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Determining the most appropriate stormwater management strategies within the development of urban landscape infrastructure using the TOPSIS method: applications to Rize city

Fatih Bekiryazici[a,*] and Cengiz Acar[b]

[a] Department of Landscape Architecture, Recep Tayyip Erdogan University, Rize, Turkey
[b] Department of Landscape Architecture, Karadeniz Technical University, Trabzon, Turkey
*Corresponding author. E-mail: fatih.bekiryazici@erdogan.edu.tr

FB, 0000-0003-2662-2310

ABSTRACT

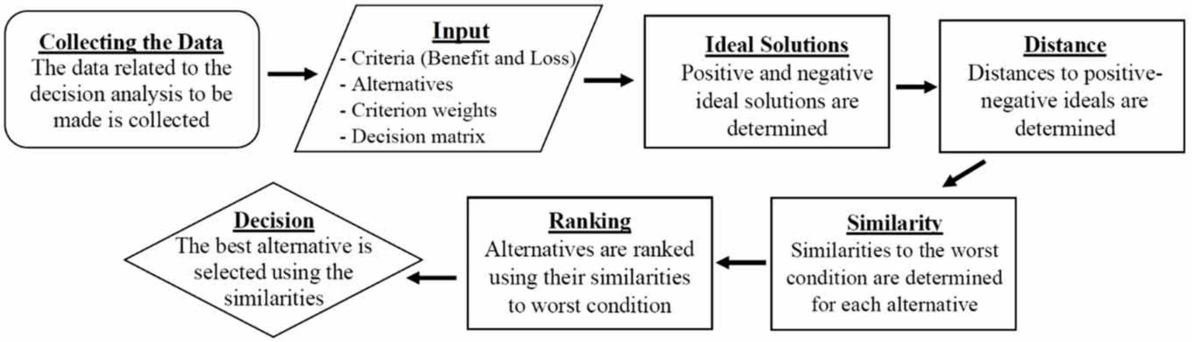
In this study, the application of multi-criteria decision-making (MCDM) methods in determining the most appropriate stormwater management strategy is examined using different areas in Rize. The determination of the most appropriate stormwater management practices for the Rize coastal park and Güneysu-Rize connection highway with TOPSIS is presented in detail within this study. In this context, commonly used applications suitable for urban areas are discussed. The criteria and their weights used for the evaluation of the selected applications were determined by consulting expert opinions from leading researchers. The most suitable applications in different scenarios such as changes in the cost or the amount of precipitation for Rize coastal park and Güneysu-Rize connection road were determined by the TOPSIS method. The TOPSIS analyses' ranking of the ideal solutions matches the results of the SWMM simulations one to one. SWMM results confirm that the outcomes of TOPSIS are the alternatives that provide maximum decrease in surface runoff.

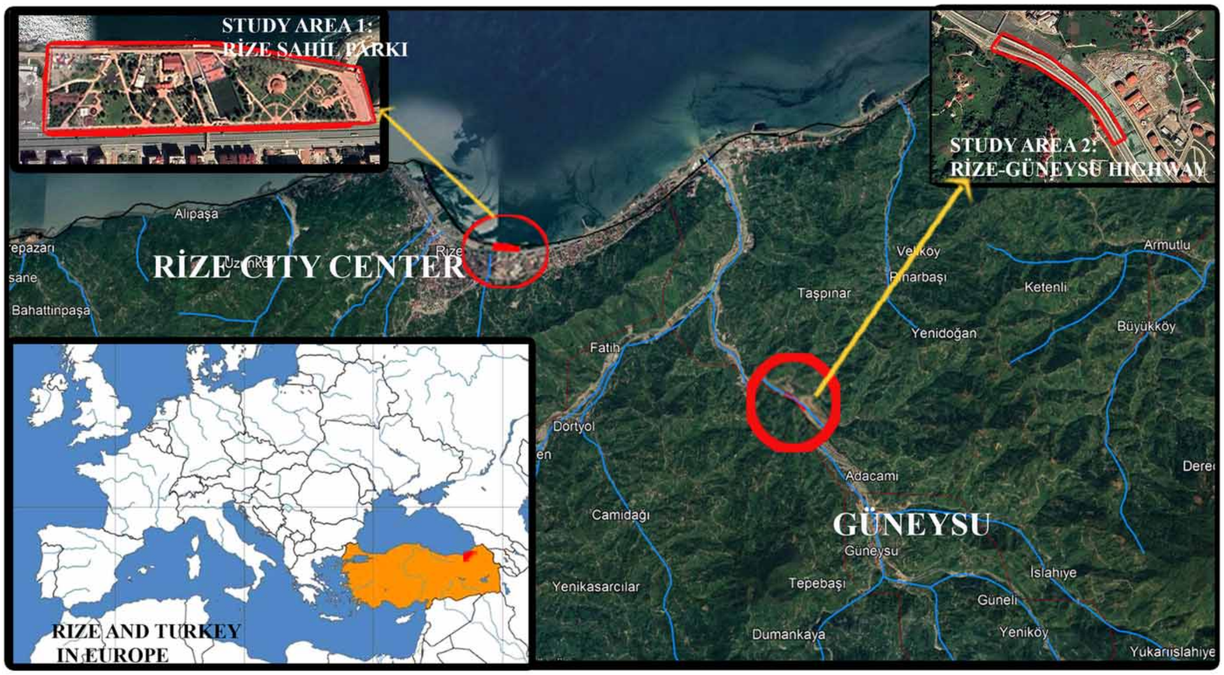
Key words: multi-criteria decision-making, Rize, stormwater management, SWMM, TOPSIS

HIGHLIGHTS

- The importance of stormwater management strategies against adverse environmental impacts such as floods, waterlogging, and water pollution is addressed through case studies on two distinct typologies.
- Highways and coastal areas are used for the analysis.
- The most suitable method for each area was determined using the MCDM method, specifically TOPSIS.
- SWMM simulation results are used to verify the results from the MCDM analysis.

