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An Integrated Approach to Determine Appropriate Stormwater Management Strategies for Urban Areas With Various Land-Uses: The Case of Güneysu

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ABSTRACT

This study focuses on a multi-criteria decision-making (MCDM) analysis backed by EPA's SWMM (storm water management model) to investigate stormwater management (SM) strategies for urban areas consisting of different land-use types. Güneysu city center (Rize, Türkiye) is used to exemplify areas consisting of impermeable surfaces, blocks of buildings, and green areas. The rising irregularity in expected rainfall coupled with unplanned urban development causes material damage and casualties worldwide. Extreme rainfalls and topographical factors worsen the scenario in regions with a high amount of precipitation. Güneysu city center consists of different land-use types located in a small region, and the reports from the Turkish Disaster and Emergency Management Presidency (AFAD) state 127 recent casualties from flood-related events in Rize. In this study, an MCDM approach is used to determine appropriate SM strategies for different land-use types in Güneysu. Additional SWMM simulations are carried out to compare total and mean surface runoff values to highlight the consistency of the findings. Results show that permeable pavements are the most suitable SM alternative for impermeable surfaces with a similarity (to ideal solution) coefficient 0.7488 in TOPSIS and a total surface runoff reduction rate of 74.271 % in SWMM. Similarly, rain gardens (TOPSIS: 0.7589, SWMM: 79.977 %) and green roofs (TOPSIS: 0.7679, SWMM: 68.789 %) are the most suitable alternatives for green areas and blocks of buildings, respectively. In contrast to literature, where SM planning studies mostly focus on a single type of land-use or single/combined SM approaches for specific regions, this study presents a tailored approach where suitable alternatives are assessed for each different type of land-use in a densely populated urban area. The most appropriate SM strategy is selected for each land-use type with an integrated approach that considers MCDM results with sensitivity analysis and SWMM simulations to achieve the best surface runoff reduction. This methodology provides a comprehensive approach for strategizing effective SM where combined SM alternatives are selected according to the specific characteristics of the land-use.

1 | Introduction

Global climate change poses a variety of challenges worldwide; however, the increasing frequency and intensity of extreme rainfall are the most significant threats to urban areas, particularly to those with high annual precipitation. In such regions, prolonged and heavy rainfall overwhelms drainage systems,

triggering urban flooding, infrastructure damage, soil erosion, and ultimately resulting in casualties. The replacement of natural land cover with impermeable surfaces due to urbanization reduces infiltration capacity and accelerates surface runoff, worsening the outcomes (Whitford et al. 2001). The resulting environmental and economic impacts, such as water quality degradation and increased recovery costs, highlight the significance

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of comprehensive SM solutions. The importance of proper SM is more critical for cities located in high-precipitation zones, since these issues cause persistent threats to urban sustainability and resilience. Effectively addressing the challenges of SM in high-precipitation urban areas requires integrated planning approaches that combine conventional drainage infrastructure with sustainable, nature-based solutions. Green infrastructure strategies, such as permeable pavements and bioswales, have shown great potential in mitigating the impacts of extreme rainfall by promoting water infiltration and reducing runoff volumes (Zeng et al. 2021). Coupled with stormwater retention systems, these strategies help mitigate pressure on urban drainage networks during peak precipitation events and even provide co-benefits, including enhanced biodiversity, improved urban esthetics, and greater climate adaptability.

A systematic approach to proper SM is inherently multidisciplinary, integrating perspectives from environmental science, engineering, urban planning, and beyond to address technical, ecological, social, and economic challenges in a comprehensive and sustainable manner. Design and optimization of SM infrastructure, the impact of precipitation patterns on stormwater systems, and cost–benefit analysis of SM solutions are some of the approaches from different perspectives. In this regard, multi-criteria decision-making (MCDM) methods offer a mathematical framework for the selection of appropriate SM strategies. This analytical framework for the selection enables the consideration of multiple influencing factors, such as hydrological conditions, cost, environmental impact, land-use, regulatory requirements, and community preferences. The use of MCDM methods for decision-making processes in a variety of fields has become increasingly popular in the last couple of decades, especially with the advance of computer technology in the late 20th century. It can be seen with quick research that more than 250 methods can be found in the current literature, and these methods enable a swift analysis of many alternatives with respect to many criteria using algorithms powered by software. Evaluation procedures, which would have been a difficult task some decades ago, can be more comprehensively processed today by using MCDM methods such as Analytic Hierarchy Process (AHP) and ELECTRE (Elimination Choix Traduisant la Relite—exception and choice reflecting reality).

In this study, the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS, Hwang and Yoon 1981) method will be used to determine the most appropriate SM strategies for different land uses. Güneysu, which is a district of Rize, Türkiye, will be used as a study area to exemplify the types of land uses involved in this study. Located on the Black Sea coastline, Rize is in the northeastern part of Türkiye and has the highest precipitation rate in the country. The city has an average of 2302 mm of annual precipitation according to the Turkish State Meteorological Service based on the data between 1928 and 2022 (Turkish State Meteorological Service (MGM), n.d.). AFAD (Turkish Disaster and Emergency Management Presidency) reports 127 casualties from floods and related disasters between 1970 and 2019, prior to the latest flood that affected Güneysu and other parts of Rize (Bekiryazıcı 2023). AFAD also reports around 221 million Turkish-lira (more than 10 million-euros) worth material damage because of the floods and landslides in Rize between 2010 and 2019 (Bekiryazıcı 2023).

TOPSIS is the second-most widely used MCDM method after AHP and finds extensive applications across various fields, including ecology. This simple yet powerful method is a suitable choice for analyzing decision-making problems in a wide range of areas. Recent applications of TOPSIS in ecology mainly focus on sustainability and security. Some of the recent important studies can be listed as follows: Pan et al. have used the TOPSIS method to evaluate vulnerability in the Yangtze River area (Pan et al. 2022). Zhao et al. have used TOPSIS and Entropy to evaluate the sustainable development of islands using data from China (Zhao et al. 2022). Ying et al. have used AHP and TOPSIS to optimize tourism strategies in China (Ying et al. 2023). Faramarzi and Hosseini have used TOPSIS for an investigation on the protection of biosphere reserves in Iran (Faramarzi and Hosseini 2023). Ma et al. have used a TOPSIS-based approach to evaluate the level of Green Development (Ma et al. 2023). Lianxiao et al. have used the TOPSIS method to evaluate regional flood disaster resilience using data from Tokyo, Japan (Lianxiao et al. 2022). It is seen that recent implementations of TOPSIS are mainly concentrated on using TOPSIS together with other methods on local scales for various ecological applications. TOPSIS has been employed numerous times in SM studies as well. This method provides a valuable tool for comparing alternatives when balancing criteria such as drainage system design, flood control strategies, water storage capacity, and environmental impacts that need to be assessed to determine the appropriate SM strategy. Some studies have highlighted the use of this method for prioritizing infrastructure in flood management or selecting the most appropriate strategies. In these applications, TOPSIS's ability to handle complex interrelationships between criteria in an objective and transparent manner has been emphasized. De Brito and Evers (2016) provided the applications of SM in terms of MCDM methods and showed the significance of these methods in this area. Axelsson et al. (2021) applied AHP-TOPSIS to prioritize infrastructure solutions for urban flood management. This approach supported the selection of flood prevention strategies in densely populated cities such as New York City. Sheikh et al. have used TOPSIS to assess low-impact development alternatives for SM in Iran (Sheikh and IZANLOO 2021). Chae et al. have used TOPSIS and VIKOR methods to investigate the siting of permeable pavements in highly urbanized watersheds (Chae et al. 2022). Mousavi et al. have used TOPSIS together with other statistical and MCDM methods to map flood susceptibility in Iran (Mousavi et al. 2022). Mani et al. have used TOPSIS for optimal management of urban runoff with low-impact development stormwater control measures (Mani et al. 2019). Shariat et al. have made a risk analysis of urban stormwater infrastructure systems using a fuzzy MCDM approach including the TOPSIS method (Shariat et al. 2019). These studies illustrate that TOPSIS is a reliable tool for evaluating alternatives in SM processes.

This study aims to provide a novel assessment approach for SM applications for regions with diverse land-use types. Feasible management approaches for different land-uses, all placed within the same region, will be assessed by TOPSIS to determine the best solution for each land-use type. These areas will then be further investigated using EPA's (United States Environmental Protection Agency) storm water management model (SWMM) to run simulations of the recommended applications. Total and mean surface runoff before and after the application of the

recommendations obtained with TOPSIS method will be compared, along with the results from other alternatives as well, to support the outcomes of the MCDM approach. The need for proper SM is dire in areas with excessive precipitation; therefore, data from a densely populated area with different land types will be used to exemplify the methodology. This study aims to add to the existing literature using TOPSIS method for SM. There are existing studies such as Luan et al. (2019) which use SWMM-TOPSIS method to evaluate green stormwater infrastructure strategy efficiencies.

