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MULTI-CRITERIA DECISION ANALYSIS FOR EVALUATION OF STORMWATER CONTROL MEASURES

VEČKRITERIJSKA ODLOČITVENA ANALIZA ZA VREDNOTENJE UKREPOV ZA OBVLADOVANJE PADAVINSKIH VODA

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Abstract

Stormwater control measures (SCMs) are technical elements designed to prevent and mitigate the negative effects of uncontrolled stormwater runoff. Different types of SCM can provide various co-benefits to the surrounding urban environment, making it important to select the most appropriate measure. This study presents a multi-criteria decision analysis (MCDA) framework for evaluating SCMs based on their optimized design parameters. Six SCM types – bio-retention cells, rain gardens, green roofs, infiltration trenches, detention ponds, and storage tanks – were optimized for a single objective: catchment outflow reduction. The resulting designs were evaluated using MCDA, incorporating additional performance criteria including capital expenditure (CAPEX), operating expenses (OPEX), land take, retained water, detained water, and plant space. The compromise programming method was applied to rank SCM scenarios based on their proximity to an ideal solution. Results indicate that landscape-integrated SCMs, particularly detention ponds, offer the most balanced performance, combining low costs with high co-benefits. Building-integrated SCMs, such as green roofs and rainwater-harvesting storage tanks, scored moderately, while underground storage tanks – representing grey infrastructure – performed the worst due to high costs and lack of co-benefits. The proposed evaluation framework enables transparent, criteria-based comparison of SCMs and supports informed decision-making in urban stormwater planning.

Keywords: urban drainage, climate change, surface runoff, blue-green infrastructure, co-benefits.

Izvleček

Ukrepi za obvladovanje padavinskih voda (UOPV) so inženirski objekti, namenjeni preprečevanju in blažitvi negativnih posledic nenadzorovanega površinskega odtoka. Raznovrstni UOPV lahko zagotovijo različne vrste dodatnih koristi v urbanem okolju, zato je ključna izbira najprimernejšega ukrepa. Ta študija predstavlja okvir večkriterijske odločitvene analize za vrednotenje UOPV na podlagi njihovih optimiziranih karakteristik. Šest vrst UOPV – bioretenzijske enote, deževni vrtovi, zelene strehe, infiltracijski jarki, suhi zadrževalniki in zbiralniki – je bilo optimiziranih s ciljem zmanjšanja odtoka iz prispevnega območja. Optimizirani ukrepi so bili ovrednoteni z večkriterijsko odločitveno analizo, ki vključuje dodatne kriterije učinkovitosti: investicijske

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stroške, obratovalne stroške, potrebno površino, shranjeno vodo, zadržano vodo in prostor za rastline. Z metodo kompromisnega programiranja so bili scenariji UOPV nato razvrščeni glede na njihovo odstopanje od idealne rešitve. Rezultati kažejo, da so najbolj učinkoviti v krajino vključeni ukrepi, zlasti suhi zadrževalniki, saj združujejo manjše stroške z visokimi dodatnimi koristmi. V objekte vključeni ukrepi, kot so zelene strehe in zbiralniki deževnice, so dosegli zmerne rezultate, medtem ko so podzemni zbiralniki (tj. siva infrastruktura) zaradi visokih stroškov in pomanjkanja dodatnih koristi dosegli najslabše rezultate. Predlagani okvir omogoča pregledno primerjavo UOPV na podlagi kriterijev in podpira informirano odločanje pri načrtovanju urbane odvodnje.

Ključne besede: urbana odvodnja, podnebne spremembe, površinski odtok, modro-zelena infrastruktura, dodatne koristi.

1. Introduction

Traditional urban drainage solutions (i.e. gray infrastructure) are typically designed with a single objective (e.g. flood protection, pollution control) in mind and do not provide co-benefits. On the other hand, nature-based stormwater control measures (SCMs) can provide multiple co-benefits (Vozelj et al., 2023). Therefore, they should be selected and designed in a way to provide as many co-benefits as possible. Decision support systems are being developed (Chow et al., 2014; Morales-Torres et al., 2016) to mark the path for stakeholders and set the framework for selecting the most suitable measure, according to site conditions, performance goals, and stakeholders' demands.

Multi-criteria decision analysis (MCDA), also known as multiple criteria analysis (MCA), multi-criteria decision making (MCDM), and multiple objective decision support (MODS), is frequently used to solve decision-making problems involving multiple criteria or options in the field of water resource management (Hajkowicz and Collins, 2007; Marttunen et al., 2017). These approaches can be defined as decision models that contain: (a) a set of decision options that need to be ranked (e.g. SCMs); (b) a set of criteria (e.g. co-benefits); and (c) a set of performance measures. Hajkowicz and Collins (2007) and Marttunen et al. (2017) found that the most frequently used MCDA methods in the field of water resource management are: fuzzy set analysis, compromise programming (CP), the analytic hierarchy process (AHP), ELECTRE, and PROMETHEE.

Different levels of SCM optimization and multi-criteria evaluation can be applied. One of the following approaches is usually applied:

1. multi-criteria evaluation and selection of SCMs with no SCM optimization,
2. single-objective optimization of SCM combined with multi-criteria evaluation and selection of SCMs, and
3. multi-objective optimization of SCM design.