GRAPHICAL ABSTRACT





Runoff	Mean	Peak
Current Situation	0.2422 m3	0.6583 m3
Stormwater Management Method Applications - Simulation		
Bioretention Areas	0.0731 m3 (69% decrease)	0.1349 m3
Rain Gardens	0.1705 m3 (29.5% decrease)	0.5502 m3
Bioswales	0.1995 m3 (17.5% decrease)	0.4425 m3
Permeable Pavements	0.2129 m3 (12% decrease)	0.6581 m3

Runoff	Mean	Peak
Current Situation	0.2059 m3	0.5121 m3
Stormwater Management Method Applications - Simulation		
Bioretention Areas	0.1913 m3 (7% decrease)	0.4654 m3
Rain Gardens	0.1337 m3 (35% decrease)	0.3249 m3
Bioswales	0.0585 m3 (71,5% decrease)	0.1094 m3
Permeable Pavements	0.0973 m3 (53% decrease)	0.2308 m3

1. INTRODUCTION

The world has been seeing a continuous increase in urbanization for decades. While the worldwide total population continues to increase, the percentage of people living in urban areas is also rising, further increasing the urban population density. UN studies report that the 3.4B worldwide urban population in 2009 is expected to increase to 6.3B in 2050, a number corresponding to around 84% of the total population (United Nations 2010). Data from Turkey suggest that the percentage of the urban population in the total population was 24.8% (5.3M) in 1950, 73.6% (57.6M) in 2015 and 76.1% (63.8M) in 2019 (URL-1 2019). This increase brings a variety of problems such as the effects of climate change and biodiversity in terrestrial ecosystems.

The development and growth of urban areas lead to an increase in impervious surfaces. Changes in the controllability of precipitation falling to the ground and the transport of pollutants and sediments from urban areas to water sources are critical issues that are some of the consequences of this urbanization (Tsihrintzis & Hamid 1997; Todeschini 2016; Tang *et al.* 2024). However, another problem, the decrease of the controllability of precipitation waters due to the increase in impermeable surfaces, results in floods, landslides etc. and these disasters claim the lives of many people. Many urban areas worldwide suffer increased flooding due to the increase in urbanization and climate change (Petit-Boix *et al.* 2017). A lack of renovation in the ageing sewer systems in many areas of the world leads to floods, especially with the increasing uneven precipitation amounts due to climate change causing large amounts of rainfall in a short time in some seasons. UN reports suggest that flooding is the greatest danger to hundreds of large cities worldwide (United Nations 2012). Short-time heavy rains pose a serious threat to many of the largest cities, particularly many cities in Asia, some of which have populations of tens of millions. Rize has an average of 2,302 mm annual precipitation (the highest annual data in Turkey) according to the Turkish State Meteorological Service based on data between 1928 and 2022 (URL-2 2023). Bekiryazıcı reports that AFAD (Disaster and Emergency Management Presidency) recorded 127 casualties from floods and related disasters between 1970 and 2019 and also reports around 221 million Turkish Liras (More than 10 million Euros) worth of material damage because of floods and landslides between 2010 and 2019 in Rize (Bekiryazıcı 2023).

One-third of all the disasters in the world throughout the 20th century were caused by floods and accounted for around half of the casualties (Adikari & Yoshitani 2009). The increase in climate change and the resulting irregular rainfall makes stormwater management crucial for every region facing these disasters. The lack of measures against floods or inadequate stormwater management practices is a threat to the lives of many cities worldwide, including Rize.

The situation in the world is not much different for Turkey too. As a country surrounded by seas located between the temperate zone and the subtropical zone, Turkey has many regions with distinct climates. Turkish State Meteorological Service reports a country-wide average of 574 mm of precipitation yearly (URL-2 2023). This average drops to 406.5 mm in Central Anatolia and goes up to 696.5 mm in the Black Sea region (URL-2 2023). The average precipitation for Rize City is 2,302.1 mm. As the province that receives the most rainfall in Turkey, Rize is affected by increasingly irregular precipitation regimes more than anywhere in the region. Turkish State Disaster and Emergency Management Presidency reports 127 deaths in Rize in over 40 years due to floods due to excessive rainfall and resulting landslides in addition to millions of Turkish liras worth property damage (AFAD 2020).

In addition to prevent flooding and landslides, rainwater and stormwater management enables recreational activities, increases water supplies and thermal comfort and offers designs that function as rainwater flow regulators (Davis *et al.* 2010; Hamel *et al.* 2013). Various stormwater management strategies have been developed over the years with each strategy offering different prospects such as design, functionality, plant diversity, etc. Although measures against floods have historically been mostly based on physical flood defense (Birkholz *et al.* 2014) public awareness and modern approaches make stormwater management a popular study area today. Parallel to rainwater management methods like Green Infrastructure, Low-Impact Development and Sponge Cities, Rainwater Infrastructure provides more ecological, sustainable, and advantageous green technologies (Lucas & Sample 2015; Luan *et al.* 2017). Methods like Bioretention areas, Rain gardens, Bioswales and Permeable pavements improve water quality by regulating runoff and reducing peak flow (Luan *et al.* 2019).

Each of these methods has its own design and/or functional advantages. Permeable pavements contain layered permeable coating systems for effective rainwater seepage, bioretention areas provide effective pollutant removal and similar assets of each method means that the optimal stormwater management strategy needs to be determined through the detailed analysis of the area being studied. The needs of the area should be listed, and the advantages/disadvantages of each method should be considered to select the most appropriate strategy.