Literature mainly consists of studies that focus on the use of a single SM strategy, or a combination of multiple SM strategies at the same time, for a single type of land-use or for a whole region. Such studies, some of which have been listed above, contain MCDM-focused investigations with area-specific analysis. This study aims to provide an integrated analysis which provides tailored SM solutions to urban areas consisting of multiple land-use types. Suitable SM alternatives are analyzed for each type of land-use within the region of interest and an MCDM analysis backed by SWMM simulations is carried out to determine the best solution for each land-use type. The TOPSIS method with a sensitivity analysis and SWMM simulations that reflect the real geographical data and the scenario modeled by each decision matrix in the TOPSIS method are used to pinpoint the most appropriate SM strategy for each case. Data from Güneysu city center in Rize, Türkiye—a densely populated area—is used to investigate the most appropriate SM strategy for areas consisting of impermeable surfaces, green areas, and areas containing blocks of buildings. Various SM alternatives, obtained among widely used approaches in literature, are investigated with the TOPSIS method using criterion weights based on expert opinions (Bekiryazıcı 2023). The TOPSIS approach is further discussed with a sensitivity analysis and results for each land-use type are determined. The decision matrices used in the TOPSIS and real geographical data for each area in Güneysu city center are then used to simulate the surface runoff reduction in a daily heavy rain scenario in SWMM with the implementation of each SM alternative for a comparative analysis. A comprehensive analysis is sought, with discussion of how changes in criteria weights may affect the outcomes, how the internal rankings of SM alternatives in the TOPSIS and SWMM approaches may be interpreted and how the findings of the study contribute to the literature. This study is intended to set an example for SM studies on areas composed of different land-use types such as city centers. The main contributions of the study can be summarized as follows:

- TOPSIS method and its use for determining the most appropriate stormwater management strategies for different land-use types in a specific region are presented.
- Three types of land uses (impermeable surfaces, green areas, and blocks of buildings) within Güneysu city center (Rize/Türkiye) are used to show how the TOPSIS method allows a straightforward analysis in relation to the changes in the environment and planning.
- Sensitivity analysis has been given to investigate the effects of changes in criteria weights on the outcomes of the MCDM analysis.

- SWMM simulations for a heavy rain scenario are carried out with matching inputs to support the results from the TOPSIS method.
- Results from SWMM and TOPSIS are compared for ordering of alternatives and the magnitudes of the outputs from both methods.

2 | Methods

This section contains a presentation of the TOPSIS method, as well as details of the study area. The decision matrices used for TOPSIS calculations for each land-use type are also given below. It is important to note that these land-use types were selected because the application area, Güneysu city center, mainly consists of impermeable surfaces, green areas, and blocks of buildings.

2.1 | TOPSIS Method

TOPSIS is an MCDM method that ranks alternatives based on their distances to an ideal solution (Hwang and Yoon 1981). It stands out among other methods with its use of positive and negative ideal solutions. Unlike other methods such as AHP (Saaty 1990) which separately determines criteria weights, SAW (Simple Additive Weight), which focuses only on maximizing scores, EDAS (Evaluation based on Distance from Average Solution) (Keshavarz Ghorabae et al. 2015) which uses the average solution for the comparison, or TODIM (an acronym in Portuguese for Interactive and Multicriteria Decision Making), which is based on prospect theory and considers the decision-maker preferences, the advantage of TOPSIS lies in balancing between criteria while considering their mutual interactions (Köseoğlu et al. 2020; Köseoğlu and Şahin 2019). A distinctive feature of TOPSIS is its use of the ideal solution concept, which provides decision-makers with robust criteria for evaluation. By relying on Euclid distances (which can also be taken as any other distance measure), it provides clear and interpretable rankings, even for complex problems. Moreover, it equally accounts for criteria aiming for maximization (positive effects) and minimization (negative effects), making it particularly effective in multidimensional issues such as environmental impact assessments, cost analyses, and risk management. TOPSIS also succeeds in computational simplicity, scalability to large datasets, and ease of integration with software tools. Its flexibility allows it to be combined with other weighting techniques, such as AHP or Entropy, further enhancing its applicability. These attributes make TOPSIS a versatile and efficient tool for the investigation of appropriate SM approaches compared to other MCDM methods. The criteria determined by the management team of an implementation project could easily be adapted into the TOPSIS algorithm; these criteria and their weights could be updated easily according to the changes in the project, the distances to the negative and positive ideal solutions could be used to further assess the alternatives, and the similarity coefficients would provide a straightforward decision-making as well as an analysis of the degree of suitability for several SM applications.

The algorithm for TOPSIS method is given as follows. Using a set of m alternatives A_1, A_2, \dots, A_m and a total of n criteria

C_1, C_2, \dots, C_n , the decision matrix A is formed as below (Hwang and Yoon 1981).

$$A = \begin{matrix} & C_1 & C_2 & \dots & C_n \\ \begin{matrix} A_1 \\ A_2 \\ \dots \\ A_m \end{matrix} & \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \end{matrix} \quad (1)$$

Here, $a_{ij}, i = 1, \dots, m, j = 1, \dots, n$ denote the value of alternatives A_i according to the criteria C_j . Some of the criteria are categorized as benefit criteria (J^+) and others as cost criteria (J^-). The decision matrix A consists of $m \times n$ values representing the value of each alternative with respect to each criterion.

The decision matrix $A = (a_{ij})_{m \times n}$ is then normalized as

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^m a_{kj}^2}} \quad (2)$$

and the normalized decision matrix $R = (r_{ij})_{m \times n}$ is obtained. The normalized decision matrix limits the values $a_{ij} \in \mathbb{R}$ of the decision matrix to the interval $[0, 1]$, that is, $r_{ij} \in [0, 1]$. The normalized decision matrix

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \dots & \dots & \dots & \dots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \quad (3)$$

is then assigned weights using the weight vector

$$W = [w_1 \ w_2 \ \dots \ w_n] \quad (4)$$

which consists of the criterion weights such that $w_j \in [0, 1]$ and $\sum_{j=1}^n w_j = 1$ corresponding to each of the criteria $C_j, j = 1, \dots, n$. The elements of the weighted normalized decision matrix $T = (t_{ij})_{m \times n}$ is obtained through the multiplication given by

$$t_{ij} = r_{ij} \times w_j, i = 1, \dots, m, j = 1, \dots, n \quad (5)$$

and thus

$$T = (t_{ij})_{m \times n} = \begin{bmatrix} r_{11}w_1 & r_{12}w_2 & \dots & r_{1n}w_n \\ r_{21}w_1 & r_{22}w_2 & \dots & r_{2n}w_n \\ \dots & \dots & \dots & \dots \\ r_{m1}w_1 & r_{m2}w_2 & \dots & r_{mn}w_n \end{bmatrix} \quad (6)$$

The positive and negative ideal solutions are determined from the values of the weighted normalized decision matrix $T = (t_{ij})_{m \times n}$. The positive ideal solution A^+ maximizes the benefit and minimizes the cost whereas the negative ideal solution A^- minimizes the benefit and maximizes the cost. For $j = 1, \dots, n$

$$A^+ = \left\{ t_j^+ \right\} = \begin{cases} \max(t_{ij}), i = 1, \dots, m, j \in J^+ \\ \min(t_{ij}), i = 1, \dots, m, j \in J^- \end{cases} \quad (7)$$

$$A^- = \left\{ t_j^- \right\} = \begin{cases} \min(t_{ij}), i = 1, \dots, m, j \in J^+ \\ \max(t_{ij}), i = 1, \dots, m, j \in J^- \end{cases} \quad (8)$$

Each alternative A_1, A_2, \dots, A_m has their distances to the positive ideal (d_i^+) and negative ideal solutions (d_i^-) measured as

$$d_i^+ = \sqrt{\sum_{j=1}^n (t_{ij} - t_j^+)^2}, d_i^- = \sqrt{\sum_{j=1}^n (t_{ij} - t_j^-)^2} \quad (9)$$

Thus, m pairs of distances to the positive and negative ideals are measured. These distances are used to obtain the similarity of each alternative to the negative ideal. The similarities to the worst condition $S_i^*, i = 1, \dots, m$ are calculated as

$$S_i^* = \frac{d_i^-}{d_i^- + d_i^+} \quad (10)$$

for each alternative such that $0 \leq S_i^* \leq 1$. As S_i^* approaches one, the alternative moves away from the negative ideal, that is, becomes a better alternative. The alternatives are ranked using S_i^* in ascending order. The alternative with the highest S_i^* value is selected as the most appropriate alternative. The calculation of the similarity coefficient detailed in (10) fundamentally measures the ratio of the Euclidean distance of each alternative to the negative ideal (d_i^-) to the sum of its distances to the positive and negative ideals ($d_i^- + d_i^+$). As the similarity coefficient approaches 1, it can be said that the rate of the distance from the alternative to the negative ideal approaches its total distance to the positive and negative ideals. This can be interpreted as the value of the alternative for each criterion being very close to the positive ideal solution (and consequently being farther from the negative ideal solution).

2.2 | Study Area

Rize is the region with the highest annual precipitation in Türkiye and one of its districts, Güneysu, has been selected as the study area. An annual precipitation of approximately 2300mm has resulted in floods and overflows numerous times in recent years. The center of Güneysu (~65 acres) contains the densely positioned square, hospital, municipality, district governorship, commercial areas, and residential areas (Figure 1a). These areas are categorized into three groups according to the land-use and ground characteristics to exemplify the methodology for different land typologies. The groups are the impermeable surfaces (i), green areas (ii), and blocks of buildings (iii). The alternatives for stormwater management (SM) strategies are given as follows:

- A_1 : Permeable pavements (PP), A_2 : Rain gardens (RG),
- A_3 : Bioswales (BS),
- A_4 : Bioretention areas (BR), A_5 : Green roofs (GR),
- A_6 : Rain barrels (RB).