The first approach is based on the integration of SCMs into a (calibrated) hydrological-hydraulic model (e.g. SWMM) and observing their influence on catchment performance (e.g. surface runoff reduction, improvement of water quality, etc.). In this case, SCM integration is usually based on land use types and identification of potential implementation areas (e.g. 10% of existing parks). In the next step, the obtained SCMs are evaluated with one of the MCDA methods (e.g. Radinja et al., 2019).

Yang and Zhang (2021) integrated nine (green and gray infrastructure) strategies into the MIKE URBAN hydrological model and observed their performance. Strategies were evaluated with eight quantifiable indicators, including flood mitigation capacity, pollution control capacity, life-cycle cost, damage cost, recreational function, biotope area ratio, and spatial consistency. Stakeholders from the government, research institutes, engineering companies, and citizen groups were interviewed to investigate the preferences for the indicators. The AHP was used for MCDM analysis to calculate the weight for each indicator. Similar research was conducted by Kourtis et al. (2020) and Li et al. (2017) by investigating SuDS performance with SWMM and using the AHP method for their integrated assessment. Furthermore, Zhu et al. (2021) applied the fuzzy analytic hierarchy process (FAHP) to evaluate the performance of five different permeable pavement scenarios, considering hydrologic, hydraulic, water quality, and economic criteria.

Wang et al. (2017) applied three SuDS schemes encompassing permeable pavements, green roofs, and bioretention cells into SWMM and observed their performance. SuDS schemes were assessed with 12 indicators covering the following factor categories: resilience, hydraulic performance, pollution control, rainwater usage, energy analysis, greenhouse gas emissions, and costs. Next, entropy weight and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) were used for MCDA.

The second approach is based on the optimization of SCMs with a specific goal (i.e. a single objective). Usually, the goal is related to the hydrological response of the catchment (e.g. peak or total outflow, flooding, etc.). When an optimal SCM design is determined, measures are evaluated with an MCDA method. Chui et al. (2016) used a SWMM that was automatically controlled by MATLAB to obtain the peak runoff in the various designs of three specific LID practices (i.e. green roof, bioretention, and porous pavement) under several design storms. Following the optimal design, defined as the design with the lowest cost (i.e. construction cost, operation, and maintenance cost) and at least 20% peak runoff reduction, was identified.

The third approach is frequently applied by coupling SWMM, which includes SCMs, with a multi-objective optimization tool/algorithm in a search for a Pareto optimal solution. Consequently, no additional MCDA method needs to be applied since the multi-objective optimization itself provides/identifies the most efficient measures. Eckart et al. (2018) developed a coupled optimization-simulation model by linking SWMM to the Borg Multiobjective Evolutionary Algorithm (Borg MOEA). The coupled model is capable of performing multi-objective optimization (i.e. minimizing peak flow in the storm sewers, reducing total runoff, and minimizing cost), which uses SWMM simulations as a tool to evaluate potential solutions to the optimization problem. Similarly, McClymont et al. (2020) coupled InfoSWMM with MATLAB and applied a standard Evolution Strategy (Beyer and Schwefel, 2002) with a mutation and crossover operator, similar to a Genetic Algorithm like NSGA-II, for optimizing SCM solutions (i.e. rain barrels, green roofs, bio-retention tanks, vegetation grass swales, and permeable pavements). The model adopts water quality and quantity as the optimization objectives and SuDS spatial distribution as decision variables. Alves et al. (2020) coupled SWMM with the genetic algorithm NSGA-II to evaluate and optimize the size of green-blue-grey measures (i.e. rainwater barrel, pervious pavement, open detention basin, pipes). Two different optimization problems were investigated: a) minimization of total costs and maximization of flood damage reduction, and b) minimization of total costs and maximization of total benefits.

A literature review showed that the frameworks enabling the evaluation of the SCMs with multiple criteria, based on their optimized parameters, can facilitate SCMs uptake in the planning phase, which is typically interdisciplinary. However, frameworks that can overcome the barriers typical of interdisciplinary projects are rarely used.

The main objective of this research is to develop an evaluation system for the co-benefits of SCMs, based on their design parameters. The approach employs MCDA to rank SCMs not only by their hydrological effectiveness (i.e. catchment outflow reduction), but also by incorporating additional evaluation criteria (i.e. CAPEX, OPEX, land take, retained water, detained water, plant space).

2. Methods

2.1 Optimizing stormwater control measures

This research builds on previous research (Radinja et al., 2021a, 2021b) that focused on applying automated modelling (AM) by using the Process-Based Modelling Tool (ProBMoT) (Džeroski et al., 2020). ProBMoT enables domain knowledge, formalized as template components for constructing process-based models, to be integrated into the procedure of equation discovery from measured data. It automatically identifies the structure and parameter values of an appropriate process-based model when the following are provided: (a) a knowledge library (i.e. a mathematical formulation of the selected domain) in the form of model components (more specifically, template entities and processes), (b) a conceptual model of the observed system, and (c) measurements. In the above-mentioned previous research, ProBMoT was used to (a) find the most suitable rainfall-runoff model by combining the choices among multiple alternatives for describing hydrological processes, (b) to calibrate the rainfall-runoff model parameters against measured data (Radinja et al., 2021b), and (c) to design SCMs based on a target catchment outflow (Radinja et al., 2021a).

