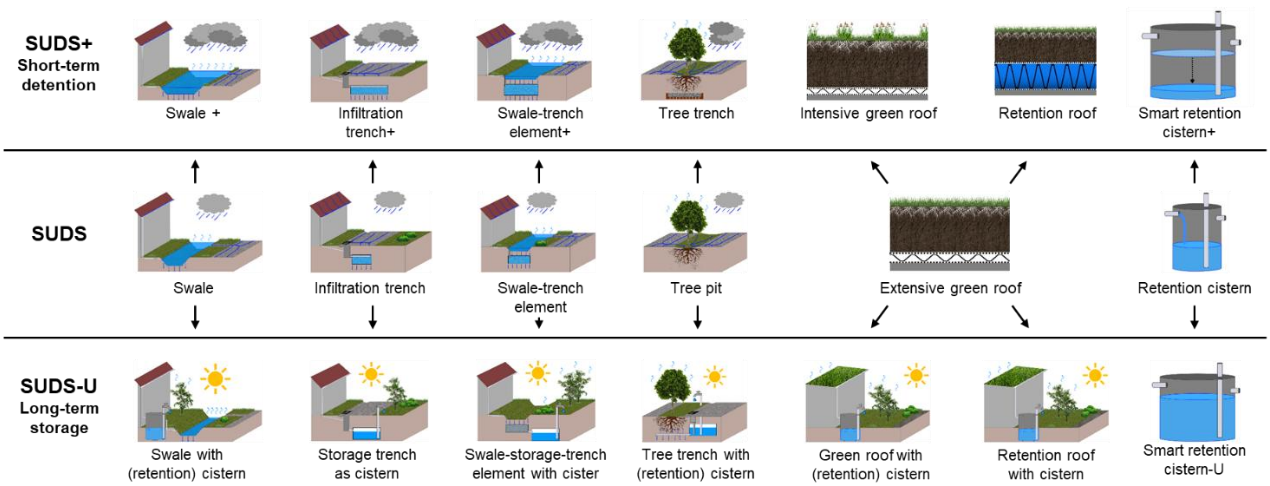

Figure 1: Overview of analysed SUDS (adapted from Dittmer, 2025 © licensed via BY-NC-SA 4.0)

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85 To evaluate their implementation characteristics and various additional benefits in a comprehensive manner, this study applies a dual-method approach combining an MCA and a CBA across two urban case study areas. Through this approach, the study aims to identify which measures should be prioritised for implementation based on their performance across a wide range of criteria, including co-benefits, and their net-benefit value.

Table 1: Description of analysed SUDS

System type	Description
SUDS Swale	Pre-dimensioning according to the German DWA guideline DWA-A 138-1 for infiltration systems. Storage depth of the swale: 0.3 m. Dimensioned for T = 5 a.
SUDS+ Swale	Same as above. Dimensioned for T = 100 a.
SUDS-U Swale with (retention) cistern	Same as above, with retention cistern. Dimensioned for T = 5 a.
SUDS Infiltration trench	Pre-dimensioning according to the German DWA guideline DWA-A 138-1 for infiltration systems. Height of the infiltration trench: 0.6 m. Dimensioned for T = 5 a.
SUDS+ Infiltration trench	Same as above. Dimensioned for T = 100 a.
SUDS-U Storage trench as cistern	Same as above, with storage trench as cistern. Dimensioned for T = 5 a.
SUDS Swale-trench element	Pre-dimensioning according to the German DWA guideline DWA-A 138-1 for infiltration systems. Storage depth of the swale: 0.3 m; height of the infiltration trench: 0.331 m (T = 5 a).
SUDS+ Swale-trench element	Same as above, with height of the infiltration trench: 0.523 m (T = 100 a).
SUDS-U Swale-storage-trench element with cistern	Same as above, with swale-storage-trench element as cistern. Dimensioned for T = 5 a.
SUDS Tree pit	Thickness of the tree substrate layer: 1.5 m. Volume of the planting pit: 13.5 m³, area of the tree grid: 6 m², shaped as a swale with a depth of 5 cm
SUDS+ Tree trench	Tree substrate layer: 1.5 m, infiltration trench (height: 0.6 m) underneath. Volume planting pit: 18.9 m³, area of the tree grid: 6 m², shaped as a swale, depth 20 cm
SUDS-U Tree pit with (retention) cistern	Same as tree pit above, with retention cistern
SUDS Extensive green roof	Multilayer construction, thickness of the substrate layer: 0.15 m.
SUDS+ Intensive green roof	Multilayer construction, thickness of the substrate layer: 0.3 m.
SUDS+ Retention roof	Multilayer construction, thickness of the substrate layer: 0.15 m, thickness of the retention layer: 0.1 m.
SUDS-U Green roof with (retention) cistern	Same as extensive green roof above, with retention cistern.
SUDS-U Retention roof with cistern	Same as retention roof above, with cistern.
SUDS Cistern	Conventional storage cistern for retention and reuse.
SUDS+ Smart retention cistern	Storage cistern with a capacity corresponding to T = 5 a. Smartly controlled based on forecast input data, enabling targeted emptying before heavy rainfall events to ensure that retention volume is available.
SUDS-U Smart retention cistern	Same as above (T = 5 a). Irrigation control based on forecast input data; targeted emptying before heavy rainfall events only to the extent strictly necessary.

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2.2 Multi-criteria analysis

In this study a five-step procedure was followed to assess the BGI solutions in focus (see Figure 2). To identify relevant categories and indicators for the MCA in a first step, a literature review of around 50 papers and reports focusing on MCAs in the context of adaptation measures, BGI and decentral rainwater management solutions was conducted. From this research, 14 sets of criteria were selected for in-depth analysis. A total of more than 175 individual criteria were derived from these criteria. The collection of individual criteria was then clustered into six categories: (1) economic criteria, (2) social criteria, (3) implementation criteria, (4) water-related criteria, (5) other environmental criteria and (6) synergies. Initially, a total of 24 criteria were selected based on their relevance to the assessment of the BGI measures in focus and on whether they account for connection to the local level, a clear operationalisation approach and a focus on urban BGI.