The selected alternatives for the study were determined based on their proven effectiveness and suitability for specific urban conditions, as demonstrated in the literature. Selected alternatives from A_1, \dots, A_6 will be investigated with TOPSIS method

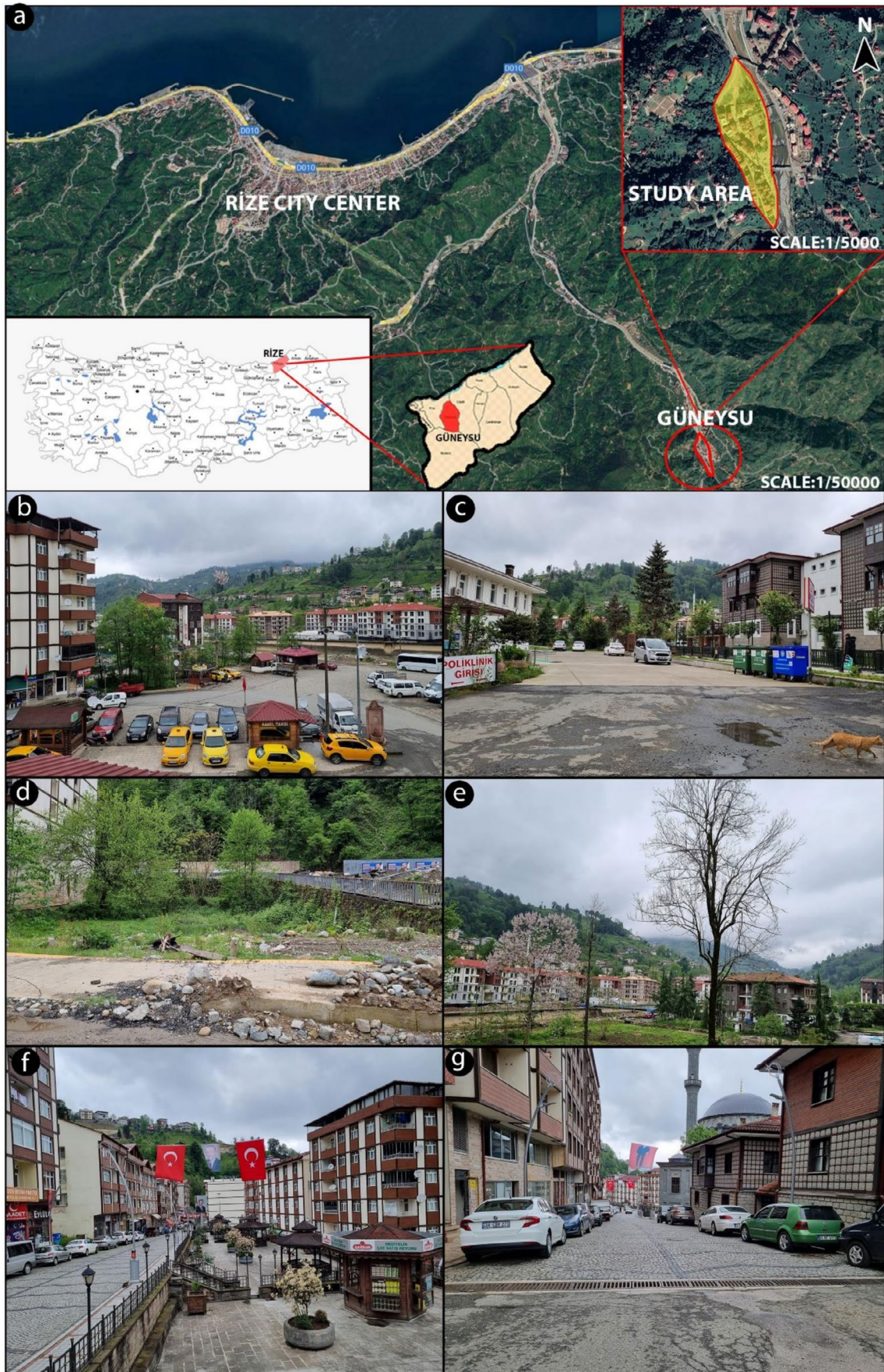


FIGURE 1 | Details of the study area (a) Location of Güneysu, (b, c) impermeable surfaces, (d, e) green areas and (f, g) blocks of buildings in Güneysu city center.

to determine the most suitable strategy for each type of land-use (i), (ii), and (iii). These alternatives will constitute the rows of the decision matrix A in (1), meaning the SM strategies PP, RG, and so forth will become the alternatives for the TOPSIS method for each decision-making problem. The selection process of suitable alternatives for each type of land-use considered the hydrological, ecological, and spatial characteristics of the study areas, ensuring that the proposed strategies align with the environmental and structural needs of high-rainfall urban zones. These alternatives are widely acknowledged in the field of sustainable urban water management as effective solutions for mitigating stormwater-related issues.

Although there are six alternatives in the study, only suitable alternatives will be assessed for each type of land use in the applications. These suitable alternatives will be assessed with TOPSIS method to determine the best approach for each type of land-use. For instance, instead of evaluating BS and BR for areas containing blocks of buildings, GR and RB will be evaluated. The first four alternatives will be assessed for impermeable surfaces and green areas in Güneysu city center, whereas only A_1 , A_5 and A_6 will be assessed for the last application. BR will not be considered as a viable option for blocks of buildings in the city center in this study.

The criteria for the assessment of the alternatives obtained from literature can be given as follows:

- C_1 : Surface cover permeability, C_2 : Slope, C_3 : Rainfall,
 C_4 : Biodiversity, C_5 : Area size, C_6 : Cost.

These six criteria will be used for all the examples focusing on Güneysu city center. It should be noted that C_1 , C_4 , and C_5 are the benefit criteria, whereas C_2 , C_3 , and C_6 are the cost criteria for this study. Here, surface cover permeability (C_1) and slope (C_2) are given as percentages (%), rainfall (C_3) refers to the annual precipitation data in mm, biodiversity (C_4) values are ratings for the alternatives from 1 to 5, area size (C_5) is given in m^2 and cost (C_6) is given in Turkish liras (TL) in the decision matrices. The criteria will be defined in terms of applicability or valuation of alternatives with respect to the given description. For instance, although the total area of Güneysu city center is the same, the different values for the alternatives related with the criterion “Area size” will refer to the area within the city center in which the alternative can be implemented. In a similar manner, surface cover permeability represents the assessment results for site-specific suitability of the alternative according to land-use compatibility, morphological constraints, and practical implementation feasibility for each area type. For instance, a value of 70 for PP in the decision matrix for impermeable surfaces refers to the fact that PP can be applied up to 70% of the area (33,000 m^2) for the impermeable surfaces in Güneysu city center. Biodiversity scores from 1 to 5 were determined with respect to vegetation structural diversity rather than species richness alone. A 1–5 scoring scale was used, where systems with multiple vegetation layers (e.g., trees, shrubs, and ground covers) received higher scores than those with a single vegetation form. The varying value for the criterion “Rainfall” refers to the precipitation data in which the application area will be subject to

after implementation of the alternative, providing a projection of resilience of the area to rainfall after the application of the SM strategy. The criterion “slope” refers to the approximate value that will be obtained after the implementation of the alternative, rather than the slope of the current area before the implementation.

2.3 | Strategies for Impermeable Surfaces

Data obtained from areas containing impermeable surfaces in Güneysu city center (Figure 1b,c) will be used to assess the alternatives $A_i, i = \overline{1, 4}$ with the criteria $C_j, j = \overline{1, 6}$. The decision matrix D_1 is given below.

$$D_1 = \begin{bmatrix} 70 & 10 & 600 & 1 & 33300 & 40000 \\ 20 & 10 & 1800 & 3 & 7400 & 10000 \\ 30 & 10 & 1600 & 3 & 11100 & 15000 \\ 10 & 10 & 2000 & 4 & 3700 & 7500 \end{bmatrix} \quad (11)$$

The values in the decision matrices have been determined through market research, area evaluation, and investigation of area information from official resources. Among the values in the decision matrix, slope refers to the value found by calculating the average slope percentages of the areas, rainfall is the value extracted according to the size of the area in the light of the data received from the General Directorate of Meteorology, vegetative diversity is valued from 1 to 5 by analyzing the total vegetative diversity in the areas (on the basis of trees, shrubs, ground cover and how many species it consists of in total) through field observations, total area size is the total size of the application areas for each alternative in square meters. For instance, the numbers on the fifth column, {33000, 7400, 11100, 3700}, refer to the size of the areas on which the corresponding alternatives can be applied. Relevant literature on cost values (Sample et al. 2003; Braden and Ando 2011; Babchanik et al. 2022), infiltration value of subsoil layers (Yang and Zhang 2011; Alizadehtazi et al. 2016; Redfern et al. 2016) and surface cover permeability (Alizadehtazi et al. 2016; Alonso de Andrade et al. 2018; Sun et al. 2018) were used to determine the corresponding values. The criteria will be weighed up using the weight vector given below.

$$w = [0.30 \quad 0.15 \quad 0.25 \quad 0.10 \quad 0.10 \quad 0.10] \quad (12)$$

This means that, for instance, the sixth criterion “Cost” has a 10% importance for the analysis. The criterion weights have been distributed to sum up to 100% and for this land-use type, the dominating criteria are “Surface cover permeability” and “Rainfall” with 30% and 25% weights, respectively. The weight vector was developed by some of the authors in a previous study based on expert opinions. Fifty leading researchers and professionals from around the world were asked about their opinions for what the weights should be for the criteria C_1, C_2, \dots, C_6 when assessing the alternatives A_1, A_2, \dots, A_6 . The responses were then averaged to obtain the weight vector (12) shown above (Bekiryazıcı 2023; Bekiryazıcı and Acar 2024). It should be noted that the criteria have the same categories (benefit or cost) in all three applications within the study.