The presented methods were applied to the real-world case study area, a part of Rožna Dolina, Ljubljana, Slovenia (Figure ***1***), by developing specific conceptual models and obtaining the necessary data, including infiltration, precipitation, flow measurements, and land use.

The conceptual model of the case study area (Figure 2**Error! Reference source not found.Error! Reference source not found.**) was structured as a single compartment (i.e. catchment), divided into two sub-compartments (i.e. sub1 and sub2), where sub1 represents the impervious part of the catchment and sub2 the pervious part of the catchment.

A new sub-compartment (i.e. sub3) (Figure 2) was introduced to account for SCMs, including SCM area and contributing areas. SCMs can be placed either within a part of an existing pervious area or an impervious area. However, in the case of green roofs, the measure itself also acts as a contributing area, by receiving direct rainfall. To ensure transparency, a separate conceptual model was defined for each SCM.

Figure 1: *Case study area in Rožna Dolina, Ljubljana, Slovenia.*

Slika 1: *Študijsko območje v Rožni dolini, Ljubljana, Slovenija.*

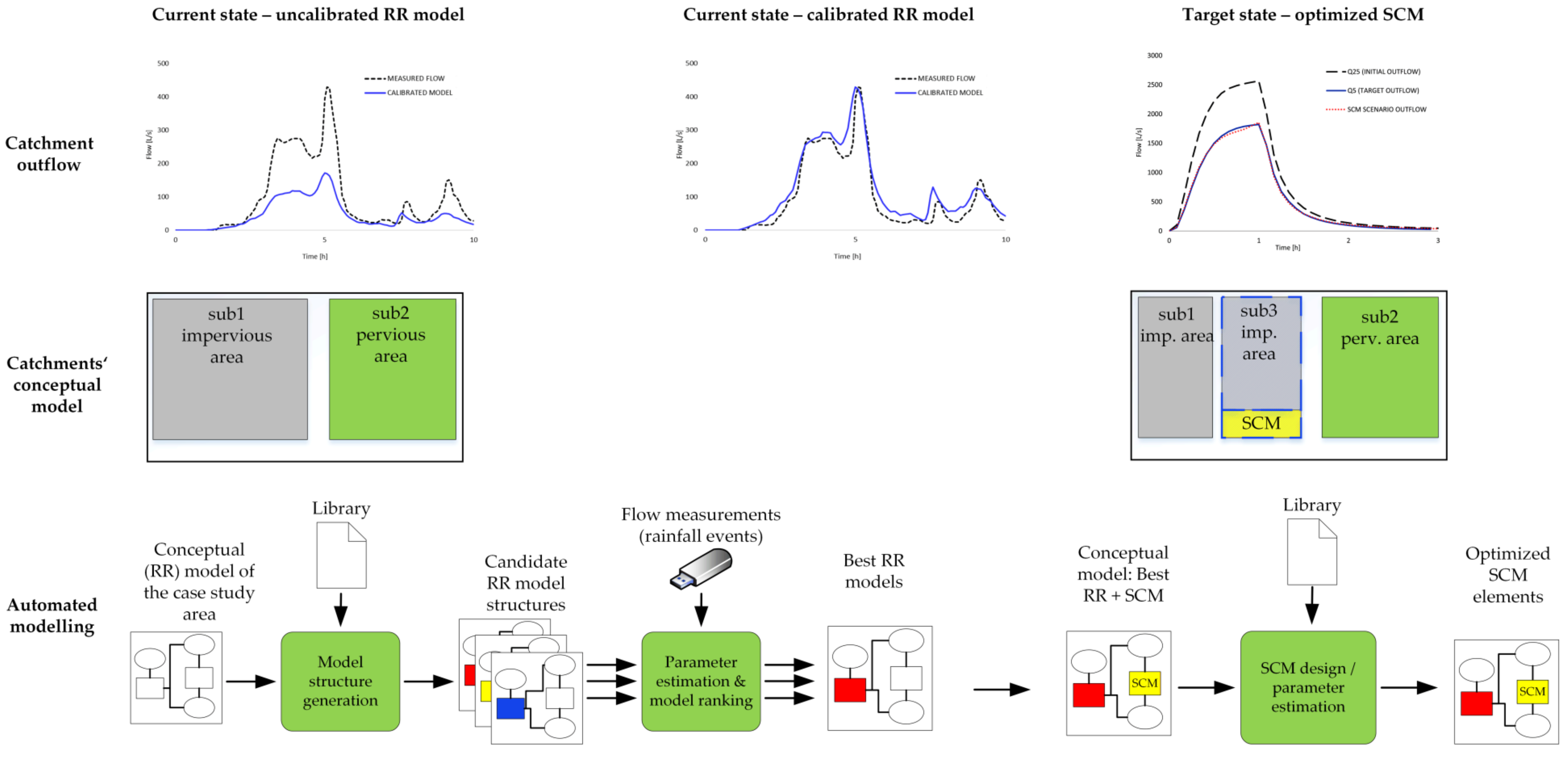

Figure 2: *Schematic workflow illustrating rainfall–runoff (RR) model discovery and SCM design using the automated modelling tool ProBMoT: from the initial catchment conceptual model with two sub-compartments to the final SCM-based conceptual model with three sub-compartments, along with their influence on catchment outflow.*