The next step was to operationalise the criteria. To this end, definitions were established for each criterion, largely based on definitions identified in previous research and one or more operationalisable indicators per criteria were developed. For each indicator a qualitative assessment scale, e.g. “low”, “medium”, “high”, was defined and an according quantitative score assigned to each rating, e.g. “low (1)”, “medium (2)”, “high (3)”. Following the operationalisation of the criteria, a first assessment of each criterion and its indicators was conducted deploying literature analysis, including empirical data modelling results from literature, supplemented by assessments and validations through expert feedback.

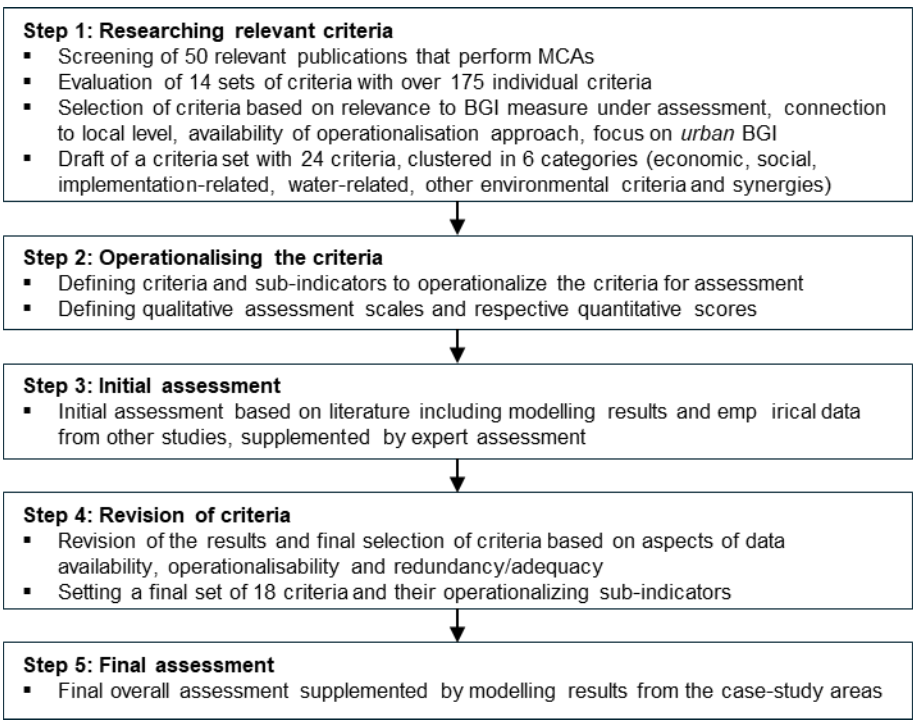

Figure 2: Analysis procedure of the MCA

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After the initial assessment, the set of criteria was revised. Criteria that proved to be redundant or inadequate in terms of data availability and operationalisability were removed. In a second assessment round, the assessment was adapted to the case study areas and the modelling results from the case studies were incorporated (Neumann et al., 2024; Rott & Schorsy, 2026). The quantitative data, particularly for water-related criteria, were normalised to one to 10 scale. Likewise, the indicator results were normalised to the same scale to enable aggregation of multiple sub-indicators for criteria with more than one indicator. Hence, the final set comprises 18 criteria and their respective sub-indicators (see Table 2). Each is associated either with a qualitative rating scale, translated into a quantitative score and normalised to a one to 10 scale, or with a quantitative modelling input that was likewise normalised to the same scale. In the final step, the results for the 18 criteria for each measure were synthesised into an overall score for each measure, enabling the ranking of BGI measures against the identified criteria. No criterion weighting was used in this assessment; each criterion made an equal contribution to the overall score.

Table 2: MCA assessment criteria, sub-indicators and assessment scales

Category	Criteria	Sub-indicators	Scale	Description
Economic criteria	Costs	Investment costs	very high (1) - very low (9)	The expenditures required to construct the measure and the annual costs for operation and maintenance (per connected surface area)
		Operation and maintenance costs	very low (1) - very high (9)	
	Innovation potential	Use of new technologies, innovative measures	low (1), medium (2), high (3)	The potential of the measure to use and promote new technologies or design approaches
Social criteria	Urban climate	Shading	none (1), low (2), medium (3), high (4)	The potential of the measure to improve the urban microclimate by cooling air temperatures through evaporation and increasing thermal comfort through shading, with positive effects on health and well-being
		Evaporation	none (1), low (2), medium (3), high (4)	
	Recreation	Recreational effect	low (1), medium (2), high (3)	The potential of the measure to enhance well-being and recreation by greening the surroundings and creating an aesthetically appealing streetscape
	Acceptance	Degree of intervention	high (1), medium (2), low (3)	The degree to which the measure requires interventions in existing infrastructure (e.g. extensive or deep construction work), provides directly perceivable relevance and visibility for residents, and generates positive or negative side effects for the public
		Perceived relevance	low (1), medium (2), high (3)	
		Externalities	negative (1), balanced /none (2), positive (3)	
	Space requirement	Surface area	modelling data on dimensions	The degree to which the measure occupies space otherwise used for other urban functions (e.g. parking, road space, courtyards), potentially leading to spatial competition
Implementation criteria	Ease of implementation	Technical feasibility	difficult (1) - simple (5)	The degree to which the measure is technically proven, established, and easy to implement