2.4 | Strategies for Green Areas

The second application contains data obtained from districts consisting of green areas in Güneysu city center (Figure 1d,e). The alternatives $A_i, i = \overline{1,4}$ will be assessed by using the criteria $C_j, j = \overline{1,6}$ with the same weight vector w . The decision matrix D_2 is given below.

$$D_2 = \begin{bmatrix} 10 & 5 & 2000 & 1 & 1300 & 2000 \\ 80 & 10 & 400 & 3 & 10400 & 15000 \\ 30 & 10 & 1600 & 3 & 3900 & 5000 \\ 20 & 10 & 1800 & 4 & 2600 & 5000 \end{bmatrix} \quad (13)$$

2.5 | Strategies for Blocks of Buildings

The third application will be made for areas of blocks of buildings in Güneysu city center (Figure 1f,g). For this application, only the first three alternatives A_1, A_5, A_6 will be assessed with the same criteria $C_j, j = \overline{1,6}$ using weight vector w . The decision matrix D_3 for blocks of buildings in Güneysu city center has been obtained as follows:

$$D_3 = \begin{bmatrix} 10 & 5 & 2000 & 1 & 2000 & 3000 \\ 70 & 5 & 600 & 3 & 22000 & 20000 \\ 10 & 10 & 2100 & 1 & 500 & 1000 \end{bmatrix} \quad (14)$$

Note that the decision matrices D_1, D_2 , and D_3 were created in a detailed manner, as shown above. The decision-making problem for the selection of the most suitable SM strategies could be investigated in a more detailed manner using additional criteria to integrate economic and lifecycle components. However, the present study adopts a hydraulically oriented comparative framework, focusing on the runoff reduction potential before broader economic considerations are introduced. Although it is acknowledged that maintenance requirements and lifecycle conditions may influence the long-term performance and sustainability of Low Impact Development (LID) systems (Sagrelus et al. 2023; Wang et al. 2021), it was decided that a detailed economic evaluation, including construction, maintenance, and lifecycle costs was beyond the scope of a concise hydraulically oriented study.

2.6 | Storm Water Management Model (SWMM)

SWMM is an open-source public software developed by the US Environmental Protection Agency (EPA) that can be used to perform simulations related to the planning, analysis, and design related to stormwater runoff (United States Environmental Protection Agency (EPA), n.d.). The software can be used to simulate surface runoff and infiltration as well as the performance of LID controls and is widely used for the investigation of SM systems. The software is publicly and freely available online at <https://www.epa.gov/water-research/storm-water-management-model-swmm> and will be used to evaluate gray infrastructure stormwater control alternatives A_1, \dots, A_6 based on the reduction in total and mean surface runoff values (given in m^3/s) for each strategy in each type of land-use. The study area (Güneysu city center) is introduced to SWMM software as three sub-catchments (sub-watersheds) according to the land-use status

and surface coverage in accordance with the problem examined in the study.

3 | Results

The similarity coefficients obtained with TOPSIS are shown below for all three land-use types (Figure 2). These results have been obtained by using a MATLAB algorithm which provides positive and negative ideal solutions along with the similarity coefficients of each alternative to these ideals for given sets of decision matrices and weight vectors.

Note that the similarity coefficients denote how close the values of the alternatives for each criterion are to the ideal solution. As the similarity coefficient for an alternative approaches one, this can be interpreted as the alternative having ideal values for each criterion compared to the other alternatives. Consequently, as the similarity coefficient for an alternative approaches zero, this will be interpreted as the alternative having values that are worse for each criterion compared to the other alternatives. For instance, an alternative—say PP—having a similarity coefficient of $S_i = 1$ means that all of its values corresponding to each criterion are the ideal values for the considered decision-making problem, whereas a similarity coefficient of zero, that is, $S_i = 0$, for PP would mean that none of its values are ideal for the case.

3.1 | Impermeable Surfaces

Using the decision matrix D_1 and the weight vector w_1 , the positive and the negative ideal solutions have been calculated with the weighted normalized decision matrix. For instance, the first column of the decision matrix is normalized by $\sqrt{\sum_{k=1}^m a_{k1}^2} = \sqrt{6300}$

given in (2) which gives $r_{11} = 0.8819$. Similar normalization of all elements in D_1 and the weighting of the normalized matrix (obtained by multiplying the normalized decision matrix with the transpose of the weight vector—as in Equation (6)) gives the weighted matrix T_1 . Using this matrix, the positive ideal solution (p_1) has been found as:

$$p_1 = \begin{bmatrix} 0.2646 & 0.0750 & 0.0471 & 0.0676 & 0.0923 & 0.0168 \end{bmatrix} \quad (15)$$

whereas the negative ideal solution (n_1) has been found as

$$n_1 = \begin{bmatrix} 0.0378 & 0.0750 & 0.1569 & 0.0169 & 0.0103 & 0.0899 \end{bmatrix}. \quad (16)$$

p_1 and n_1 have been obtained from the decision matrix using the normalization (2) for (11). The normalized matrix is multiplied with the weight vector (12) using the vector multiplication (5). p_1 and n_1 are determined from the weighted normalized decision matrix using (7) and (8). The distances between alternatives to the positive and negative ideal solutions p_1 and n_1 , and the similarity coefficients $S_{1i}, i = \overline{1,4}$ calculated from these distances are given below (Table 1). Results show that permeable pavements (PP) are the best alternative for this type of land use (Figure 2).

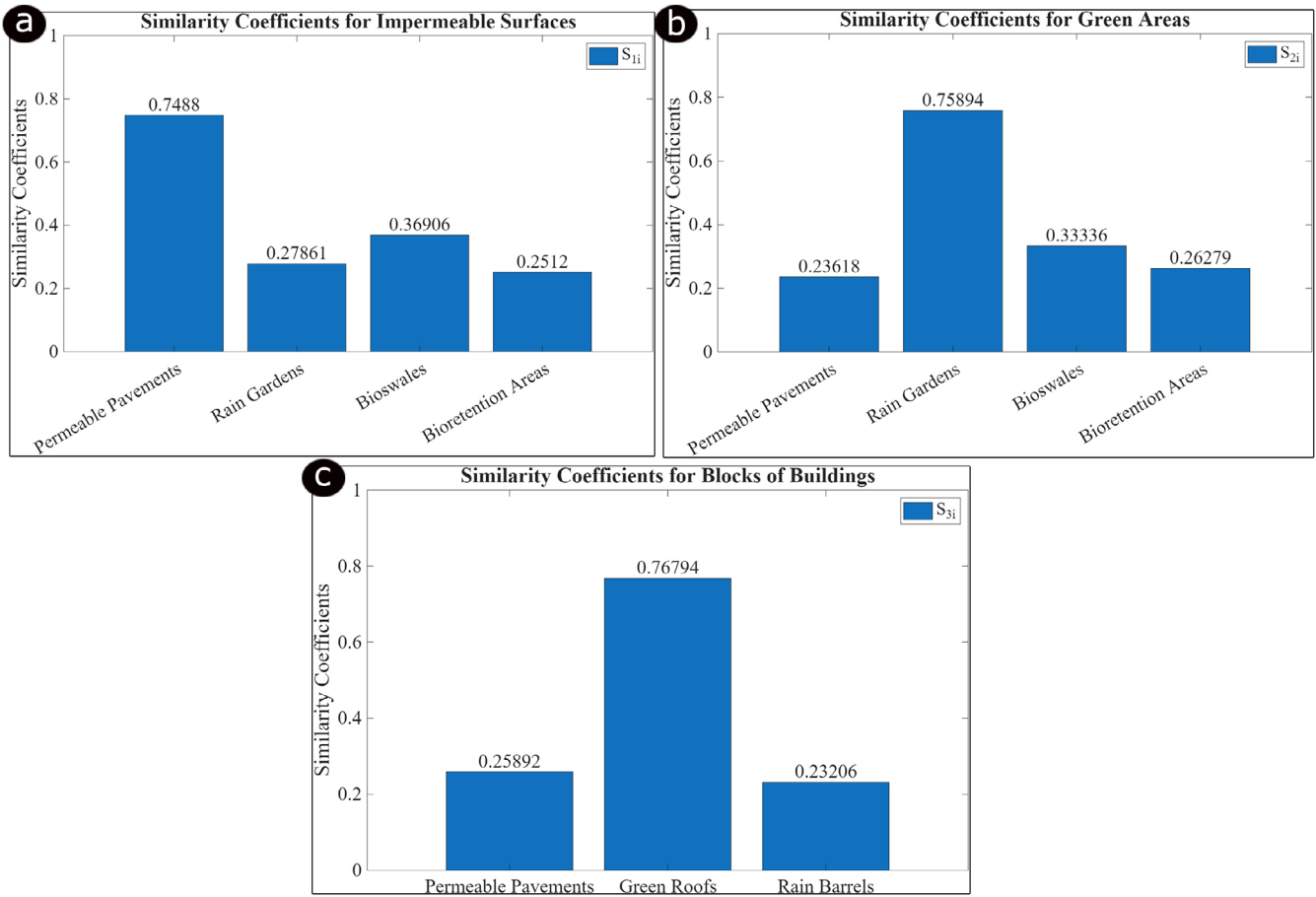


FIGURE 2 | Similarity coefficients S_{1i} (impermeable surfaces), S_{2i} (green areas) and S_{3i} (blocks of buildings).

TABLE 1 | Results for impermeable surfaces.

Alternatives	Distances to		Coefficient
	p_1	n_1	S_{1i}
Permeable pavements	0.0889	0.2650	0.7488
Rain gardens	0.2237	0.0864	0.2786
Bioswales	0.1827	0.1069	0.3691
Bioretention areas	0.2650	0.0889	0.2512

TABLE 2 | Results for green areas.

Alternatives	Distances to		Coefficient
	p_2	n_2	S_{2i}
Permeable pavements	0.2854	0.0883	0.2362
Rain gardens	0.0899	0.2829	0.7589
Bioswales	0.2084	0.1042	0.3334
Bioretention areas	0.2460	0.0877	0.2628

A similarity coefficient of 0.7488 means that PP is the best stormwater management strategy for impermeable surfaces in Güneysu city center. The other alternatives have similarity coefficients varying around 0.27 to 0.37, meaning permeable pavements are clearly the best alternative for this type of land use.