Slika 2: *Shema odkrivanja modelov površinskega odtoka in načrtovanja UOPV z orodjem za avtomatizirano modeliranje ProBMoT. Prikazan je razvoj strukture konceptualnega modela od izhodiščnega konceptualnega modela z dvema podrazdelkoma* do konceptualnega modela, *ki vključuje UOPV in sestoji iz treh podrazdelkov, ter njihov vpliv na odtok z območja.*

Initial SCM optimization results indicated that a single SCM with uniform characteristics could not consistently accommodate event dynamics to achieve the desired catchment outflow. For example, detention ponds and storage tanks provide temporary storage, after which outflow resumes (Radinja et al., 2021a). To overcome this limitation, the original SCM sub-compartment (i.e. sub3) was divided into three sub-units (i.e. sub3, sub4, and sub5). This approach enabled the design of elements of the same SCM type with varying characteristics (e.g. dimensions). The optimized configuration of these SCM sub-units forms distinct SCM scenarios.

In this study, SCMs are based on the principles and equations used by SWMM for modelling Low Impact Development (LID) controls (Rossman, 2015), i.e. bio-retention cell (BRC) (*Error! Reference source not found.*), rain garden (RG), green roof (GR), and infiltration trench (IT). Bio-retention cells (BRCs) are depressions that contain vegetation grown in an engineered soil mixture placed above a gravel storage bed. They provide storage, infiltration, and evapotranspiration of both direct rainfall and runoff captured from surrounding areas.

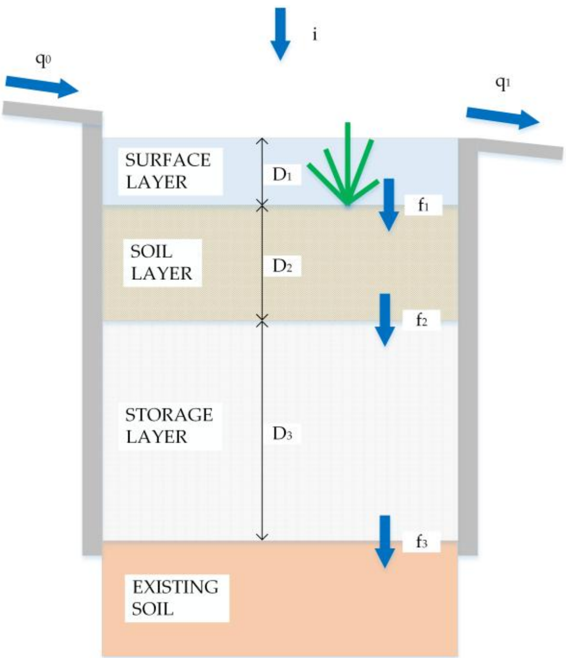

Figure 3: *A conceptual model of a typical bio-retention cell (adapted from Rossman, 2015).*

Slika 3: *Konceptualni model bioretenzijske enote (povzeto po Rossman, 2015).*

As such, BRCs can be used as a generic SCM model, which can be then customized to describe the behavior of other SCM types. Based on the principles and equations typical for these measures, two additional SCMs were defined, namely the detention pond (DP) and the storage tank (ST).

The processes that characterize individual SCMs are described with equations that are presented in Radinja et al. (2021a). However, the variables and constants used are presented in Table 2 and 2, as we refer to them later on in the text.

Table 1: *Variables used for the description of SCMs.*

Preglednica 1: *Spremenljivke, uporabljene za opis UOPV.*

Variables			
EPA-SWMM Name	ProBMoT Name	Description	Unit
d_1	d1	depth of water stored on the surface	m
d_3	d3	depth of water in the storage layer	m
θ_2	mc2	soil layer moisture content (volume of water/total volume of soil)	fraction
i	i	precipitation rate falling directly on the surface layer	m/s
q_0	q0	inflow to the surface layer from runoff captured from other areas	m/s
q_1	q1	surface layer runoff or overflow rate	m/s
f_1	f1	infiltration rate of surface water into the soil layer	m/s
f_2	f2	percolation rate of water through the soil layer into the storage layer	m/s
f_3	f3	exfiltration of water from the storage layer into native soil	m/s

Table 2: *Constants used to describe SCMs.*

Preglednica 2: *Konstante, uporabljene za opis UOPV.*

Constants			
EPA-SWMM Name	ProBMoT Name	Description	Unit
A	A	surface area	m^2
W	W	surface width	m
S	S	surface slope	m/m
n_1	n1	surface roughness coeff.	$s/m^{1/3}$
n_3	n3	drainage mat roughness coeff.	$s/m^{1/3}$
D_1	D1	freeboard height for surface ponding	m
D_2	D2	thickness of the soil layer	m
D_3	D3	thickness of the storage layer	m
ϕ_1	VF1	void fraction of any surface volume	fraction
ϕ_2	VF2	porosity of the soil layer	fraction
ϕ_3	VF3	void fraction of the storage layer	fraction
K_{2S}	K2S	soil's saturated hydraulic conductivity	m/s
K_{3S}	K3S	native soil's saturated hydraulic conductivity	m/s
ψ_2	SH2	suction head at the infiltration wetting front formed in the soil	m
HCO	HCO	percolation decay constant	/
θ_{20}	IMC2	soil's initial moisture content or its wilting point	fraction
θ_{FC}	FC	soil's field capacity moisture content	fraction

For MCDA, a search for the optimal SCM design was conducted for the design event DE_Q5_P25. This design event represents a combination of an outflow typical of 5-year precipitation (i.e. Q5) and precipitation with a 25-year return period (i.e. P25).