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		Regulatory, planning and permitting complexity	difficult/complex (1) - unproblematic (2)	The complexity of planning and permitting processes, including the availability of established legal procedures and technical standards
	Flexibility	Adaptive flexibility	low (1), medium (2), high (3)	The potential of the measure to be modified at low cost and thus flexibly adapted to different climate futures
Water related criteria	Flood mitigation potential	Overflow	modelling data on overflow	The potential of the measure to reduce flooding, as indicated by its overflow
	Water pollution control	Combined sewer overflow reduction (=overflow)	modelling data on overflow	The potential of the measure to protect waterbodies by reducing combined sewer overflows (surface water, indicator = overflow) and filtering suspended solids (groundwater)
		Filtering of suspended solids	low (1), low-medium (2), medium-high (3), high (4)	
	Water storage	Use-volume	modelling data on use-volume	The potential of the measure to store water for irrigation or reuse purposes
	Infiltration	Infiltration share	modelling data on infiltration	The potential of the measure to infiltrate water (compared to runoff and evaporation share)
	Evaporation	Evaporation share	modelling data on evaporation	The potential of the measure to evaporation water (compared to runoff and infiltration share)
Other environmental criteria	Noise reduction	Noise reduction	none (1), low (2)	The potential of the measure to reduce noise in the surrounding area
	Biodiversity and habitat diversity	Number of vegetation layers	one layer (1), two layers (2), three layers (3), more than three layers (4)	The potential of the measure to increase habitat diversity and promote biodiversity in the urban streetscape
	Elimination of air pollution	Filtering of particulate matter	none (1), low (1), medium (2), high (3)	The potential of the measure to remove or filter air pollutants and fine particulate matter, thereby improving air quality
	Climate impact	Greenhouse gas emissions during construction	data from CO_2 accounting	The degree of greenhouse gas emissions associated with the construction of the measure, including the production and installation of materials and systems
Synergies	Synergies extreme rainfall/drought	Overflow	modelling data on overflow	The potential of the measure to retain stormwater during heavy rainfall events, slow discharge to the sewer system as well as store water for irrigation during dry periods (combined effect of overflow prevention and water storage)
		Use-volume	modelling data on use-volume	

2.3 Cost-benefit analysis

The CBA consisted of following six steps (see Figure 3). For the CBA, first, a literature scoping of existing CBAs was conducted to identify studies assessing similar BGI measures and to examine which cost and benefit components were evaluated and through which methodologies they were monetised. Based on this, a structured overview was developed indicating the benefits for each BGI type. Subsequently, nine benefit components and two cost components were then

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combined to create a matrix that shows which benefits are applicable for each measures. For each benefit and cost component, based on the literature review, appropriate monetisation methods were selected, and the required data inputs and sources were identified. The benefit matrix was adjusted to prevent double counting and reflect data availability during the first evaluation and data gathering phase. In Addition, expert consultations were conducted to validate the plausibility of assumed benefits. The final list of monetised components consists of seven benefit and two cost components. Furthermore, the selected monetisation methods were reviewed and if necessary adjusted based on data availability. See Table 3 for an overview of all benefit and cost components and the applied monetisation methods. In a last step, functions were developed and the calculation of the benefits and cost components in monetary terms was carried out.

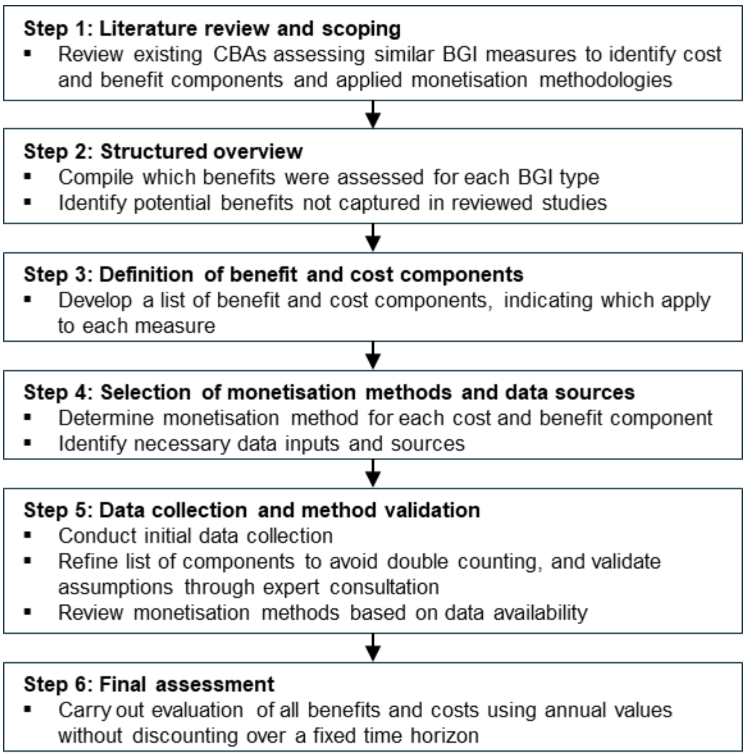

Figure 3: Analysis procedure of the CBA

The analysis was performed using annual values. To convert the investment costs into annual values, assumptions regarding the service life of the measures were applied in accordance with DWA-A 133 (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall, 2021; Neidhart et al., 2023). Only the benefit component of flood protection was not calculated on an annual basis but rather for one rainfall event with a return period of 100 years. Hence these values are presented separately and not included in the calculation of the total annual benefit.

When the benefit transfer method was applied, values were adjusted for inflation to 2024 values. For most components, a range of monetised values (minimum, median, and maximum) was calculated to reflect different scenarios and to consider uncertainties in the assessment. Note that while for all components the minimum, median, and maximum were based on varying

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input data, for the calculation of construction related emissions the difference values are based on applying two different monetisation methods. Note that the robustness of the results is addressed in Section 3.3, an overview of the level of uncertainty of the results of each component is given in Table 3.