3.2 | Green Areas

The same method has been used to obtain the positive and negative ideal solutions p_2 and n_2 for the second application area using the decision matrix D_2 and the weight vector w . Using (7) and (8) on the weighted normalized decision matrix obtained from (12) and (13), the positive ideal solution (p_2) has been found as:

$$p_2 = [0.2717 \quad 0.0416 \quad 0.0317 \quad 0.0676 \quad 0.0906 \quad 0.0120] \tag{17}$$

whereas the negative ideal solution (n_2) has been found as

$$n_2 = [0.0340 \quad 0.0832 \quad 0.1584 \quad 0.0169 \quad 0.0113 \quad 0.0898] \tag{18}$$

The distances of the alternatives to the positive and negative ideal solutions have been given below along with the similarity coefficients S_{2i} , $i = 1, 4$ (Table 2, Figure 2).

Results show that RG are the best alternative by far with a similarity coefficient of 0.7589 for green areas in Güneysu city center.

3.3 | Blocks of Buildings

The TOPSIS method has been applied to assess the first three strategies for the area containing blocks of buildings in Güneysu city center, for which the decision matrix D_3 and the weight vector w are used. The positive ideal solution (p_3) has been found as:

$$p_3 = \begin{bmatrix} 0.2941 & 0.0612 & 0.0507 & 0.0905 & 0.0996 & 0.0049 \end{bmatrix} \quad (19)$$

and the negative ideal solution (n_3) has been found as

$$n_3 = \begin{bmatrix} 0.0420 & 0.1225 & 0.1773 & 0.0302 & 0.0023 & 0.0988 \end{bmatrix}. \quad (20)$$

The distances of the alternatives to the positive and negative ideal solutions have been given below in addition to the similarity coefficients S_{3i} , $i = 1, 4$ (Table 3, Figure 2).

Results show that GR are clearly ahead of PP and RB for the area containing the blocks of buildings in Güneysu city center. GR are the most suitable SM strategy for this type of land-use with a similarity coefficient of 0.7679 positioned above the second alternative PP with a similarity coefficient of 0.2589.

Another advantage of applying the TOPSIS method for the analysis is the ability to adapt to changing conditions within the investigation. For instance, if the ‘‘Cost’’ criterion suddenly becomes of crucial importance, the weight vector can be simply updated to model this condition and the corresponding change for the new most appropriate strategy can be observed. If the weight vector becomes $w^* = [0.10 \ 0.05 \ 0.10 \ 0.05 \ 0.05 \ 0.65]$, the new suitable strategy for the green areas in Güneysu suddenly becomes PP, with RG now becoming the least favorable alternative, due to its significantly higher cost.

3.4 | Sensitivity Analysis

To evaluate the robustness and reliability of the proposed SWMM-backed MCDM framework, a sensitivity analysis is conducted with respect to variations in criterion weights. Since the weighting scheme plays a crucial role in MCDM processes and directly influences the TOPSIS ranking outcomes, even moderate changes in criterion importance may affect the prioritization of stormwater management strategies. In this study, multiple weighting scenarios are considered by assigning different weight distributions to the evaluation criteria based on alternative planning perspectives. For each scenario, the TOPSIS procedure is reapplied using different but close weights and the resulting

similarity coefficients and ranking orders are compared. This analysis aims to determine whether the recommended stormwater management strategies remain stable under varying assumptions about criterion importance and to demonstrate the robustness of the proposed decision framework.

For the impermeable surfaces case, the sensitivity analysis was performed by slightly modifying the weights. The initial weight vector $w^{(0)}$ represents the base evaluation scenario. Additional scenarios $w^{(1)}-w^{(3)}$ were generated by moderately increasing the weights of relatively influential criteria and reducing the others. In particular, the weights of the first three criteria ($C_1 - C_3$), which have relatively higher initial importance levels, were individually increased by 0.05. Three criteria ($C_4 - C_6$) with relatively small weights were not varied individually, as their limited contribution to the overall decision score suggests that they are less likely to cause noticeable changes in the ranking results. This allowed us to focus on the criteria that are expected to have a more meaningful impact on the decision process. As seen in Table 4, the ranking order remains stable despite these moderate weight changes. Minor numerical differences in similarity coefficients were observed, but they did not lead to any changes in the prioritization of alternatives. This indicates that the TOPSIS method gives consistent and reliable results for impermeable surface conditions.

A similar sensitivity analysis was also conducted for the green areas scenario using the same alternative weighting schemes applied in the impermeable surfaces case. The weights of the first three criteria were slightly increased (+ 0.05), while the remaining criteria were adjusted to preserve the unity constraint. The TOPSIS procedure was then repeated for green area conditions. The results show that the ranking order of the alternatives remained unchanged across all tested weight scenarios (Table 5). This stability indicates that the proposed decision framework yields consistent outcomes for green area planning conditions and is not affected by moderate variations in criterion importance.

A similar sensitivity analysis was also performed for the blocks of buildings scenario using the same alternative weighting schemes considered in the impermeable surfaces case (Table 6). The weight strategy was the same, and the results indicate that the ranking order of the alternatives remained unchanged across all tested weighting scenarios. This consistency suggests that the TOPSIS provides stable and reliable outcomes for urban block-scale stormwater management decisions and is not influenced significantly by moderate variations in criterion importance.

Overall, the sensitivity analyses conducted for impermeable surfaces, green areas, and blocks of buildings demonstrate the robustness of the TOPSIS method consistently. Across all three problem settings, alternative weighting scenarios were generated by moderately increasing the weights of the most influential criteria while adjusting the remaining ones to preserve the unity constraint. The repeated TOPSIS analyses showed that these moderate variations in criterion importance did not lead to any significant changes in the ranking structure of stormwater management alternatives. Although minor numerical differences in performance scores were observed, the prioritization of alternatives remained stable in all cases. This overall consistency suggests that the decision-making framework provides reliable and stable recommendations

TABLE 3 | Results for blocks of buildings.

Alternatives	Distances to		Coefficient
	p_3	n_3	S_{3i}
Permeable pavements	0.2990	0.1045	0.2589
Green roofs	0.0938	0.3105	0.7679
Rain barrels	0.3105	0.0938	0.2321

TABLE 4 | Impermeable surfaces.

Scenario	Weights	Ranking
$w^{(0)}$	$\begin{bmatrix} 0.30 & 0.15 & 0.25 & 0.10 & 0.10 & 0.10 \end{bmatrix}$	$A_1 > A_3 > A_2 > A_4$
$w^{(1)}$	$\begin{bmatrix} 0.35 & 0.14 & 0.24 & 0.09 & 0.09 & 0.09 \end{bmatrix}$	$A_1 > A_3 > A_2 > A_4$
$w^{(2)}$	$\begin{bmatrix} 0.29 & 0.14 & 0.30 & 0.09 & 0.09 & 0.09 \end{bmatrix}$	$A_1 > A_3 > A_2 > A_4$
$w^{(3)}$	$\begin{bmatrix} 0.29 & 0.20 & 0.24 & 0.09 & 0.09 & 0.09 \end{bmatrix}$	$A_1 > A_3 > A_2 > A_4$

TABLE 5 | Green areas.

Scenario	Weights	Ranking
$w^{(0)}$	$\begin{bmatrix} 0.30 & 0.15 & 0.25 & 0.10 & 0.10 & 0.10 \end{bmatrix}$	$A_2 > A_3 > A_4 > A_1$
$w^{(1)}$	$\begin{bmatrix} 0.35 & 0.14 & 0.24 & 0.09 & 0.09 & 0.09 \end{bmatrix}$	$A_2 > A_3 > A_4 > A_1$
$w^{(2)}$	$\begin{bmatrix} 0.29 & 0.14 & 0.30 & 0.09 & 0.09 & 0.09 \end{bmatrix}$	$A_2 > A_3 > A_4 > A_1$
$w^{(3)}$	$\begin{bmatrix} 0.29 & 0.20 & 0.24 & 0.09 & 0.09 & 0.09 \end{bmatrix}$	$A_2 > A_3 > A_4 > A_1$

TABLE 6 | Blocks of buildings.

Scenario	Weights	Ranking
$w^{(0)}$	$\begin{bmatrix} 0.30 & 0.15 & 0.25 & 0.10 & 0.10 & 0.10 \end{bmatrix}$	$A_2 > A_1 > A_3$
$w^{(1)}$	$\begin{bmatrix} 0.35 & 0.14 & 0.24 & 0.09 & 0.09 & 0.09 \end{bmatrix}$	$A_2 > A_1 > A_3$
$w^{(2)}$	$\begin{bmatrix} 0.29 & 0.14 & 0.30 & 0.09 & 0.09 & 0.09 \end{bmatrix}$	$A_2 > A_1 > A_3$
$w^{(3)}$	$\begin{bmatrix} 0.29 & 0.20 & 0.24 & 0.09 & 0.09 & 0.09 \end{bmatrix}$	$A_2 > A_1 > A_3$

for different urban surface conditions and is not overly sensitive to reasonable fluctuations in criterion weights.

3.5 | SWMM Simulation

The geographical data for Güneysu city center has been introduced into the system and the existing conditions have been simulated for a generic precipitation data of 90 mm rainfall within a 10-h period (Figure 3) which corresponds to heavy rainfall for a certain area in a day. The sub-catchments in Güneysu city center were divided to represent each of the areas with dense building blocks, green areas, and areas covered with impervious surfaces. In this way, the area sizes, topographic data (slope, average surface permeability ratio, etc.), and land-use details (land-use types, areas of each type, etc.) of all the sub-catchments were specified in the software. The map of Güneysu city center showing the sub-catchments, the network of conduits and junctions and the outlet is given in the figure along with the details about the duration and intensity of rainfall (Figure 3).