The same or better hydrological performance than the goal catchment outflow (i.e. total volume ratio (TVR) and peak flow ratio (PFR) $\leq$ 1.0) was required. Thus, the hydrological performance of SCMs is not a part of the MCDA. Furthermore, some of the previously imposed design constraints were removed (e.g. area). In this way, SCMs can be compared along with additional criteria, while providing similar hydrological performance.

2.2 Multi-criteria decision analysis for stormwater control measures

An evaluation system was developed (Table 3) that enables the assessment of SCMs with additional criteria (e.g. capital expenditure (CAPEX), operating expenses (OPEX), plant space, etc.). It is based on the SCM design parameters. Namely, the optimized SCM design parameter values are used to quantify SCM performance against additional criteria.

Table 3**:** *Characteristics of criteria used within the multi-criteria decision analysis.*

Preglednica 3: *Značilnosti kriterijev, uporabljenih v večkriterijski odločitveni analizi.*

Criteria group	Criteria [unit]	Used SCM variables and parameters	Criteria calculation
Finances and land take	CAPEX [€]	A, D1, D2, D3, VF1-3, K2S	Table 4
	OPEX [€]	A, D1, D2, D3	Table 5
	Land take [m^2]	A	A
Co-benefits	Retained water [m^3]	A, D1	A × D1
	Detained water [m^3]	i, q0, q1	$i + q_0 - q_1$
	Plant space [%]	VF1	(1 - VF1) × 100

The criteria land take, retained water, detained water, and plant space can be simply calculated with the already determined SCM variables and parameters (Table 3). For the determination of CAPEX and OPEX, additional information was provided (i.e. Table 4 and Table 5).

Table 4: *Cost items used for the calculation of capital expenditure (CAPEX) for SCMs.*

Preglednica 4: *Uporabljene postavke za izračun investicijskih stroškov posameznih UOPV.*

CAPEX[1]									SCM							
			UST		RWH-ST		DP		IT		RG		BRC		GR	
Cost item	unit	€/unit	Item	Parameter	Item	Parameter	Item	Parameter	Item	Parameter	Item	Parameter	Item	Parameter	Item	Parameter
Clearing & grubbing	m^2	1.30	X	A	X	A	X	A	X	A	X	A	X	A		
Excavation	m^3	11.48	X	SCM V[2]			X	SCM V	X	SCM V	X	SCM V	X	SCM V		
Haul/dispose of excavated material	m^3	11.27	X	SCM V			X	SCM V	X	SCM V	X	SCM V	X	SCM V		
Topsoil placement and grading	m^3	6.29									X	D2*A	X	D2*A		
Soil media/planting media	m^3	30.25									X	D2*A	X	D2*A		
Soil mix for GR	m^2	31.76													X	D2*A
Clay liner	m^2	15.74					X	SCM A								
Pea gravel	m^3	35.20													X	D3*A
Base coarse gravel	m^3	31.03							X	D3*A	X	D3*A	X	D3*A		
Vegetation – typical	m^2	58.79									X	A	X	A		
Vegetation – complex	m^2	88.41													X	A
Slotted PVC underdrain pipe	m	45.44							X	SCM Length						
Waterproof membrane	m^2	20.69					X	A							X	A
Root barrier	m^2	3.96													X	A
Geotextile filter layer	m^2	7.99							X	A	X	A	X	A	X	A
Overflow structure(s)	each	4030.53					X									
Aboveground storage tank	m^3	241.61			X	SCM V										
Underground storage tank	m^3	617.46	X	SCM V												
Engineering	%		X		X		X		X		X		X		X	
Contingency	%		X		X		X		X		X		X		X	

[1]Adapted from the Low Impact Development Life Cycle Costing Tool (Uda et al., 2013), and the Low Impact Development Stormwater Control Cost Estimation Analysis (U.S. Environmental Protection Agency, 2015).

[2]SCM V – SCM volume

In the context of MCDA, the SCM ST is further divided into two subtypes: underground storage tank (UST) and rainwater-harvesting storage tank (RWH-ST). We consider UST as a typical representative of centralized gray infrastructure, where each element has a volume of a few hundred m^3. On the other hand, we consider RWH-ST as a rainwater harvesting SCM, where each element has a volume of only a few m^3. Differences between the sub-types appear with the criteria CAPEX (Table 4), land take, and retained water – water reuse.

The CAPEX (Table 4) and OPEX (Table 5) values for SCMs were calculated based on the values proposed by the Low Impact Development Life Cycle Costing Tool (Uda et al., 2013). The tool was first released in 2013 and updated in 2018. Furthermore, Low Impact Development Stormwater Control Cost Estimation Analysis (U.S. Environmental Protection Agency, 2015) was used to determine the most relevant cost items used for CAPEX calculation. Please note that the costs of land and the infrastructure for conveying water from contributing areas to SCMs (e.g. pipes, swales, etc.) were not considered.

Table 5: *Annual operating expenses (OPEX) and assumed dimensions of SCM units.*

Preglednica 5: *Letni stroški vzdrževanja in predpostavljene dimenzije enot za UOPV.*

SCM	OPEX[1]	Assumed SCM unit dimensions	
		Design area [m^2]	Design width [m]
UST	27.01 €/m^3		
RWH-ST	27.01 €/m^3		
DP	9.75 €/m^2	50	
IT	0.61 €/m^2	25	2
RG	6.07 €/m^2	25	5
BRC	6.07 €/m^2	25	5
GR	0.72 €/m^2	100	

[1]Adopted from Uda et al. (2013).