Table 3: CBA components, monetisation methods and calculation inputs

Benefit and cost components	Monetisation method	Inputs		Level of uncertainty
Flood protection	Damage costs	Building and infrastructure damage cost (calculated based on GDV, 2023; Nicklin et al., 2019)	Inundated areas (> 4,9 cm inundation) (case study modelling results from Neumann et al., 2024)	High
Water storage and irrigation use	Alternative costs	Costs of drinking water	Water storage volume (case study modelling results from Rott & Schorsy, 2026)	Low-medium
Rainwater infiltration	Alternative costs	Costs of grey sewage water treatment (Berliner Wasserbetriebe, 2024; Stadtentwässerungsbetriebe Köln, 2023)	Infiltration volume (case study modelling results from Rott & Schorsy, 2026)	Low-medium
Indoor temperature regulation	Alternative costs	Estimated energy costs for cooling (for summer days)	Energy saving potential through SUDS (Bevilacqua, 2021; Han et al., 2025; M A Rahman & Ennos, 2016)	High
Air quality regulation	Damage costs	Health damage costs (Matthey et al., 2024)	Amount of filtered particulate matter (Center for Neighborhood Technology & American Rivers, 2010; Gorbachevskaya & Herfort, 2012; Speak et al., 2012; Yang et al., 2008) and spatial extent of measure (case study modelling results from Rott & Schorsy, 2026)	High
Urban aesthetics, flora and fauna	Benefit transfer	Willingness-to-pay estimates (Dehnhardt et al., 2020; Welling et al., 2020)	Spatial extent of the measures (case study modelling results from Rott & Schorsy, 2026)	High
Investment, operation and maintenance costs	Market-prices	Market prices for SUDS (Neidhart et al., 2023)	Spatial extent of the measures (case study modelling results from Rott & Schorsy, 2026)	Medium
Construction-related emissions	Market-prices (min. scenario) – Damage costs (max. scenario)	Market price of carbon emission certificates (ICAP, 2025) – Health, agriculture, sea level rise and building energy consumption related damage costs (Matthey et al., 2024)	Spatial extent of the measures (case study modelling results from Rott & Schorsy, 2026)	High

2.4 Case studies

The MCA and CBA in this study are conducted for two pilot areas in Berlin (in Kreuzberg; 340 ha) and Cologne (Cologne-Kalk; 296 ha). Hydrological modelling was performed for these case study areas to evaluate the effects of implementing the

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SUDS, SUDS+, and SUDS-U measures on the water balance (details see Neumann et al., 2024; Rott & Schorsy, 2026). This study incorporates modelling results of the water balance and pluvial flooding, as well as the dimensioning of the SUDS for the two pilot areas ((Neumann et al., 2024; Rott & Schorsy, 2026). The water balance modelling was carried out for a 2,500 m² roof area connected to each SUDS type. For the MCA, a joint scoring for the pilot areas in Berlin and Cologne was conducted, using averaged values for the two pilot areas where modelling data specific to each pilot area was included. The CBA was conducted separately for each pilot area. Especially for the CBA, it is important to note that the impacts of measures were modelled using the different dimensioning standards for SUDS, SUDS+ and SUDS-U measures (see Sect. 2.1). The hydrological modelling was set up in a way that spatial constraints were not considered, and the number of elements was determined based on the volume required to retain all roof runoff. Additionally, assumptions on building infrastructure were made according to the characteristics of the analysed pilot areas. It is relevant to note that benefit values for flood protection were only calculated for the Berlin pilot area as hydraulic flood modelling results were only available for this area.

3 Results

3.1 Multi-criteria analysis

Table 4 provides an overview of the scoring results. Under the premise of equal weighting, infiltration trenches show the lowest overall scores, followed by standalone cisterns. This is due to the fact that both are underground measures that do not include any green elements. In the categories selected for this multi-criteria analysis, particularly the environmental and social criteria, measures with green elements achieve significantly higher scores as they offer additional benefits in these areas. In addition, underground measures also perform poorly in the implementation-related criteria, as their implementation often requires more invasive construction work. Retrofitting or adapting them in existing infrastructures is also more difficult.

Swale-trench elements and tree pits without cisterns receive a medium overall score. Their ratings vary across individual criteria: measures with trees, for example, achieve high scores in the environmental criteria, while especially the SUDS and SUDS+ versions perform relatively poorly in the water-related criteria. For the swale-trench elements, weaknesses lie primarily in the social and implementation-related criteria as well as in the economic evaluations.

The highest scores are achieved by swales and green roofs. Both measures offer diverse additional benefits through their green elements and, compared to the SUDS with trees, they perform better in the water-related criteria. Swales are particularly convincing due to their ease of implementation and low costs, in addition they achieve consistently medium to high ratings in all other categories. Green roofs also obtain consistent medium to high scores, while not standing out in particular categories. The highest overall scores are achieved by the SUDS-U Swale with retention cistern and the SUDS-U Tree pit with retention cistern. Both variants achieve at least medium, but mostly high, ratings across all categories. Generally, SUDS-U variants score higher than their SUDS and SUDS+ counterparts; this is consistent across the MCA except for the SUDS-U Cistern. This can be attributed, in part, to their high scores in the category of innovation potential and water storage and the associated

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180 synergy effects causing good performance under rainwater evaporation, urban climate, and recreation. This is due to the fact that indirect irrigation effects are taken into account in the evaluation, with positive effects on these criteria.

Table 4: Normalised MCA scores

	Costs	Innovation potential	Urban climate	Recreation	Acceptance	Space requirement	Ease of imple-mentation	Flexibility	Flood mitigation potential
SUDS Swale	10	1	2	1	6	7	10	10	8
SUDS+ Swale	8	6	2	1	5	4	9	10	9
SUDS-U Swale with (retention) cistern	3	10	7	6	5	6	8	10	6
SUDS Infiltration trench	7	1	1	1	3	9	3	1	8
SUDS+ Infiltration trench	6	6	1	1	3	8	2	1	9
SUDS-U Storage trench as cistern	3	10	6	6	1	7	1	1	1
SUDS Swale-trench element	5	1	1	1	5	8	8	1	8
SUDS+ Swale-trench element	4	6	2	1	3	6	7	1	10
SUDS-U Swale-storage-trench element with cistern	2	10	6	6	3	6	6	1	6
SUDS Tree pit	6	1	6	6	10	1	10	1	6
SUDS+ Tree trench	3	6	6	6	8	3	8	1	6
SUDS-U Tree trench with (retention) cistern	2	10	10	10	6	8	7	1	6
SUDS Extensive green roof	9	1	3	1	8	10	8	6	8
SUDS+ Intensive green roof	4	1	6	10	8	10	7	6	10
SUDS+ Retention roof	7	6	4	1	8	10	7	6	10
SUDS-U Green roof with (retention) cistern	3	10	8	6	6	8	7	6	5
SUDS-U Retention roof with cistern	2	10	9	6	6	6	7	6	6
SUDS Cistern	3	1	6	6	3	9	10	1	2
SUDS+ Smart retention cistern	1	10	6	6	1	8	6	1	8
SUDS-U Smart retention cistern	1	10	8	6	1	9	6	1	2