Multi-Criteria decision-making (MCDM) methods are powerful tools that provide standard analysis methods for such decision-making processes. Dating back to the pioneering studies of Benjamin Franklin, MCDM methods have become essential elements in a wide range of study areas. From the evaluation of sustainable transportation systems (Awasthi *et al.* 2011) to the selection of warehouse locations (Ashrafzadeh *et al.* 2012), MCDM methods are used as popular tools in many important everyday applications. The emergence of novel MCDM methods has gained speed in the late 20th century with the advances in computer technology. Popular MCDM methods like the Analytical Hierarchy Process (AHP), Elimination and Choice Expressing the Reality (ELECTRE) and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) are only some of the known techniques with many applications in the literature.

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is one of the most essential and widely used MCDM methods. The method has been proposed by C. L. Hwang and K. Yook in 1981. TOPSIS offers an intuitive and clear logic for decision-making, easy and efficient computation, the ability to measure the appropriateness of each alternative in comparison to ideal solutions and a visual representation of results (Roszkowska 2011). Its easily applicable implementation to the problem of stormwater management strategy selection problem and the advantages listed above are the main motivations for choosing the TOPSIS method for this study. Throughout the years, the TOPSIS method has been modified using different aspects of the method, however, both the modifications and the original method are still widely used. Current trends in the use of the method are focused on the use of entropy-based TOPSIS method (Chen 2019), the use of TOPSIS method in decision-support systems (Rahim et al. 2018), the use of TOPSIS in Green Supplier Selection problem (Pınar *et al.* 2021; Köseoğlu 2022) and the use of TOPSIS-based method in the evaluation of energy-based applications (Sadat *et al.* 2021). Despite all the above features and versatility, TOPSIS has some challenges, difficulties and limitations such as sensitivity, linear relationships, numerical data dependence, decision-making inconsistencies, and uncertainties. In order to minimise all these limitations, in this study, we have applied methods such as determining the criteria weights with the help of expert opinions, supporting the ideal solutions with alternative scenarios and verifying the ideal solutions with SWMM.

There are several studies on the use of the TOPSIS method within the context of stormwater management in the literature. The main tendency in these studies is to use the TOPSIS method to determine the most appropriate rainwater collection areas and the most appropriate strategies to reduce flood risk. Many of these studies are carried out on a local scale, concentrating on the data of a single city/region. Some of the recent studies can be exemplified as follows. A study by Wang *et al.* uses the TOPSIS method to design sustainable drainage systems for stormwater collection (Wang *et al.* 2017). Jayasooriya *et al.* used the TOPSIS method for an examination of the use of green infrastructure for stormwater management in the industrialized regions of Melbourne (Jayasooriya *et al.* 2018). Haider *et al.* have used the TOPSIS method to evaluate rainwater collection in arid regions for flood risk management (Haider *et al.* 2019). Chiu *et al.* have used TOPSIS with Geographical Information Systems (GIS) to analyze the use of rainwater collection systems in drinking water conservation plans for Iran (Chiu *et al.* 2020). Zeng *et al.* have made a TOPSIS-based study for the evaluation of green infrastructure in climate change scenarios (Zeng *et al.* 2021). Tahvili *et al.* have used TOPSIS to determine suitable rainwater collection areas in arid regions in Iran (Tahvili *et al.* 2021). Chae *et al.* have used TOPSIS and VIKOR methods to investigate the use of permeable pavements in basins with high urbanization rates (Chae *et al.* 2022). In a similar study, Luan *et al.* used TOPSIS with the SWMM method to evaluate Green Stormwater Infrastructure strategies efficiencies in rapidly urbanizing areas (Luan *et al.* 2019).

As mentioned above, Rize, the province with the highest rainfall in Turkey, is frequently exposed to disasters such as floods, inundations and landslides caused by excessive rainfall due to recent global climate change. These exposures cause serious damage to urban infrastructure, resulting in loss of property and lives. In this study, we have carried out a series of analyses and recommendations for the development of stormwater infrastructure, taking into account the topographical and hydrological structure of Rize. Using the MCDM/TOPSIS method, we have tried to determine the stormwater management strategy that best fits the typology of existing uses for different functional uses of the city (recreation, transportation, sports, entertainment, etc.). We then supported the data obtained with simulative studies in the SWMM program to see how much it affects the before/after changes in surface runoff. The results are in exact agreement with the data we obtained as a result of TOPSIS. This study aims to provide a guideline for improving local stormwater management efforts using MCDM and suggests that by using different methods and areas, stormwater infrastructure in urban areas can be improved and cities can become more resilient to future global climate change scenarios.

2. METHODS

The most appropriate stormwater management strategies suitable for specific locations have been determined using a complex approach. A literature review has been conducted to determine the most frequently used criteria for the assessment of stormwater management strategies in various scientific studies. The long list of criteria has been sent to landscape architects and environmental engineering experts all over the world for consultation. Their expert opinions have been used to make a shortlist of criteria and criteria weights specifically designed for the application areas – Rize Coastal Park and Güneysu-Rize highway. Four alternative stormwater management strategies that are the most suitable and frequently used methods for urban areas have been selected for assessment. The TOPSIS method was used to analyze these strategies in both study areas, taking into account variable conditions. It is important to note that these conditions may vary depending on the field type. For instance, the criteria used to select the most suitable stormwater strategy in the first study area, the coastal park, include surface cover permeability, slope, rain precipitation, plant diversity, total area, and cost. In the second study area, Güneysu-Rize Highway, the criteria are surface cover permeability, amount of green space, road width/field size, slope, rain precipitation, stream bed width, stream-road link width, and cost. The results have been simulated in SWMM to verify that the most appropriate strategies suggested by TOPSIS are really the ones that provide the best performance in decreasing surface runoff.