The following financial assumptions were made when revalorizing prices: a) an inflation rate of 3% per annum, and b) an exchange rate of 1 € = 1.52 Can$. These are user-defined parameters that can be adjusted (i.e. updated) according to the latest financial conditions. Nevertheless, the ratios between SCM prices will remain the same. Thus, these two parameters have no direct impact on the final MCDA results.

To determine CAPEX for an SCM scenario, additional assumptions about SCM units' dimensions were made (Table 5). For example, from the design area and design width of the infiltration trench, the length of the slotted PVC underdrain pipe was determined, enabling the calculation of CAPEX for this cost item.

After SCMs performance was quantified with additional criteria, the results were compared using MCDA, specifically the Compromise Programming (CP) approach (Yu, 1973; Zelany, 1974). The objective of CP is to select the solution that is closest to the ideal solution, emphasizing the importance of distance and distance measurement in decision-making. Assuming all objectives are maximization objectives (i.e. more is better), then the CP model can be described with the family of L_p metrics (Eq. 1) (Ringuest, 1992):

$$min\ L_p = \left[\sum_{i=1}^{q}\left(w_i \frac{(f_i^* - f_i(x))}{(f_i^* - f_{i*}(x))}\right)^p\right]^{1/p} = \left[\sum_{i=1}^{q}(w_i d_i)^p\right]^{1/p},\ x \in X \qquad (1),$$

where x is the vector of decision variables; X represents the feasible set; $f_i(x)$ is the mathematical expression for the ith criterion $(i \in \{1, \ldots, q\})$; $f^* = f_1^*(x), \ldots, f_i^*(x), \ldots, f_q^*(x)$ represents the vector of the anchor values or ideal point; $f_* = f_{1*}(x), \ldots, f_{i*}(x), \ldots, f_{q*}(x)$ represents the vector of nadir values or anti-ideal point; $d_i = \frac{(f_i^* - f_i(x))}{(f_i^* - f_{i*}(x))}$ stands for the degree of discrepancy for the ith criterion (i.e. the normalized difference between the anchor value and the actual achievement of the ith criterion); w_i is the weight or relative importance attached to the ith criterion; and p is the parameter that determines which of the family of L_p metrics is to be used ($1 \leq L_p \leq \infty$; (André and Romero, 2008). The effect of p is to place more or less emphasis on the relative contribution of individual deviations.

The larger the value of p chosen, the greater is the emphasis given to the largest of the deviations forming the total. When $p = \infty$, the largest of the deviations completely dominates the distance measure. The value $p = 1$ implies the longest geometric distance between two points, meaning that the deviations are summed over all dimensions (Ringuest, 1992).

In this study, financial and land take criteria were assigned a weight value of 1.0. On the other hand, co-benefit criteria were assigned a weight value of 0.7, resembling the traditional evaluation of these criteria by the stakeholders, which are usually considered as less important or are not considered at all (Alves et al., 2018; El Hattab et al., 2020). The p parameter value in the L_p metric was assigned a value of 1.0.

3. Results

The optimized configuration of SCM scenarios for the design event DE_Q5_P25 is presented in Table 6. Consult Table 2 for additional explanations of the SCM parameters. As previously mentioned, the same or better hydrological performance than the target catchment outflow was required (i.e. TVR and PFR of $\leq$1.0). Table 6 also presents the hydrological performance of the SCM scenarios using the Nash–Sutcliffe efficiency (NSE) coefficient, TVR, and PFR. All the scenarios met the desired criteria. Therefore, the hydrological performance of SCMs is not considered in the MCDA.

Based on the optimized SCM design and the presented MCDA evaluation methods (Table 3, Table 5, and Table 4), SCM scenario performance was evaluated with additional criteria (Table 7). Underground storage tanks and green roofs need no additional area (i.e. land take) for their implementation. Only rainwater-harvesting storage tanks retain water in a way that it can be reused. Detention ponds, infiltration trenches, rain gardens, and bio-retention cells detain water and enhance the natural water cycle. Infiltration trenches, rainwater-harvesting, and underground storage tanks provide no plant space since the whole volume of the storage layer is dedicated to water (i.e. the void fraction is 1.00). 10% of the volume of the detention ponds' storage layer is dedicated to plants (i.e. the void fraction is 0.90). Rain gardens, bio-retention cells, and green roofs provide 20% of the storage layer volume for plants (i.e. the void fraction is 0.80).

The obtained results were used to determine ideal and anti-ideal values of the criteria used within compromise programming (Table 8). Afterwards, normalized differences between scenarios were calculated for each criterion (Table 8), enabling the calculation of Lp metrics values. Based on the results of compromise programming, three SCM groups can be formed: (1) landscape-integrated SCMs, (2) building-integrated SCMs, and (3) gray infrastructure.