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Table 4: ***Cont.***

	Water pollution controle	**Water storage**	**Infiltration**	**Evapo-ration**	**Noise reduction**	**Biodiversity and habitat diversity**	**Elimination of air pollution**	**Climate impact**	**Synergies extreme rainfall / drought**	**Sum (max 180)**
SUDS Swale	9	1	9	2	10	7	6	10	1	**110**
SUDS+ Swale	9	1	9	2	10	7	6	10	1	**108**
SUDS-U Swale with (retention) cistern	7	9	9	7	10	10	6	9	8	**128**
SUDS Infiltration trench	6	1	10	1	1	1	1	10	1	**65**
SUDS+ Infiltration trench	6	1	10	1	1	1	1	9	1	**67**
SUDS-U Storage trench as cistern	1	8	3	6	1	4	6	9	5	**74**
SUDS Swale-trench element	9	1	10	1	10	7	6	10	1	**92**
SUDS+ Swale-trench element	10	1	9	2	10	7	6	10	1	**95**
SUDS-U Swale-storage-trench element with cistern	7	8	3	6	10	10	6	9	8	**105**
SUDS Tree pit	1	1	10	3	10	10	6	10	1	**98**
SUDS+ Tree trench	1	1	10	2	10	10	6	10	1	**97**
SUDS-U Tree pit with (retention) cistern	4	9	10	6	10	10	6	9	8	**124**
SUDS Extensive green roof	9	1	1	4	10	7	10	7	1	**103**
SUDS+ Intensive green roof	10	1	1	6	10	10	10	2	1	**112**
SUDS+ Retention roof	10	1	1	5	10	10	10	4	1	**110**
SUDS-U Green roof with (retention) cistern	7	4	3	9	10	10	10	5	5	**117**
SUDS-U Retention roof with cistern	7	2	3	10	10	10	10	1	4	**111**
SUDS Cistern	2	9	3	6	1	4	6	8	6	**80**
SUDS+ Smart retention cistern	6	10	3	6	1	4	6	8	10	**91**
SUDS-U Smart retention cistern	2	10	3	6	1	4	6	9	7	**85**

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3.2 Cost-benefit analysis

The results of the CBA are documented in Table 5 to Table 8. The following overview illustrates that comparable patterns can be observed for the pilot areas in Cologne and Berlin, while the pilot areas show difference e.g. in soil composition and rainfall patterns, the differences in the monetised values primarily result from variations in the spatial extent of the pilot areas (see Sect. 2.4). Green roofs and measures including trees, particularly in the SUDS and SUDS+ configurations, achieve the highest total benefits. Their values range from approximately EUR 2.5 million/ to just over EUR 24 million per year in the Berlin pilot are and EUR 1.5 million/a to nearly EUR 15 million/a in the cologne pilot area across the minimum and maximum scenarios. The highest benefit contributions are associated with the category urban aesthetics, flora and fauna, whereas SUDS and SUDS+ measures yield no monetised benefits in the categories water storage and irrigation use and rainwater infiltration.

Medium benefit values, ranging from approximately EUR 900,000/a to just over EUR 1 million/a in Berlin and from around EUR 300,000/a to EUR 850,000/a in Cologne (across minimum and maximum scenarios), are observed for the SUDS and SUDS+ configurations of infiltration trenches, swale–trench systems, and infiltration swales. Simpler green elements, such as grassed swales, achieve lower benefits in the categories air quality regulation and urban aesthetics, flora and fauna, and have no effects on indoor temperature regulation.

The lowest benefit values, below approximately EUR 350,000/a in Berlin and EUR 260,000/a in Cologne across the minimum and maximum scenarios, are calculated for the SUDS-U storage trench with cistern, the SUDS-U swale–storage trench with cistern, and the standalone cisterns. Similar to the MCA results, these measures show low benefits across most components as they feature little to no vegetated components. Notably, indirect effects through irrigation of urban green spaces, such as potential improvements in air quality regulation or urban aesthetics, flora and fauna, could not been quantified, as no sufficiently estimates on the physical relationships are documented, although such benefits may plausibly occur.

The total costs consist of investment, operation and maintenance costs, and construction-related GHG emissions. Generally, construction-related emission costs, even in the maximum scenario, make up a significantly smaller share compared to annual investment and operation and maintenance costs. Furthermore, due to their larger scale or combination of components, the SUDS+ and SUDS-U measures are generally more costly than their respective SUDS configurations.

The highest costs occur for intensive green roofs and the SUDS-U retention roof, ranging from approximately EUR 6 million/a in the minimum scenario to EUR 26 million/a in the maximum scenario in Berlin and between EUR 3 million/a to EUR 16 million/a across the minimum and maximum scenario in Cologne. This is due to the comparatively high investment costs associated with these measures and, in the case of the intensive green roof, additionally to the high maintenance costs for intensively vegetated roofs.

In the medium cost range are smart cisterns, measures with trees, the SUDS-U Swale with a retention cistern, the SUDS-U Swale-storage-trench element with cistern as well as the SUDS+ Retention roof and the SUDS-U Green roof with a retention cistern. In Berlin costs for these measures range between approximately EUR 1.2 million/a and EUR 3.3 million/a in the minimum scenario and EUR 4 – 14 million/a in the maximum scenario and in Cologne values across the minimum and

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maximum scenario range between EUR 750.000 – EUR 10 million per year. The lowest total costs are calculated for SUDS and SUDS+ configurations of swales, trenches, and swale-trench systems ranging between EUR 100.000/a – EUR 1,3 million/a across the minimum and maximum scenario in Berlin and between approximately EUR 100.000/a – EUR 1 million/a in Cologne.