Sub-catchment sizes and slopes were calculated using Google Earth data and average surface permeability ratios were determined for each sub-catchment area based on Manning's

roughness values frequently used in the literature (based on the land-uses and surface coverings) (Kalyanapu et al. 2009; Arcement and Schneider 1989; Li and Zhang 2001). Principal input parameters for the sub-catchments containing impermeable surfaces, green areas, and blocks of buildings were specified in the program so that the simulation matches the cases investigated with the TOPSIS method. The correspondence between the TOPSIS decision matrices and SWMM inputs are presented below, where the settings for the sub-catchments and LID controls were specifically determined to guarantee synchronization between TOPSIS-SWMM investigations as well as synchronization between simulation results between sub-catchments. The settings given below have been obtained from the literature, and the remaining SWMM parameters have been used with their default values (Sun et al. 2022; Luan et al. 2017). The SWMM simulation has been designed to model a scenario that could result in material damage on an area whose parameters were specified in accordance with the real region and the inputs from TOPSIS decision matrices. The details for the Manning's roughness coefficient (N) for impervious areas (N-Imperv), Manning's roughness coefficient (N) for pervious areas (N-Perv), Average slope (%), Depression storage depth on impervious area (Dstore-Imperv) (in mm), Depression storage depth on pervious area (Dstore-Perv) (in mm), Width (m) and percentage of impervious areas for each of the sub-catchments have been given below (Table 7).

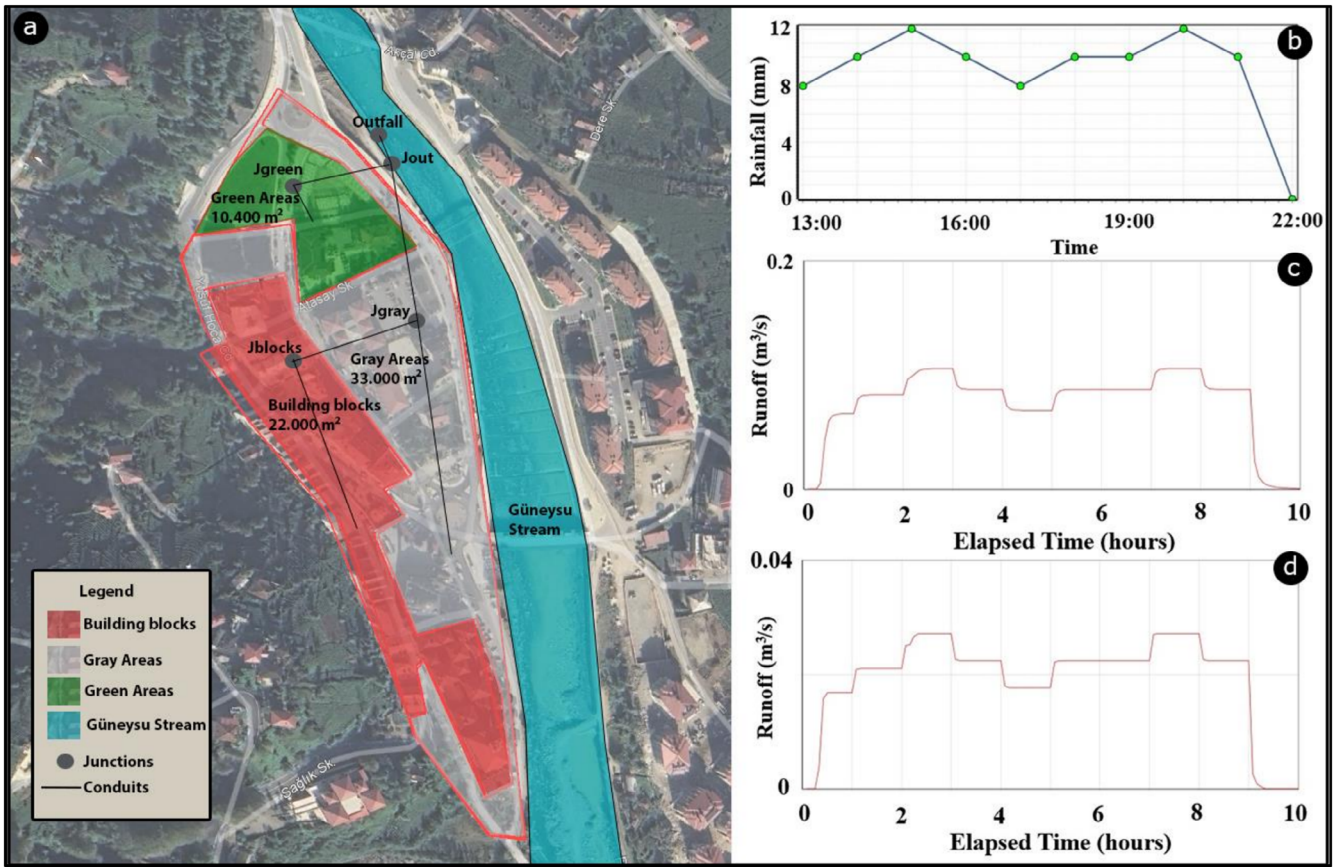


FIGURE 3 | (a) Güneysu city center divided into sub-catchments i—2.2 ha area for blocks of buildings, ii—3.3 ha area for impermeable surfaces, and iii—1.04 ha area for green areas; (b) initial rainfall simulated in SWMM, a total of 90 mm rainfall within 10 h; (c) surface runoff data for impermeable surface (in m^3/s) before the application of permeable pavements; (d) surface runoff data for impermeable surface (in m^3/s) after the application of permeable pavements.

TABLE 7 | Sub-catchment details.

Sub-catchment type and name	Area (ha)	N-Imperv	N-Perv	Dstore-Imperv	Dstore-Perv	Slope (%)	Width (m)	Imperv %
Impermeable Surfaces	3.3	Concrete, Asphalt—0.013	Short Grass, Lawn—0.15	Pavement—2.5	Short Grass, Lawn—4	8	470	90
Green Areas	1.04	Concrete, Asphalt—0.013	Short Grass, Lawn—0.15	Smooth Asphalt—1	Short Grass, Lawn—4	6	150	20
Blocks of Buildings	2.2	Concrete, Roofs—0.011	Short Grass, Lawn—0.15	Urban Surface—2	Compact Soil—3.5	14	420	90

SM alternatives A_1, \dots, A_6 were implemented to each sub-catchment in accordance with the decision matrices D_1, D_2, D_3 given in (11), (13), and (14). For instance, permeable pavements were applied to 70% of the area in impermeable surfaces since $d_{11} = 70$ in D_1 and to 10% of the area in green areas and blocks of buildings since $d_{11} = 10$ in D_2 and D_3 with a berm height value of 150 mm and a width of 1 m for each type of land-use. Bioswales were implemented to 30% of the area in impermeable surfaces and green areas since $d_{13} = 30$ in D_2 and D_3 with a surface slope of 2%, swale side slope of 3% and a surface roughness coefficient of 0.2 (Manning's N). Green roofs were applied to 70% of the area in blocks of buildings, treating 100% of the impervious surfaces, with a berm height of 50 mm and a soil thickness of 100 mm.

Results show that the initial total surface runoff for areas consisting of impermeable surfaces, green areas and blocks of buildings are obtained as 82.32, 17.73, and 84.65 m^3/s , respectively. Results for total runoff and mean runoff values are given below (Table 8). Once the initial runoff is obtained, stormwater management (SM) alternatives $A_i, i = 1, 6$ are applied to the city center in SWMM according to the data described in the decision matrices and specified above. The resulting total and mean surface runoff values for each land-use type (measured in m^3/s) after application of each alternative are given below.

The similarity coefficients S_i indicate that PP is the most suitable SM strategy for impermeable surface in Güneysu city center

TABLE 8 | SWMM results of runoff data Güneysu (in m³/s).

Impermeable surfaces				
Alternatives	Total runoff	Relative decrease	Mean runoff	Relative decrease
Initial simulation	82.32	—	0.077	—
Permeable pavements	21.18	74.271% ↓	0.022	71.429% ↓
Rain gardens	64.46	21.696%	0.065	15.584%
Bioswales	58.43	29.021%	0.055	28.571%
Bioretention areas	70.91	13.861%	0.072	6.494%
Green areas				
Alternatives	Total runoff	Relative decrease	Mean runoff	Relative decrease
Initial Simulation	17.73	—	0.006	—
Permeable pavements	14.36	19.007%	0.005	16.667%
Rain gardens	3.55	79.977% ↓	0.001	83.333% ↓
Bioswales	16.24	8.404%	0.005	16.667%
Bioretention areas	14.19	19.966%	0.005	16.667%
Blocks of buildings				
Alternatives	Total runoff	Relative decrease	Mean runoff	Relative decrease
Initial Simulation	84.65	—	0.054	—
Permeable pavements	69.12	18.346%	0.046	14.815%
Green roofs	26.42	68.789% ↓	0.019	64.815% ↓
Rain barrels	84.57	0.095%	0.054	0.000%

(Figure 2) followed by BS, RG, and BR, respectively. PP is still the most suitable SM strategy for impermeable surfaces according to the simulation results with a clear distinction in terms of the relative decrease ratios (Table 8) in total and mean runoff reduction. The similarity coefficient for PP is once again clearly above the coefficients of other SM alternatives for impermeable surfaces in TOPSIS results (Table 1). PP provides a 74.271% decrease in total surface runoff (given in m³/s) compared to the initial runoff value for the areas consisting of impermeable surfaces in Güneysu city center. The remaining alternatives are also ranked similarly as well. BS (29.021%), RG (21.696%), and BR (13.861%) are the following alternatives for decreasing total surface runoff for this land-use type in Güneysu. This is a strong indicator of the suitability of TOPSIS for determining the most appropriate SM strategy. The similarity of the internal rankings and relative proportions of SWMM total surface runoff decreases and TOPSIS similarity coefficients highlights the alignment between the results of the methods. Clearly, PP is much closer to 1 compared to the other alternatives, which is also similar for the relative decrease values from SWMM. The decrease in surface runoff provided by PP in SWMM is also significantly more than the relative decrease provided by the other alternatives. This is also a result of the correspondence between the decision matrix D_1 and the parameters used for the alternatives in SWMM. Since TOPSIS decision matrices and SWMM input parameters are calibrated to provide matching models for the impermeable surfaces in Güneysu city center, similar results are obtained for the suitability of the alternatives. Note that the

runoff reduction graphs for only impermeable surfaces have been given in Figure 3 for a concise presentation.