The best scores were received by landscape-integrated SCMs, i.e. detention ponds, rain gardens, infiltration trenches, and bio-retention cells. The best overall score (i.e. Lp value of 1.44) was achieved by detention ponds. They demand the lowest CAPEX and low values of OPEX and land take. Furthermore, detention ponds detain the highest amount of water that can re-enter the natural water cycle. Rain gardens and infiltration trenches obtained similar scores (i.e. Lp values of 1.83 and 1.89, respectively). Although infiltration trenches demand the lowest OPEX and low land take, they do not provide space for plants. On the contrary, rain gardens compensate for the slightly higher values of OPEX and land take by providing maximum space for plants. Bio-retention cells scored an Lp value of 2.24. Their performance is similar to rain gardens; however, they perform worse for most of the criteria. Furthermore, they demand the biggest land take among all SCMs.

Table 6: *Optimal SCMs parameter values for the design event DE_Q5_P25, which were used within multi-criteria decision analysis.*

Preglednica 6: *Optimalne vrednosti parametrov UOPV za projektni naliv DE_Q5_P25, ki so bili uporabljeni v večkriterijski odločitveni analizi.*

SCM Scenario	Sub[1]	SCM parameters[2]																	Hydrological performance indicators		
		A	W	S	n1	n3	D1	D2	D3	VF1	VF2	VF3	K2S	K3S	SH2	HCO	IMC2	FC	NSE[3]	TVR[4]	PFR[5]
		m^2	m	m/m	$s/m^{1/3}$	$s/m^{1/3}$	m	m	m	fraction	fraction	fraction	m/s	m/s	m	/	fraction	fraction			
3UST	Sub3	400					4.00			1.00									0.978	0.923	0.943
	Sub4	300					1.00			1.00											
	Sub5	400					3.87			1.00											
3RWH-ST	Sub3	600					2.50			1.00									0.978	0.923	0.942
	Sub4	600					2.50			1.00											
	Sub5	300					1.00			1.00											
3DP	Sub3	300					1.00			0.90									0.983	0.931	0.945
	Sub4	696					2.50			0.90											
	Sub5	690					2.50			0.90											
3IT	Sub3	966					0.19		3.50	1.00		0.35		2.60E-05					0.991	0.939	0.940
	Sub4	981					0.16		3.45	1.00		0.35		2.60E-05							
	Sub5	400					0.00		0.90	1.00		0.35		2.60E-05							
3RG	Sub3	806					0.10	0.60		0.80	0.50		3.32E-05	2.60E-05	0.05	39.3	0.08	0.15	0.971	0.966	0.935
	Sub4	2000					0.30	0.85		0.80	0.50		3.32E-05	2.60E-05	0.05	39.3	0.08	0.15			
	Sub5	2000					0.30	0.70		0.80	0.50		3.32E-05	2.60E-05	0.05	39.3	0.08	0.15			
3BRC	Sub3	500					0.10	0.60	0.90	0.80	0.50	0.35	3.32E-05	2.60E-05	0.05	39.3	0.08	0.15	0.989	0.954	0.931
	Sub4	3000					0.30	0.71	0.90	0.80	0.50	0.35	3.32E-05	2.60E-05	0.05	39.3	0.08	0.15			
	Sub5	3000					0.30	0.99	0.16	0.80	0.50	0.35	3.32E-05	2.60E-05	0.05	39.3	0.08	0.15			
3GR	Sub3	18000	1800	0.02	0.40	0.02	0.08	0.13	0.03	0.80	0.50	0.30	3.88E-05		0.08	39.3	0.08	0.4	0.998	1.025	0.991
	Sub4	18000	1800	0.02	0.40	0.02	0.07	0.13	0.05	0.80	0.50	0.30	3.88E-05		0.08	39.3	0.08	0.4			
	Sub5	18000	1800	0.02	0.40	0.02	0.01	0.13	0.05	0.80	0.50	0.30	3.82E-05		0.08	39.3	0.08	0.4			

[1]sub-compartment, [2]A Description of the SCM parameters is provided in Table 2, [3]Nash–Sutcliffe efficiency coefficient, [4]total volume ratio, [5]peak flow ratio

Table 7: *Performance of SCM scenarios evaluated with additional criteria.*

Preglednica 7: *Uspešnost scenarijev UOPV, ocenjenih z dodatnimi kriteriji.*

SCM Scenario	Criteria					
	Finances and land take			Co-benefits		
	CAPEX [€]	OPEX [€]	Land take [m^2]	Retained water - water reuse [m^3]	Detained water - water cycle [m^3]	Plant space [%]
3UST	3,465,287.91 €	114,527.50 €	0	0	0	0.0
3RWH-ST	1,178,101.23 €	96,617.57 €	1500	3300	0	0.0
3DP	330,012.29 €	16,448.93 €	1687	0	3765	10.0
3IT	703,671.26 €	1,421.59 €	2347	0	3314	0.0
3RG	775,704.87 €	29,169.53 €	4806	0	3271	20.0
3BRC	1,368,431.32 €	39,448.29 €	6500	0	3382	20.0
3GR	8,448,316.37 €	38,636.78 €	0	0	0	20.0

Table 8: *Evaluation of SCM scenarios using compromise programming.*

Preglednica 8: *Vrednotenje scenarijev UOPV z uporabo kompromisnega programiranja.*