When considering the cost-benefit ratio under maximum cost and minimum benefit assumptions, the SUDS tree pit and the SUDS+ tree trench perform best, achieving the highest net-benefit values in both pilot areas. The SUDS and SUDS+ variants of swales and trenches, as well as the combined SUDS swale-trench elements, also perform well, maintaining positive cost-benefit ratios. Under these assumptions, net-negative ratios of varying magnitude are observed for all combined SUDS-U measures with cisterns, for standalone cisterns, and for measures incorporating green roofs. However, when assuming minimum costs and maximum benefits, all measures show positive cost–benefit ratios.

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Table 5: Monetised benefits pilot area Berlin in EUR 1.000

	per event (T = 100)	per year				
	Flood protection	Water storage and irrigation use	Rainwater infiltration	Indoor temperature regulation		
				min	med	max
SUDS Swale	1.843	-	851	-	-	-
SUDS+ Swale	2.977	-	818	-	-	-
SUDS-U Swale with (retention) cistern	-	221	719	-	-	-
SUDS Infiltration trench	1.867	-	902	-	-	-
SUDS+ Infiltration trench	2.839	-	935	-	-	-
SUDS-U Storage trench as cistern	-	221	106	-	-	-
SUDS Swale-trench element	2.143	-	865	-	-	-
SUDS+ Swale-trench element	2.982	-	848	-	-	-
SUDS-U Swale-storage-trench element with cistern	-	221	106	-	-	-
SUDS Tree pit	-	-	833	485	2.564	6.540
SUDS+ Tree trench	-	-	847	485	2.564	6.540
SUDS-U Tree pit with (retention) cistern	-	221	737	485	2.564	6.540
SUDS Extensive green roof	2.788	-	-	65	439	1.308
SUDS+ Intensive green roof	2.978	-	-	97	659	1.962
SUDS+ Retention roof	2.978	-	-	65	439	1.308
SUDS-U Green roof with (retention) cistern	-	221	106	65	439	1.308
SUDS-U Retention roof with cistern	-	221	106	65	439	1.308
SUDS Cistern	860	221	106	-	-	-
SUDS+ Smart retention cistern	2.762	221	106	-	-	-
SUDS-U Smart retention cistern	2.423	221	106	-	-	-

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Table 5: ***Con.***

	per year								
	Air quality regulation			Urban aesthetics, flora and fauna			**Total benefits (without flood protection)**		
	min	med	max	min	med	max	**min**	**med**	**max**
SUDS Swale	7	11	14	96	96	96	**954**	**958**	**961**
SUDS+ Swale	15	23	30	206	206	206	**1.039**	**1.047**	**1.054**
SUDS-U Swale with (retention) cistern	7	11	14	96	96	96	**1.043**	**1.047**	**1.050**
SUDS Infiltration trench	-	-	-	-	-	-	**902**	**902**	**902**
SUDS+ Infiltration trench	-	-	-	-	-	-	**935**	**935**	**935**
SUDS-U Storage trench as cistern	-	-	-	-	-	-	**327**	**327**	**327**
SUDS Swale-trench element	4	6	8	55	55	55	**924**	**926**	**928**
SUDS+ Swale-trench element	10	15	21	140	140	140	**998**	**1.003**	**1.009**
SUDS-U Swale-storage-trench element with cistern	4	6	8	55	55	55	**386**	**388**	**390**
SUDS Tree pit	271	1.076	1.861	10.979	12.983	14.986	**12.568**	**17.456**	**24.220**
SUDS+ Tree trench	212	839	1.451	8.560	10.122	11.684	**10.104**	**14.372**	**20.522**
SUDS-U Tree pit with (retention) cistern	69	273	473	2.791	3.301	3.810	**4.303**	**7.096**	**11.781**
SUDS Extensive green roof	100	400	1.000	2.377	2.377	2.377	**2.542**	**3.216**	**4.685**
SUDS+ Intensive green roof	200	800	1.999	7.471	10.187	13.244	**7.768**	**11.646**	**17.205**
SUDS+ Retention roof	100	400	1.000	2.377	2.377	2.377	**2.542**	**3.216**	**4.685**
SUDS-U Green roof with (retention) cistern	100	400	1.000	2.377	2.377	2.377	**2.869**	**3.543**	**5.012**
SUDS-U Retention roof with cistern	100	400	1.000	2.377	2.377	2.377	**2.869**	**3.543**	**5.012**
SUDS Cistern	-	-	-	-	-	-	**327**	**327**	**327**
SUDS+ Smart retention cistern	-	-	-	-	-	-	**327**	**327**	**327**
SUDS-U Smart retention cistern	-	-	-	-	-	-	**327**	**327**	**327**

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Table 6: Monetised costs pilot area Berlin in EUR 1.000

	per year									
	Investment costs			Operation and maintanance costs			Construction related emissions		**Total costs**	
	min	med	max	min	med	max	min	max	**min**	**max**
SUDS Swale	93	137	181	36	78	121	1	10	**130**	**312**
SUDS+ Swale	199	293	387	76	167	259	1	20	**276**	**666**
SUDS-U Swale with (retention) cistern	487	1.067	2.992	821	1.648	2.476	6	86	**1.314**	**5.554**
SUDS Infiltration trench	100	159	218	7	14	21	2	30	**109**	**269**
SUDS+ Infiltration trench	196	313	429	15	28	40	4	60	**215**	**529**
SUDS-U Storage trench as cistern	371	590	809	28	52	76	8	112	**407**	**997**
SUDS Swale-trench element	230	307	383	32	69	105	2	26	**264**	**514**
SUDS+ Swale-trench element	587	782	976	83	176	269	4	56	**674**	**1.301**
SUDS-U Swale-storage-trench element with cistern	694	1.408	3.699	959	1.921	2.884	9	120	**1.662**	**6.703**
SUDS Tree pit	351	1.229	2.108	998	1.497	1.997	8	110	**1.357**	**4.215**
SUDS+ Tree trench	1.013	2.068	3.245	834	1.271	1.708	6	86	**1.853**	**5.039**
SUDS-U Tree pit with (retention) cistern	483	1.246	3.346	1.057	1.984	2.912	8	104	**1.548**	**6.362**
SUDS Extensive green roof	436	872	1.308	452	905	1.357	9	121	**897**	**2.786**
SUDS+ Intensive green roof	2.149	4.298	6.447	3.971	7.941	11.912	25	342	**6.145**	**18.701**
SUDS+ Retention roof	711	1.423	2.134	1.206	2.413	3.619	13	176	**1.930**	**5.929**
SUDS-U Green roof with (retention) cistern	1.235	2.767	7.017	2.047	4.094	6.141	20	276	**3.302**	**13.434**
SUDS-U Retention roof with cistern	2.235	5.037	13.020	4.247	8.494	12.741	35	471	**6.517**	**26.232**
SUDS Cistern	393	933	2.810	785	1.570	2.355	18	243	**1.196**	**5.408**
SUDS+ Smart retention cistern	1.071	2.540	7.651	2.137	4.274	6.411	24	331	**3.232**	**14.393**
SUDS-U Smart retention cistern	708	1.679	5.059	1.413	2.826	4.239	16	219	**2.137**	**9.517**