Considering the similarity coefficients S_{2i} for green areas and the relative decreases in SWMM for green areas (Table 8), it is seen that the same relation between the total surface runoff decrease of the best alternative to other alternatives is found once again. The similarity coefficient for RG (0.7589) is much closer to 1 and is followed by BS, BR, and PP. The decrease obtained with RG (79.977%) is much higher than the others, ordered as BR (19.966%), PP (19.007%), and BS (8.404%), respectively.

The internal ordering and the proportion of values for relative surface runoff decreases for alternatives of blocks of buildings are also similar for TOPSIS and SWMM. GR are the most appropriate alternative with a similarity coefficient of 0.7679, which is much higher than the next two alternatives: PP (0.2589) and RB (0.2321). SWMM simulations provide similar results with GR providing 68.789% decrease in total surface runoff whereas PP provide 18.346% and RB provide 0.095% decrease in total surface runoff for blocks of buildings in Güneysu city center.

The fact that PP received significantly higher similarity coefficient for impermeable surfaces may be related to its suitability for application in an already densely built city center. The decision matrices were formed using realistic assumptions and literature/market research and were compared to the other alternatives. PP have a wider application area since they can be

easily implemented on roads, pavements, and so forth. Similarly, green roofs have a wider applicability potential in a densely built city center where they can be applied on the roofs of buildings. It should be noted that the weights of the criteria are also important for these outcomes, and as exemplified above, a set of criteria that significantly promotes a single condition may result in a different result.

4 | Discussion

This study aimed to provide an integrated perspective to the selection of the most appropriate stormwater management (SM) strategy for regions containing several districts with topological differences. The data from Güneysu, Rize have been used as an example to present how an SWMM-backed MCDM approach could be used to investigate appropriate SM strategies for different parts of the city with varying structural properties. The selection of Güneysu is important, since the study area is one of the districts with the highest annual precipitation amount in Turkey (and the surrounding region), and as recent floods in 2021 and 2023 show (Figure 4), the increasing effects of global climate change and irregular urbanization only make proper SM more crucial for this area. Although Rize has a geography

rich in urban hydrology, this situation evolves into a negative situation for the city, since almost all the districts are located in river basins. Due to the increasing urbanization and global climate change, extreme rainfall exposes the urban settlements in river basins and corridors to disasters such as floods and landslides, causing material damage and casualties. It is seen in AFAD 2010–2020 data that the floods, landslides, and related disaster damages occurring after the rains have reached extremely serious points. As a matter of fact, as Silaydın Aydın and Kahraman (2022) state, Rize is one of the provinces with the highest vulnerability level in their study, in which they determined the vulnerability levels of cities against floods caused by extreme rainfall.

It is known that the negative effects of global climate change such as extreme weather conditions, rise in sea levels, and extreme precipitation are increasing. Therefore, the issue of stormwater management has become one of the most important planning priorities for Rize, and traditional methods have proven to be insufficient. In their study, Brierley and Fryirs (Brierley and Fryirs 2009) stated that traditional methods are a system based on a drainage system that aims to remove stormwater from urban areas to prevent flooding. The study indicates that this system is a single-functional approach and

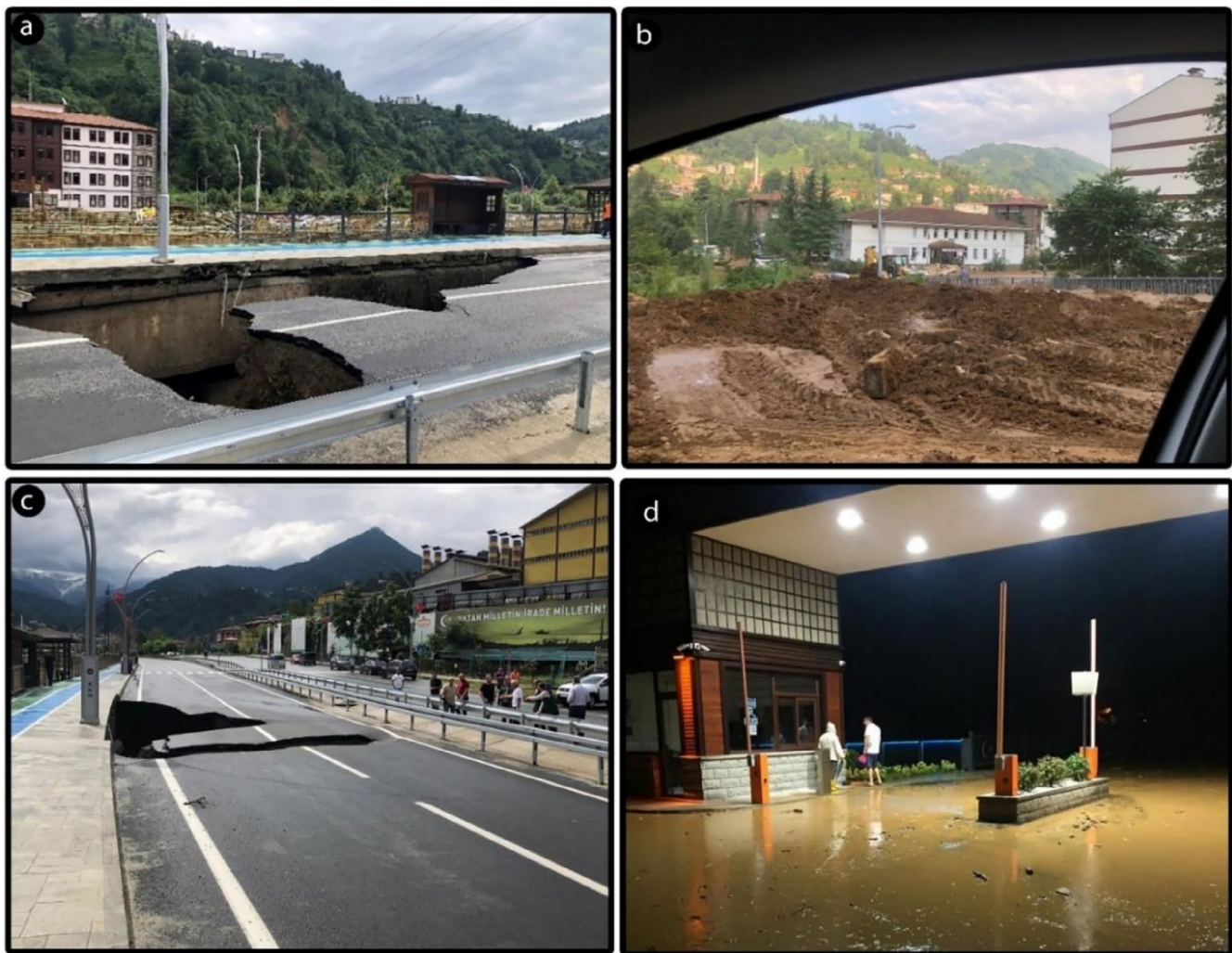


FIGURE 4 | (a) Road collapse in Güneysu, Rize after rainfall on August 25, 2023, and (b–d) flooded residential area near Güneysu on July 14, 2018 (6 casualties).

natural hydrological and geomorphic processes required for a healthy basin-ecosystem functioning were ignored. There are no studies for the province of Rize on stormwater management strategies and only few studies have been conducted for Turkey (Demir 2012; Müftüoğlu and Perçin 2015; Ünal and Akyüz 2018). However, there are many international studies on the subject (Barbosa et al. 2012; Hale 2016; Berland et al. 2017; Qiao et al. 2018; Wu et al. 2019; Jemberie and Melesse 2021; Wang et al. 2022). Our study addresses a critical gap in a scientific approach to stormwater management.

This study contributes significantly to the field by offering a tailored approach to SM for regions with diverse land-use types. By analyzing different strategies for specific area types, such as residential zones, commercial areas, or green spaces, the study provides a framework for decision-makers to implement more precise and effective stormwater solutions. Unlike the traditional methods that apply a uniform strategy across entire cities, the results of this study allow for nuanced decision-making, aligning strategies with the unique characteristics of each area. Studies such as (Sheikh and Izanloo 2021; Bekiryazici and Acar 2024; Jato-Espino et al. 2014; Leng et al. 2020; Yang and Zhang 2021; Zhu et al. 2021; Nazari et al. 2023) focus on the use of several MCDM approaches, including TOPSIS, to investigate different SM techniques for a specific region considered as a whole. Single, various, or combined SM approaches are assessed for various regions around the world, such as Bojnord (Iran), Tehran (Iran), or Chaoju (China) using methods like AHP and TOPSIS. There are several other studies such as (Chae et al. 2022; Makropoulos et al. 2007; Gogate et al. 2017; Jayasooriya et al. 2018; Alhumaid et al. 2018; Kaykhosravi et al. 2022) which focus on a certain type of area such as arid environments, highly urbanized watersheds or new urban developments from various regions such as Melbourne (Australia), Toronto (Canada) or Pune City (India). An overall evaluation of the literature shows that studies are mostly designed for single (or a combination of) stormwater management alternatives, or a specific type of area, resulting in a narrow evaluation. This study aims to provide clearer insights into the suitability of SM strategies for diverse land-use types. Our study presents a more extensive approach that uses a versatile combination of SWMM and TOPSIS to determine appropriate SM strategies for each different land-use type located in a region. The integrated approach followed throughout the study, investigating the selection of the best alternative SM strategy in densely populated urban settings with different land-use types, contains a multi-layered analysis with SWMM and TOPSIS approaches and an additional sensitivity analysis. Compared to the existing studies in literature, where more complex mathematical frameworks such as fuzzy numbers are sometimes used even with the methods mentioned here, this study develops a more accessible and systematically calibrated investigation. By presenting the methodology for diverse land-uses, the study extends the practical usability of the scope of the integrated approach. Additionally, the approach used in this study to investigate combined approaches also presents a unique approach compared to the existing studies in literature. The studies mentioned above focus on SM strategies—separately or combined—applied to certain regions, whereas this study proposes a tailored approach to combined SM strategy selection for urban areas. Rather than proposing a combination of several SM alternatives for the whole region, viable alternatives are selected for each sub-region and analyzed so that different SM strategies can be applied

in combination—but separately—to the whole region based on their performance on each type of land-use existing in the region of interest. While further analysis could also be studied on combined approaches for sub-regions in future studies, the existing approach provides a more accessible presentation of the methodology both in terms of a clearer display of the theoretical analysis and the tailored approach for urban settings with multiple land-use types to the reader.