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is one of the most simple, yet powerful, MCDM methods and is a suitable choice for analyzing decision-making problems in a wide range of areas. Given a set of m alternatives $A_1, A_2, \ldots, A_m$ and a total of n criteria $C_1, C_2, \ldots, C_n$, the decision matrix A is formed as shown in the following(Köseoğlu *et al.* 2020).

$$A = \begin{array}{c} \\ A_1 \\ A_2 \\ \ldots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \ldots & C_n \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \end{array}$$

Here, $a_{ij}, i = 1, \ldots, m, j = 1, \ldots, n$ denotes the value of alternative A_i according to the criterion C_j. Some of the criteria are grouped into benefit criteria (J^+) and others as cost criteria (J^-). The decision matrix consists of $m \times n$ values. The decision matrix $A = (a_{ij})_{m \times n}$ is then normalized using

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

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 to numbers between zero and one: $r_{ij} \in [0, 1]$. The normalized decision matrix

$$R = \begin{bmatrix} r_{11} & r_{12} & \ldots & r_{1n} \\ r_{21} & r_{22} & \ldots & r_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ r_{m1} & r_{m2} & \ldots & r_{mn} \end{bmatrix}$$

is then assigned weights using the weight vector

$$W = [\,w_1 \quad w_2 \quad \ldots \quad w_n\,]$$

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

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

The positive and negative ideal solutions are determined from the values of the weighted normalized decision matrix $T = (t_{ij})_{m \times n}$ such that 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.

$$A^+ = \{t_j^+\}, j = 1, \ldots, n = \begin{cases} \max(t_{ij}), & i = 1, \ldots, m, j \in J^+ \\ \min(t_{ij}), & i = 1, \ldots, m, j \in J^- \end{cases}$$

$$A^- = \{t_j^-\}, j = 1, \ldots, n = \begin{cases} \min(t_{ij}), & i = 1, \ldots, m, j \in J^+ \\ \max(t_{ij}), & i = 1, \ldots, m, j \in J^- \end{cases}$$

Each alternative $A_1, A_2, \ldots, A_m$ has its distances to the positive ideal (d_i^+) and negative ideal solutions (d_i^-) measured through the distances

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

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

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

$$S_i^* = \frac{d_i^-}{d_i^- + d_i^+}$$

for each alternative such that $0 \le S_i^* \le 1$. The closer S_i^* is to one the better the alternative is, and hence, the alternatives are ranked using S_i^* in ascending order. The alternative with the highest S_i^* is the most appropriate alternative.

3. APPLICATIONS

Data from Rize coastal park and Güneysu-Rize highway are used as numerical examples for the application of TOPSIS to determine the most appropriate stormwater management strategies within the development of urban landscape infrastructure. These areas are shown in Figure 1.

Rize has the highest precipitation in Turkey and the increase in the irregularity of rainfall has dire effects on the city. Over 500,000,000 Turkish Liras material damage has been reported in the last decade in addition to 127 casualties in over 40 years. Hence, two different area types have been selected in Rize for applications. The locations of the application areas – Rize Coastal Park and Güneysu-Rize highway have been shown in Figure 1. Rize Coastal Park is an urban park of about 54,090 m^2 containing cafes, sports fields, playgrounds, and an amusement park. Güneysu-Rize highway is about 14,471 m^2 and is the road linking Güneysu to the city center (Figure 2).

In this research, where TOPSIS was used to determine the most appropriate stormwater management strategy for both study areas, all criteria that may affect the surface movement of rainfall from the moment it lands on the ground were listed in the literature. Afterwards, an e-mail was sent to 50 of the most cited researchers (we have no prior acquaintance with any of them and none of them is Turkish) whose specialities are 'Urban Hydrology', 'Stormwater Management' in Google Scholar profiles and who have published similar publications to our study topic. They were briefly informed about the study, the prepared list of criteria was sent to them, and they were told that they could add or remove these criteria if they wished, and they were asked to determine their weights as a total of 100. Criteria weights were determined by averaging the data of the respondents.

3.1. Rize coastal park

The most appropriate stormwater management strategy for Rize coastal park will be selected from the alternatives 'A_1: Permeable pavements', 'A_2: Rain gardens', 'A_3: Bioswale' and 'A_4: Bioretention areas'. These alternatives will be assessed according to the following criteria 'C_1: Surface cover permeability', 'C_2: Slope', 'C_3: Rain precipitation', 'C_4: Plant diversity', 'C_5: Total area' and 'C_6: Cost' with the weights of criteria given as $W = [0.30 \quad 0.15 \quad 0.25 \quad 0.10 \quad 0.10 \quad 0.10]$ (or also as