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Table 7: Monetised benefits pilot area Cologne in EUR 1.000

	per year				
	Water storage and irrigation use	Rainwater infiltration	Indoor temperature regulation		
			min	med	max
SUDS Swale	-	714	-	-	-
SUDS+ Swale	-	721	-	-	-
SUDS-U Swale with (retention) cistern	84	786	-	-	-
SUDS Infiltration trench	-	727	-	-	-
SUDS+ Infiltration trench	-	743	-	-	-
SUDS-U Storage trench as cistern	84	175	-	-	-
SUDS Swale-trench element	-	713	-	-	-
SUDS+ Swale-trench element	-	720	-	-	-
SUDS-U Swale-storage-trench element with cistern	84	175	-	-	-
SUDS Tree pit	-	751	369	1.950	4.976
SUDS+ Tree trench	-	741	369	1.950	4.976
SUDS-U Tree pit with (retention) cistern	84	793	369	1.950	4.976
SUDS Extensive green roof	-	-	49	334	995
SUDS+ Intensive green roof	-	-	74	502	1.493
SUDS+ Retention roof	-	-	49	334	995
SUDS-U Green roof with (retention) cistern	84	175	49	334	995
SUDS-U Retention roof with cistern	84	175	49	334	995
SUDS Cistern	84	175	-	-	-
SUDS+ Smart retention cistern	84	175	-	-	-
SUDS-U Smart retention cistern	84	175	-	-	-

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Table 7: ***Cont.***

	per year								
	Air quality regulation			Urban aesthetics, flora and fauna			**Total benefits (without flood protection)**		
	min	med	max	min	med	max	**min**	**med**	**max**
SUDS Swale	5	7	10	48	48	48	**767**	**769**	**772**
SUDS+ Swale	9	14	19	93	93	93	**823**	**828**	**833**
SUDS-U Swale with (retention) cistern	5	7	10	48	48	48	**923**	**925**	**928**
SUDS Infiltration trench	-	-	-	-	-	-	**727**	**727**	**727**
SUDS+ Infiltration trench	-	-	-	-	-	-	**743**	**743**	**743**
SUDS-U Storage trench as cistern	-	-	-	-	-	-	**259**	**259**	**259**
SUDS Swale-trench element	3	5	6	31	31	31	**747**	**749**	**750**
SUDS+ Swale-trench element	7	10	13	66	66	66	**793**	**796**	**799**
SUDS-U Swale-storage-trench element with cistern	3	5	6	31	31	31	**293**	**295**	**296**
SUDS Tree pit	189	748	1.294	5.537	6.547	7.558	**6.846**	**9.996**	**14.579**
SUDS+ Tree trench	133	526	910	3.896	4.607	5.318	**5.139**	**7.824**	**11.945**
SUDS-U Tree pit with (retention) cistern	66	263	455	1.948	2.304	2.659	**3.260**	**5.394**	**8.967**
SUDS Extensive green roof	76	304	759	1.310	1.310	1.310	**1.435**	**1.948**	**3.064**
SUDS+ Intensive green roof	152	607	1.518	4.116	5.613	7.297	**4.342**	**6.722**	**10.308**
SUDS+ Retention roof	76	304	759	1.310	1.310	1.310	**1.435**	**1.948**	**3.064**
SUDS-U Green roof with (retention) cistern	76	304	759	1.310	1.310	1.310	**1.694**	**2.207**	**3.323**
SUDS-U Retention roof with cistern	76	304	759	1.310	1.310	1.310	**1.694**	**2.207**	**3.323**
SUDS Cistern	-	-	-	-	-	-	**259**	**259**	**259**
SUDS+ Smart retention cistern	-	-	-	-	-	-	**259**	**259**	**259**
SUDS-U Smart retention cistern	-	-	-	-	-	-	**259**	**259**	**259**

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Table 8: Monetised costs pilot area Cologne in EUR 1.000

	per year									
	Investment costs			Operation and maintanance costs			Construction related emissions		**Total costs**	
	min	med	max	min	med	max	min	max	**min**	**max**
SUDS Swale	85	125	165	25	54	84	1	7	**111**	**256**
SUDS+ Swale	163	239	316	47	104	161	1	13	**211**	**490**
SUDS-U Swale with (retention) cistern	342	731	2.000	415	834	1.254	3	45	**760**	**3.299**
SUDS Infiltration trench	93	148	203	5	10	15	2	22	**100**	**240**
SUDS+ Infiltration trench	169	268	368	10	18	26	3	39	**182**	**433**
SUDS-U Storage trench as cistern	262	417	573	15	28	41	5	61	**282**	**675**
SUDS Swale-trench element	237	316	395	25	54	83	1	19	**263**	**497**
SUDS+ Swale-trench element	504	671	839	54	115	176	3	35	**561**	**1.050**
SUDS-U Swale-storage-trench element with cistern	539	1.031	2.548	483	969	1.456	5	66	**1.027**	**4.070**
SUDS Tree pit	321	1.125	1.929	695	1.043	1.390	6	76	**1.022**	**3.395**
SUDS+ Tree trench	837	1.708	2.681	524	799	1.073	4	54	**1.365**	**3.808**
SUDS-U Tree pit with (retention) cistern	370	1.005	2.514	652	1.179	1.707	5	65	**1.027**	**4.286**
SUDS Extensive green roof	436	872	1.308	344	688	1.032	7	92	**787**	**2.432**
SUDS+ Intensive green roof	2.149	4.298	6.447	3.021	6.042	9.063	19	260	**5.189**	**15.770**
SUDS+ Retention roof	711	1.423	2.134	918	1.836	2.753	10	134	**1.639**	**5.021**
SUDS-U Green roof with (retention) cistern	984	2.171	5.219	1.175	2.351	3.526	13	173	**2.172**	**8.918**
SUDS-U Retention roof with cistern	1.342	2.919	6.640	1.875	3.751	5.626	17	227	**3.234**	**12.493**
SUDS Cistern	257	609	1.836	390	780	1.170	9	121	**656**	**3.127**
SUDS+ Smart retention cistern	760	1.803	5.431	1.154	2.308	3.462	13	179	**1.927**	**9.072**
SUDS-U Smart retention cistern	463	1.097	3.304	702	1.404	2.106	8	109	**1.173**	**5.519**