CP parameters	Criteria						
	Finances and land take			Co-benefits			
	CAPEX [€]	OPEX [€]	Land take [m^2]	Retained water - water reuse [m^3]	Detained water - water cycle [m^3]	Plant space [%]	
Ideal value	330,012.29 €	1,421.59 €	0	3300	3765	20.00	
Anti-ideal value	8,448,316.37 €	114,527.50 €	6500	0	0	0.00	
Weights (w_i)	1.00	1.00	1.00	0.70	0.70	0.70	
SCM Scenario	d_i - normalized differences (degree of a discrepancy)						
3UST	0.38	1.00	0.00	1.00	1.00	1.00	
3RWH-ST	0.09	0.84	0.23	0.00	1.00	1.00	
3DP	0.00	0.13	0.26	1.00	0.00	0.50	
3IT	0.05	0.00	0.36	1.00	0.12	1.00	
3RG	0.05	0.25	0.74	1.00	0.13	0.00	
3BRC	0.13	0.34	1.00	1.00	0.10	0.00	
3GR	1.00	0.33	0.00	1.00	1.00	0.00	
SCM Scenario	$(w_i d_i)^p$						**L_p**
3UST	0.38	1.00	0.00	0.70	0.70	0.70	3.48
3RWH-ST	0.09	0.84	0.23	0.00	0.70	0.70	2.57
3DP	0.00	0.13	0.26	0.70	0.00	0.35	1.44
3IT	0.05	0.00	0.36	0.70	0.08	0.70	1.89
3RG	0.05	0.25	0.74	0.70	0.09	0.00	1.83
3BRC	0.13	0.34	1.00	0.70	0.07	0.00	2.24
3GR	1.00	0.33	0.00	0.70	0.70	0.00	2.73

The second-best scores were received by building-integrated SCMs, i.e. rainwater-harvesting storage tanks and green roofs, with Lp values of 2.57 and 2.73, respectively. The worst score was received by the representative of gray infrastructure, i.e. the underground storage tank, with an Lp value of 3.48. Although above and underground storage tanks rely on the same processes, rainwater-harvesting storage tanks demand lower CAPEX and OPEX than underground storage tanks while providing co-benefits of water retention in subcatchments. On the other hand, land needs to be provided for their implementation. Furthermore, underground storage tanks demand the highest OPEX, yet they do not provide any co-benefits. Green roofs demand the highest CAPEX and retain or detain no water. However, no land needs to be provided for the implementation of green roofs, and they provide maximum space for plants.

4. Discussion

Considering specific conditions of the experimental catchment, the MCDA results showed that landscape-integrated SCMs (i.e. detention ponds, infiltration trenches, rain gardens, and bio-retention cells) are preferred over building-integrated SCMs (i.e. green roofs, and rainwater-harvesting storage tanks). Specifically, the latter have high CAPEX and OPEX and provide only one co-benefit. Underground storage tanks proved to be the least favorable SCM as they provide no co-benefits, demand the highest OPEX, and the second-highest CAPEX. Alves et al. (2019) showed that a combination of green-blue-grey infrastructure is likely to result in the best adaptation strategy, as these alternatives complement each other by providing different types of benefits. Thus, in future research, SCM scenarios that combine different green-grey measures should be compiled and investigated.

The selection of evaluation criteria used in MCDA has a direct impact on evaluation results. Therefore, it is important to select criteria that cover different SCM aspects in order to minimize biased evaluation. In this research, two criteria groups (i.e. finances and land take, and co-benefits) were used, each comprised of three criteria.

The proposed evaluation framework could be further expanded with additional criteria. For example, carbon sequestration by plants could be calculated from the SCM area and plant space (i.e. parameter VF1). However, additional specifications regarding plant type should be provided. Similarly, savings on cooling/heating buildings due to green roofs or mitigating urban heat islands with other measures could be evaluated based on the SCM area (Alves et al., 2019).

No adaptations of the framework are needed for the investigation of future scenarios that can be expressed through input data or existing parameters. For example, the impacts of changing climate patterns (e.g. higher rainfall intensities) or urbanization (e.g. increased imperviousness) can be easily investigated by introducing new input data or changing existing parameters. In this way, the proposed evaluation framework can be used to identify more robust and resilient SCM scenarios.

To further improve the results of the applied MCDA, interviews with stakeholders and experts should be carried out to obtain additional information on the criteria's importance (Guzmán-Sánchez et al., 2018; Zhu et al., 2021). Consequently, new weights would be assigned to SCM evaluation criteria, potentially changing the scores of SCM scenarios and the order of preference for their implementation.

5. Conclusions

The presented research is based on a single-objective (i.e. catchment outflow) optimization of six alternative SCM scenarios. The resulting SCM design parameters were then evaluated using an MCDA, incorporating additional performance criteria such as CAPEX, OPEX, land use, retained water, detained water, and plant space. The main findings of the research are as follows:

1. The developed evaluation system, which is based on multi-criteria decision analysis, provides a transparent procedure that uses the

designed SCM parameter values to quantify and evaluate SCMs according to additional criteria.

2. Given the local conditions of the analyzed experimental urban catchment and considering additional criteria, the landscape-integrated SCMs were evaluated as more favorable measures as compared to the building-integrated SCMs, while at the same time providing similar hydrological performance (i.e. reduction of urban catchment outflow).
3. The lowest score was achieved by the underground storage tank, representing grey infrastructure or centralized SCMs.

Data availability

The data presented in this paper can be obtained from the corresponding author upon request.

Declaration of interest

The author declares no conflicts of interest. This paper was reviewed and corrected for grammar and style using deepl.com.

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