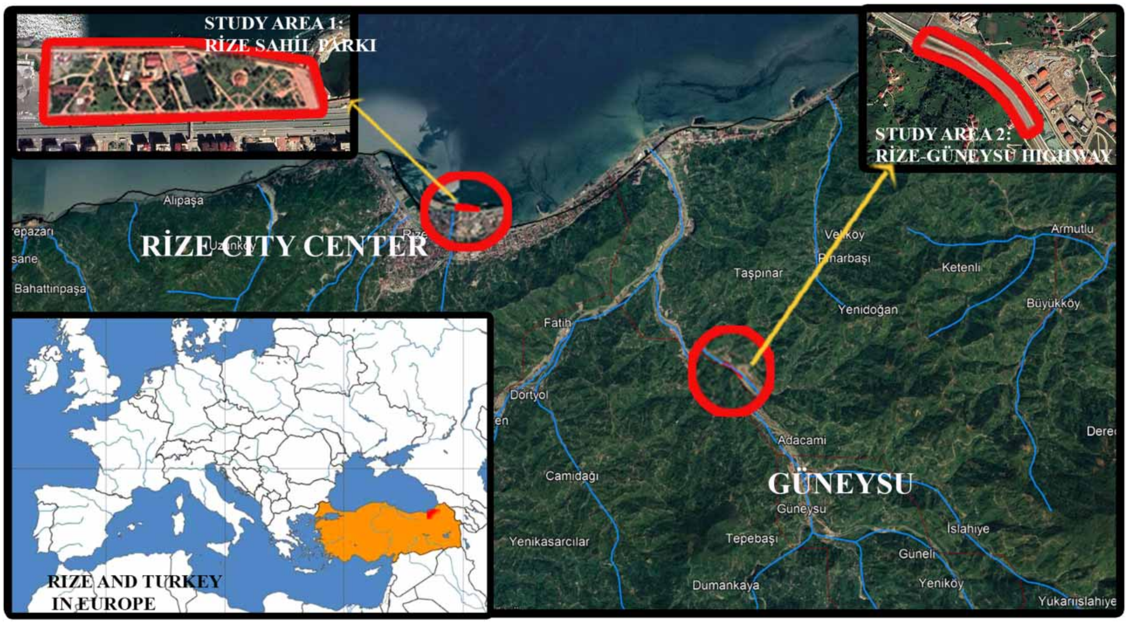


Figure 1 | The locations of the studied areas.

Figure 2 | Views from the application areas (left: Coastal Park and Right: Highway).

$w_j, j = 1, \ldots, 6$). Note that while the values of criteria like slope and total area seem like they should be the same for all alternatives, these are about the outcome values if the alternatives are applied to the areas. For instance, 'total area' denotes the total area in which the alternative can be applied in the application field and not the total area of the application area. The weight vector suggests that the assessment is done by using a 25% weight for the rain precipitation criterion. Here, 'C_1: Surface cover permeability', 'C_4: Plant diversity' and 'C_5: Total area' are the benefit criteria (marked $+$ in the decision matrix A) whereas 'C_2: Slope', 'C_3: Rain precipitation' and 'C_6: Cost' are the cost criteria (marked $-$ in the decision matrix A).

The decision matrix $A = (a_{ij})_{4\times 6}$ is formed by the examination of these four alternatives according to the given criteria and the resulting values are given in the following.

$$A = \begin{array}{c|cccccc|} & C_1^+ & C_2^- & C_3^- & C_4^+ & C_5^+ & C_6^- \\ & w_1 & w_2 & w_3 & w_4 & w_5 & w_6 \\ A_1 & 30 & 5 & 1,700 & 1 & 22,924 & 25,000 \\ A_2 & 90 & 8 & 1,100 & 4 & 11,000 & 20,000 \\ A_3 & 80 & 20 & 1,300 & 3 & 7,500 & 15,000 \\ A_4 & 90 & 10 & 200 & 5 & 25,540 & 40,000 \end{array}$$

For instance, $a_{26} = 20,000$ represents that the alternative 'A_2: Rain gardens' has a value of 20, 000 for the criteria 'C_6: Cost', meaning that the cost of Rain gardens for Rize Coastal Park is estimated to be around 20, 000 units.

TOPSIS method can be easily implemented into a computer algorithm (Figure 3) and the mathematical computation package MATLAB has been used for the applications.

The normalized decision matrix $R = (r_{ij})_{4\times 6}$ and the weighted normalized decision matrix $T = (t_{ij})_{4\times 6}$ are obtained as follows.

$$R = \begin{bmatrix} 0.1957 & 0.2060 & 0.7041 & 0.1400 & 0.6227 & 0.4683 \\ 0.5871 & 0.3296 & 0.4556 & 0.5601 & 0.2988 & 0.3746 \\ 0.5219 & 0.8241 & 0.5384 & 0.4201 & 0.2037 & 0.2810 \\ 0.5871 & 0.4120 & 0.0828 & 0.7001 & 0.6938 & 0.7493 \end{bmatrix}$$

$$T = \begin{bmatrix} 0.0587 & 0.0309 & 0.1760 & 0.0140 & 0.0623 & 0.0468 \\ 0.1761 & 0.0494 & 0.1139 & 0.0560 & 0.0299 & 0.0375 \\ 0.1566 & 0.1236 & 0.1346 & 0.0420 & 0.0204 & 0.0281 \\ 0.1761 & 0.0618 & 0.0207 & 0.0700 & 0.0694 & 0.0749 \end{bmatrix}$$

Using the weighted normalized decision matrix, the positive ideal solution vector is found as

$$A^{+} = [\,0.1761 \quad 0.0309 \quad 0.0207 \quad 0.0700 \quad 0.0694 \quad 0.0281\,]$$

Whereas, the negative ideal solution vector becomes

$$A^{-} = [\,0.0587 \quad 0.1236 \quad 0.1760 \quad 0.0140 \quad 0.0204 \quad 0.0749\,]$$

The similarities to the worst condition coefficients S_i^*, $i = 1, 2, 3, 4$ corresponding to each of the criteria A_i, $i = 1, 2, 3, 4$ are given in the following.

$$S_1^* = 0.3414,\ S_2^* = 0.6091,\ S_3^* = 0.4297,\ S_4^* = 0.7949$$

which, when ranked, gives

$$S_1^* < S_3^* < S_2^* < S_4^*$$

This means that 'A_4: Bioretention areas' are the most appropriate stormwater management strategy for Rize Coastal Park. The comparison of similarity coefficients for this application has been shown in Figure 4 along with the coefficient for alternative scenarios (Figure 6).