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3.3 Limitations, discussion and future research

Both analyses are constrained by the definition of system boundaries and the selection of criteria and components included. For the MCA, the main constraints concern data quality, local specificity, and methodological assumptions. Differences in data availability, particularly for newer, less documented BGI measures, affect the robustness of results. The dependence of measure performance on local conditions restricts the transferability of results to urban contexts with comparable characteristics e.g. in terms of soil composition, topography and climate. Furthermore, the outcomes are sensitive to the choice and weighting of criteria; although equal weighting was applied, alternative configurations could alter the ranking of measures. Some criteria, such as ecological connectivity or distribution effects, were excluded due to data gaps or difficulties in operationalisation, and therefore a number of aspects are not represented in the assessment.

The monetisation of environmental and social benefits and costs in the framework of the CBA introduces additional uncertainties. First, a central limitation arises from uncertainties in the underlying biophysical relationships, such as the extent to which trees or green roof vegetation retain particulate matter and the resulting implications for human health. Second, many relevant effects, such as air purification, biodiversity, or health impacts, are difficult to quantify and lack standardised methods and values for monetisation. In this paper, biodiversity related aspects were analysed using a benefit transfer approach based on willingness-to-pay estimates from another city, which implies limitations in the accuracy for the case study areas. Additionally, the estimation of damage costs from heavy rainfall is limited by the reliance on non-public data, while publicly accessible datasets such as HOWAS21 contain too few relevant cases ($n = 9$), highlighting the need for more comprehensive open data to support robust economic assessments. Additional research and modelling should be conducted to generate inundation data for the calculation of flood damage costs on local level. Besides robust inundation data, cost data for damages per building or infrastructure is needed for future assessment.

Moreover, the results show that monetised components in the CBA are highly sensitive to the chosen monetisation method, evidenced by the variation in estimates for the construction-related emission costs. There, higher bound estimates calculated deploying damage costs are 10 to 15-fold higher than their lower bound estimates calculated through applying market prices. The results represent the variation between the used market-based approach and a broader economic assessment, including external costs. The estimated number shows the sensitivity of the choice of monetisation method, especially for greenhouse gas emissions. Further research could be implemented regarding the measurement of greenhouse gas emission for additional measures to include this cost-component in decision making processes. Moreover, measures' sequestration potential should be linked to emissions during the building phase and maintenance of the analysed SUDS.

In the current analysis, indirect irrigation effects are not quantified for the SUDS-U variants because of a lack of robust information on vegetation growth rates, although such effects may plausibly generate additional benefits and could add to discussions on long-term synergies between managing flood and drought risks for these measures. The modelling further did not consider climate change impacts and some indirect interactions, such as those between irrigation and urban cooling effects.

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The incorporation of expected volume of future rainfall would be highly relevant for long-term decisions, as it would improved the basis for urban planning.

Further research potential can be seen in empirical assessments specific for the new developed SUDS-U to generate a more concise information base for the new designed measures. Additionally, an analysis of combination of SUDS+ and SUD-U (SUDS+U) could reap relevant results in terms of synergies between extreme rainfall events and drought mitigation.

4 Conclusions

Considering the research question which SUDS measures should be prioritised for implementation in urban areas based on their performance across multiple evaluation criteria and their net-benefit value we find that both the MCA and CBA highlight the stronger performance of measures with vegetated components, such as swales, green roofs and trees. In an urban environment swales and tree-based measures consistently perform well across both assessments, combining relatively low costs and ease of implementation with diverse ecosystem and social benefits. In contrast, underground systems such as infiltration trenches and standalone cisterns rank mediocre to low in the analyses, underlining the importance of integrating green elements for social and environmental co-benefits. Contradicting outcomes can be observed in green roofs. Due to their high costs they have mostly negative cost-benefit ratios in the CBA, yet in the MCA they score high as investment and maintenance costs factor in as only one criterium amongst 18 and carry the same weight as for example, aspects of biodiversity or recreation. This illustrates well that the results of the MCA depend on the choice and weighing of the assessed criteria.

Overall, the combined MCA-CBA approach offers a broad assessment of SUDS, yet it remains limited by data availability and methodological challenges. While the MCA captures the broad range not only of (co-)benefits but also of other implementation characteristics in a non-monetary framework, the CBA complements it by providing monetised values for benefits and costs. However, its results depend on the selection of valuation methods which rely on the availability of robust data inputs to reduce uncertainties.

Data availability: Modelling data results have been generated with the "Comparison tool for rainwater management systems (SUDS, SUDS+ and SUDS-U)" publicly available under https://doi.org/10.5281/zenodo.18299661.

Author contribution: Conceptualization: JT, FD; Data curation: FD, JT, HS, US; Formal analysis: FD, JT, HS, US; Funding acquisition: JT, US, HS; Investigation: FD, JT, HS, US; Methodology: JT, FD; Project administration: JT; Supervision: JT; Writing: FD; Writing (review and editing): JT, US.

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