MCDM methods such as AHP and TOPSIS have been used in different fields to analyze various decision-making problems from the evaluation of intrusion detection (Alhakami 2024) to forage grass selection (de Oliveira et al. 2024) alongside SM. Numerous feasible management strategies for various area types within a region are analyzed using the TOPSIS method backed by SWMM simulations. SWMM has been used along with MCDM methods including TOPSIS at various stages of the analysis in literature; however, this study uses SWMM as a means for presenting the consistency of the results obtained with TOPSIS (for the data from Güneysu, Rize, Turkey). Using the same data for creating the decision matrices, it is aimed to guarantee that SWMM simulations provide results for the same scenarios considered for TOPSIS. Note that an exact validation of the results obtained by TOPSIS and SWMM methods would only be possible through measuring the real surface runoff reduction after the implementation of each SM alternative on the area being studied. Since this is not feasible in real-life settings, the agreement of the results from both methods is used to present the consistency of the most appropriate SM strategies being proposed. The similarity coefficients from the TOPSIS method and the rates of surface runoff decrease from SWMM are compared for the first two examples below (Figure 5).

Results show that as well as the most appropriate SM strategy, the ordering of the alternatives and the multitude of the similarity coefficients are also similar for these two approaches. This is a clear indicator of the suitability of using TOPSIS for determining the suitability of various SM strategies for different types of land-uses around the world. TOPSIS provides a straightforward and versatile analysis tool for battling the increasing risk of floods and other related disasters. This study provides a basis for new analysis based on data from other types of land-uses in different regions.

The findings of our study are listed below for a clear presentation:

- The TOPSIS method enables a functional tool for analyzing various scenarios in determining the most appropriate SM strategy.
- Although all of the land-use types are within the Güneysu city center, TOPSIS suggests different strategies for impermeable surfaces, green areas, and blocks of buildings.
- The TOPSIS method allows a quick adaptation to changes in planning. A change of criteria or criterion weights can easily be made to investigate the new application. The sensitivity analysis shows that the MCDM approach is stable with respect to minor fluctuations in criteria weights.
- SWMM simulations support the results obtained in TOPSIS. The ordering of the alternatives in terms of their suitability to each land-use type is obtained in the exact same order with SWMM.

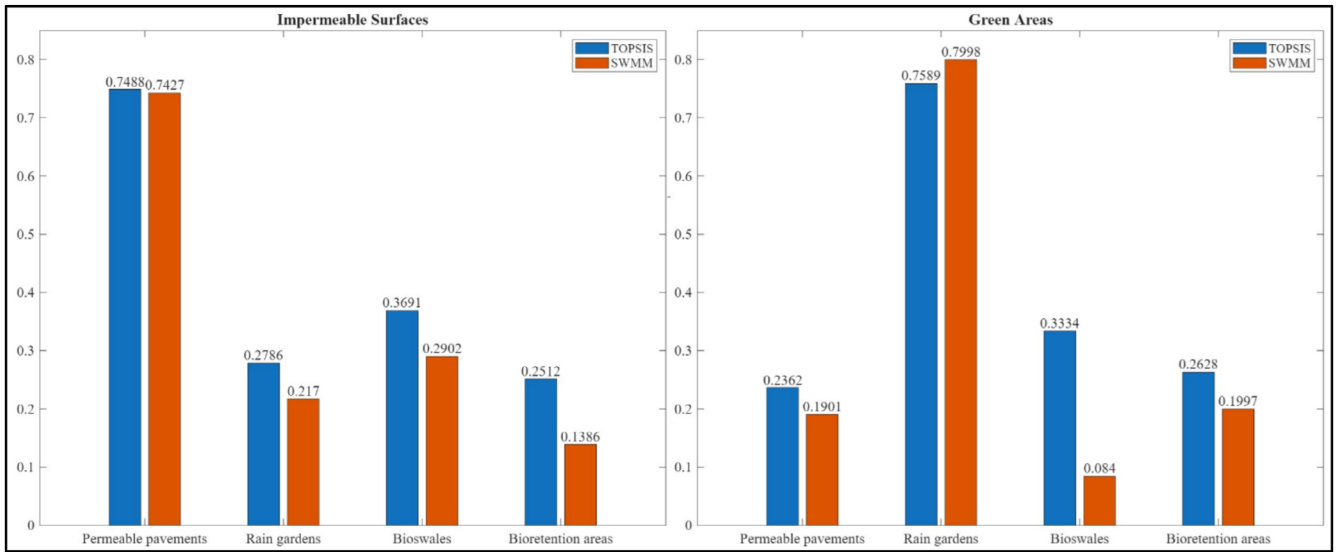


FIGURE 5 | Comparison of results from TOPSIS (similarity coefficients) and SWMM (total surface runoff reduction rates) for impermeable surfaces and green areas.

Matching inputs to TOPSIS and SWMM also result in a correspondence for the outputs of both methods (Figure 5). The magnitude of the most suitable strategy in each land-use type is significantly higher compared to the other alternatives in both TOPSIS and SWMM.

While this study offers a novel perspective on SM, it is not without limitations. Firstly, the analysis is geographically specific to Güneysu, Rize, and its findings may not be directly applicable to regions with differing climatic, hydrological, or socio-economic conditions. Second, the exclusion of dynamic factors such as long-term climate change impacts or future urbanization trends limits the predictive capabilities of the study. Future studies could also contain economically focused components for the MCDM analysis since certain aspects, such as maintenance costs, were excluded from the analysis for a hydraulically oriented concise study focusing on the runoff reduction potential before broader economic considerations. It is known that certain maintenance requirements of the SM strategies analyzed in this study, such as the periodic cleaning of permeable pavements to prevent clogging and vegetation and drainage maintenance of green roofs, may affect long-term hydraulic efficiency and sustainability performance (Sagrelis et al. 2023; Wang et al. 2021). However, hydrological effectiveness was used as the primary screening perspective to provide an accessible presentation to the reader and the integration of lifecycle and economic analyses criteria and climate resilience metrics into the MCDM framework represents a valuable direction for future research. Incorporating real-time data and machine learning tools into MCDM analyses could further enhance decision-making processes. Additionally, extending this approach to include stakeholder perspectives and public participation could help bridge the gap between technical feasibility and social acceptability, ultimately fostering more sustainable urban SM systems.

From a policy perspective, this research highlights the importance of localized SM strategies and their integration into urban development plans. Local governments could use this framework to prioritize infrastructure investments, focusing on the

specific needs of different urban areas. For instance, in regions with high impervious surfaces, permeable pavements and infiltration trenches may provide cost-effective and efficient solutions, as suggested by the findings of this study.

5 | Conclusion

This study presents a comprehensive framework that integrates TOPSIS method with SWMM simulations to address stormwater management (SM) challenges in regions with diverse land-use types. By accounting for the typological differences within the study area, the research fills a critical gap in literature, offering a more versatile and adaptable methodology. Feasible alternatives for each land type are investigated with TOPSIS and SWMM using expert opinion-based criteria and weights. The integrated technique consists of a multi-layered approach for the selection of appropriate SM for different land-uses in urban settings using TOPSIS and SWMM methods as well as a sensitivity analysis for MCDM analysis. Calibration of the input parameters for SWMM to the decision matrices used for TOPSIS method ensures that both approaches model the same scenario from different perspectives. Although the literature mainly focuses on certain regions and SM strategies individually, this study focuses on the selection of the best alternative SM strategy for specific land-use types and proposes an integrated methodology for densely populated urban areas containing different types of land uses. The findings not only provide valuable insights for Güneysu but also lay the groundwork for broader applications in urban planning and sustainable development. Results from both TOPSIS and SWMM show that permeable pavements are the most suitable SM strategy for impermeable surfaces whereas rain gardens and green roofs are the most suitable SM strategies for green areas and blocks of buildings, respectively. All these SM alternatives achieve significantly better results in TOPSIS and SWMM compared to the other alternatives for each type of land-use. Results for the similarity coefficient in TOPSIS, which shows how close the alternative is to the ideal solution for the decision-making problem, and SWMM results for total surface runoff reduction match for all three types

of land-use in Güneysu city center. PP gets a similarity coefficient of 0.7488 in TOPSIS and 74.271% runoff reduction in SWMM for impermeable surfaces, rain gardens get a similarity coefficient of 0.7589 in TOPSIS and 79.977% runoff reduction in SWMM for green areas, and green roofs gets a similarity coefficient of 0.7679 in TOPSIS and 68.789% runoff reduction in SWMM for blocks of buildings, respectively. Data from other locations could easily be implemented within this framework to perform such a comprehensive investigation. The applications of this approach for various specific locations could be enriched with investigations of other land-use types. Future studies in this field should also aim to refine the approach by incorporating broader economic, climatic, and participatory dimensions, ensuring its applicability across various contexts and regions.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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