3.2. Güneysu-Rize highway

The data from the Güneysu-Rize highway will be used as a second numerical example for the use of TOPSIS method to find the most appropriate stormwater management strategy. The alternatives 'A_1: Permeable pavements', 'A_2: Rain gardens', 'A_3: Bioswale' and 'A_4: Bioretention areas' will be assessed according to the following criteria 'C_1: Surface cover permeability', 'C_2: Slope', 'C_3: Rain precipitation', 'C_4: Amount of green space', 'C_5: Road width/Field size', 'C_6: Stream bed width', 'C_7: Stream-road link width' and 'C_8: Cost' with the weights of criteria given as $W = [\,0.20 \quad 0.05 \quad 0.30 \quad 0.05 \quad 0.10 \quad 0.10 \quad 0.10 \quad 0.10\,]$ (or also as w_j, $j = 1, \ldots, 8$).

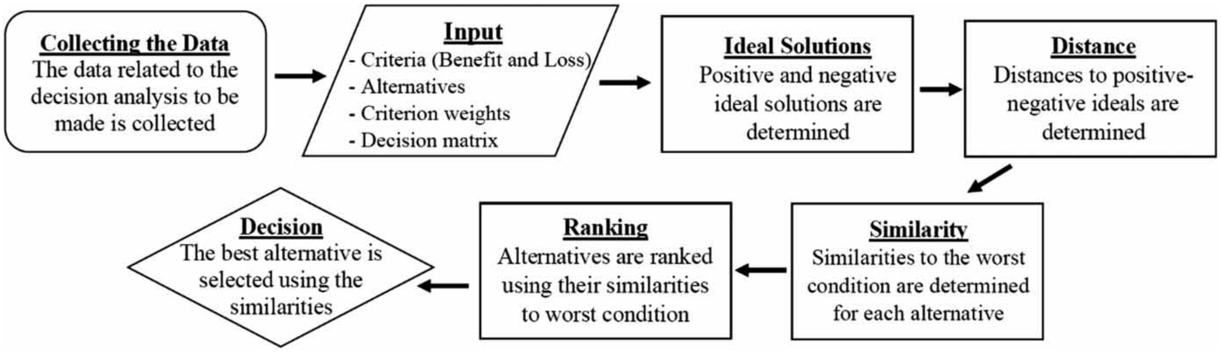


Figure 3 | TOPSIS flowchart.

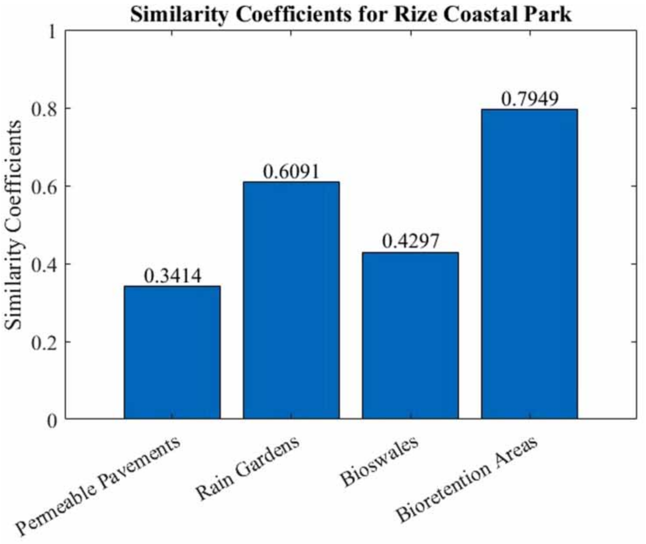


Figure 4 | Similarity coefficients for the Rize coastal park.

Here, 'C_1: Surface cover permeability', 'C_4: Amount of green space' and 'C_5: Road width/Field size' are the benefit criteria (marked $+$ in decision matrix A) whereas 'C_2: Slope', 'C_3: Rain precipitation', 'C_6: Stream bed width', 'C_7: Stream-road link width' and 'C_8: Cost' are the cost criteria (marked $-$ in decision matrix A). The decision matrix $A = (a_{ij})_{4\times 8}$ is given as follows.

$$A = \begin{array}{c|cccccccc|} & C_1^+ & C_2^- & C_3^- & C_4^+ & C_5^+ & C_6^- & C_7^- & C_8^- \\ & w_1 & w_2 & w_3 & w_4 & w_5 & w_6 & w_7 & w_8 \\ A_1 & 40 & 5 & 1,300 & 1 & 7,000 & 30 & 60 & 20,000 \\ A_2 & 30 & 10 & 1,500 & 1 & 3,000 & 36 & 72 & 7,000 \\ A_3 & 60 & 10 & 500 & 4 & 5,000 & 20 & 40 & 10,000 \\ A_4 & 10 & 10 & 1,800 & 1 & 1,600 & 42 & 85 & 5,000 \end{array}$$

In similarity to the first example, $a_{38} = 10,000$ means that the cost of Bioswales for Güneysu-Rize highway is estimated to be around $10,000$ units.

The normalized decision matrix $R = (r_{ij})_{4\times 8}$ and the weighted normalized decision matrix $T = (t_{ij})_{4\times 8}$ are obtained as follows.

$$R = \begin{bmatrix} 0.5080 & 0.2774 & 0.4769 & 0.2294 & 0.7568 & 0.4543 & 0.4522 & 0.8348 \\ 0.3810 & 0.5547 & 0.5503 & 0.2294 & 0.3243 & 0.5452 & 0.5426 & 0.2922 \\ 0.7620 & 0.5547 & 0.1834 & 0.9177 & 0.5405 & 0.3029 & 0.3014 & 0.4174 \\ 0.1270 & 0.5547 & 0.6604 & 0.2294 & 0.1730 & 0.6361 & 0.6405 & 0.2087 \end{bmatrix}$$

$$T = \begin{bmatrix} 0.1016 & 0.0139 & 0.1431 & 0.0115 & 0.0757 & 0.0454 & 0.0452 & 0.0835 \\ 0.0762 & 0.0277 & 0.1651 & 0.0115 & 0.0324 & 0.0545 & 0.0543 & 0.0292 \\ 0.1524 & 0.0277 & 0.0550 & 0.0459 & 0.0541 & 0.0303 & 0.0301 & 0.0417 \\ 0.0254 & 0.0277 & 0.1981 & 0.0115 & 0.0173 & 0.0636 & 0.0641 & 0.0209 \end{bmatrix}$$

Using the weighted normalized decision matrix $T = (t_{ij})_{4\times 8}$, the positive ideal solution vector A^+ and the negative ideal solution vector becomes A^- are obtained as follows

$$A^+ = [0.1524 \quad 0.0139 \quad 0.0550 \quad 0.0459 \quad 0.0757 \quad 0.0303 \quad 0.0301 \quad 0.0209]$$

$$A^- = [0.0254 \quad 0.0277 \quad 0.1981 \quad 0.0115 \quad 0.0173 \quad 0.0636 \quad 0.0641 \quad 0.0835]$$

The similarities to the worst condition coefficients S_i^*, $i = 1, 2, 3, 4$ corresponding to each of the criteria A_i, $i = 1, 2, 3, 4$ are given in the following.

$$S_1^* = 0.4760,\ S_2^* = 0.3589,\ S_3^* = 0.8626,\ S_4^* = 0.2306$$

which, when ranked, gives

$$S_4^* < S_2^* < S_1^* < S_3^*$$

This means that 'A_3: Bioswale' is the most appropriate stormwater management strategy for the Güneysu-Rize highway. Similarity coefficients are shown in Figure 5.

3.3. Alternative scenarios

Finding the most appropriate stormwater management strategy is not the only advantage of the TOPSIS method. TOPSIS also enables a quick and hassle-free analysis of alternative scenarios while analyzing the decision problem. Once the flow of the method (Figure 3) is coded into the computer algorithm, any addition of new alternatives or criteria or a change in the criteria weights reduces to changing a couple of numbers in the program.

An example can be given for the problem of determining the most appropriate stormwater management strategy for Rize Coastal Park. In the case that the cost of 'A_2: Rain gardens' is halved, i.e. reduced from 20, 000 to 10, 000 units, the decision maker just needs to replace the value of the element a_{26} in the decision matrix and a new run of the program instantly gives the new similarity coefficients as follows.

$$S_1^* = 0.3409,\ S_2^* = 0.6193, S_3^* = 0.4314, S_4^* = 0.7645$$

The new similarity coefficients show that with 50% decrease in the cost of 'A_2: Rain gardens', all the similarity coefficients change due to the changes in the positive and negative ideal solutions. However, the most appropriate alternative remains unchanged. Another alternative scenario can be thought of as a case where the budget is the most crucial factor in the assessment. The use of a weight factor in fitting this case $W = [\,0.10 \quad 0.10 \quad 0.25 \quad 0.10 \quad 0.10 \quad 0.35\,]$ gives the new set of similarity coefficients.

$$S_1^* = 0.4042,\ S_2^* = 0.6029, S_3^* = 0.5521, S_4^* = 0.5233$$

The new coefficients show that 'A_2: Rain gardens' is the most appropriate strategy for such a scenario. 'A_4: Bioretention areas' not only loses its first place but becomes the third most appropriate scenario due to its high cost and the 35% weight for the 'C_6: Cost' criteria. The new similarity coefficients for the first example are shown in the figure (Figure 6).

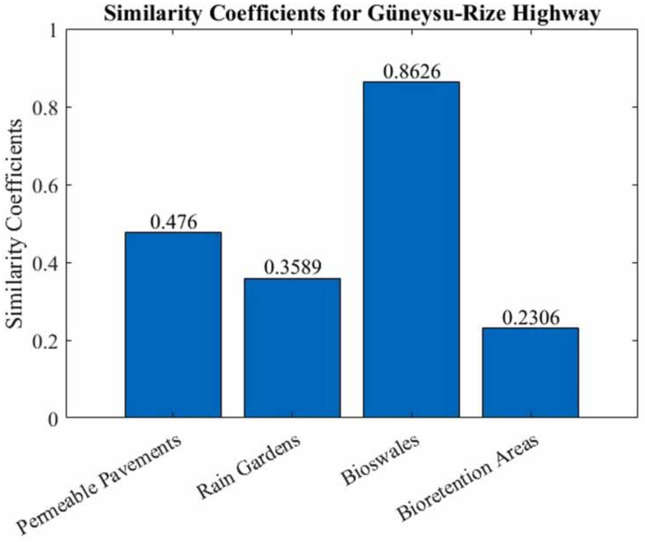


Figure 5 | Similarity coefficients for the Güneysu-Rize Highway.

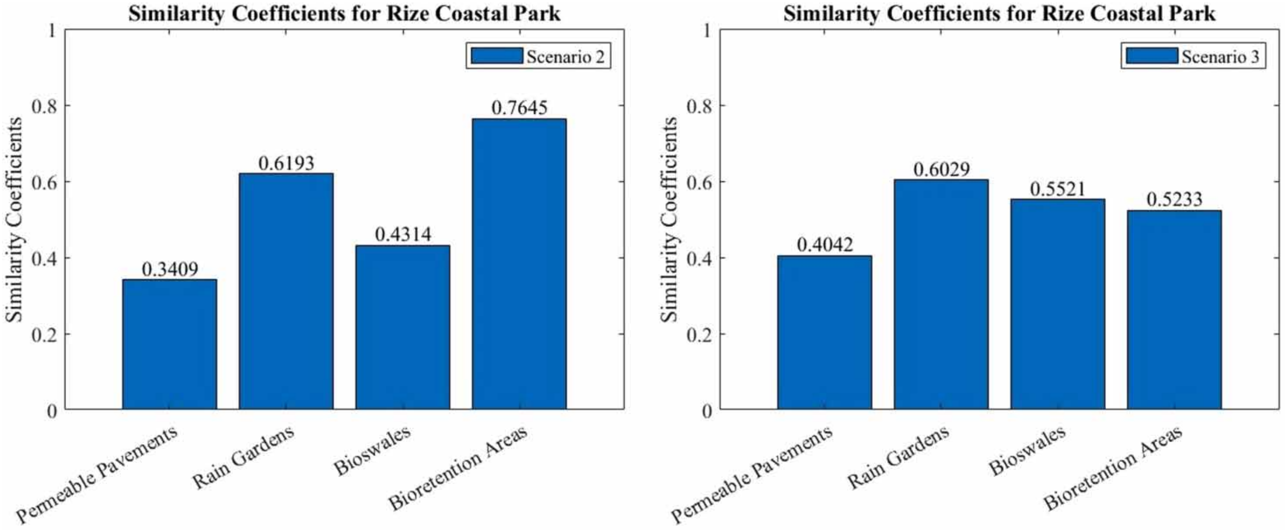


Figure 6 | Similarity coefficients for the Rize coastal park with alternative scenarios.

Similar alternations can be investigated for the second example. A scenario where the criteria 'C_2: Slope' and 'C_5: Road width/Field size' have dominating weights that can be simulated by using the weight vector $W = [\,0.05 \quad 0.35 \quad 0.05 \quad 0.05 \quad 0.35 \quad 0.05 \quad 0.05 \quad 0.05\,]$. In this case, the similarity coefficients are obtained as follows.

$$S_1^* = 0.8154,\ S_2^* = 0.2486,\ S_3^* = 0.5357,\ S_4^* = 0.1182$$

These coefficients correspond to 'A_1: Permeable pavements' becoming the most appropriate strategy for the Güneysu-Rize highway. A third scenario can also be analyzed for the Güneysu-Rize highway, where the values of the alternatives for 'C_3: Rain precipitation' becomes

$$\overbrace{\begin{bmatrix} 1,300 \\ 1,500 \\ 500 \\ 1,800 \end{bmatrix}}^{C_3} \rightarrow \overbrace{\begin{bmatrix} 1,000 \\ 1,700 \\ 300 \\ 1,900 \end{bmatrix}}^{C_3}$$

The scenario might account for a case with varying rain precipitation and the similarity coefficients for this case are obtained as follows.

$$S_1^* = 0.5430,\ S_2^* = 0.3042,\ S_3^* = 0.8743,\ S_4^* = 0.2130$$

Still, 'A_3: Bioswale' is the most appropriate stormwater management strategy for the Güneysu-Rize highway. A comparison of the coefficients is given in Figure 7.

The use of additional alternatives, additional criteria, changing criteria weights etc. results in a possible infinite number of different scenarios for these, and most other, applications. As seen above, TOPSIS enables a straightforward transition between scenarios and swift decision-making.

The results have been verified in EPA's Storm Water Management Model (EPA SWMM v5.1) using simulations corresponding to the data used for both applications.

3.4. SWMM simulations

The application areas have been divided into several sub-catchments in SWMM and the simulations have been made with and without the use of the alternative stormwater management strategies to make a comparison of the surface runoff. The

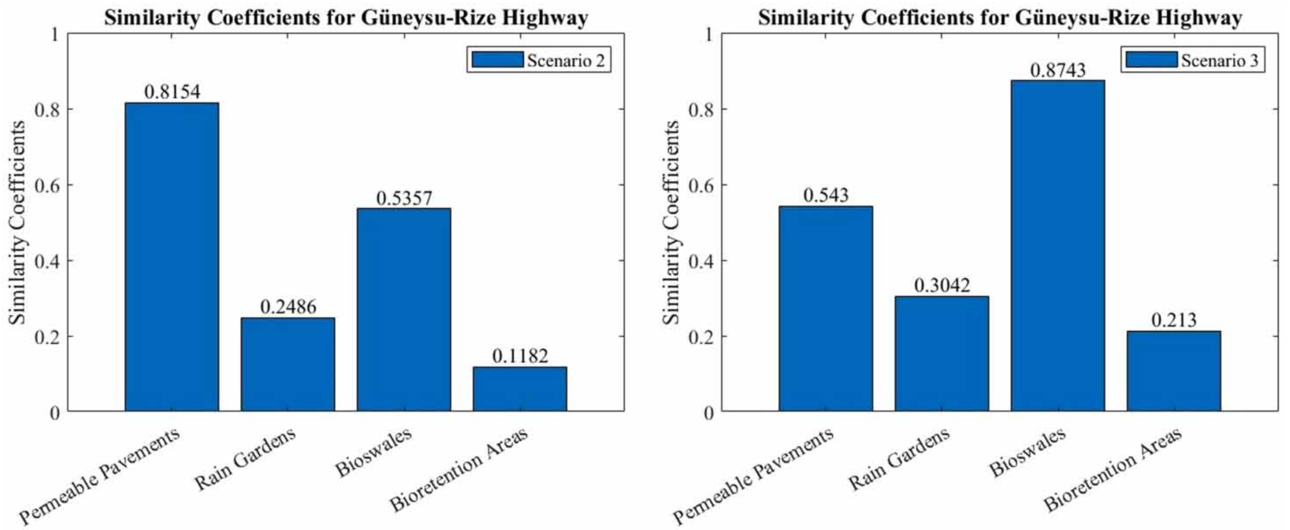


Figure 7 | Similarity coefficients for the Güneysu-Rize highway with alternative scenarios.

division of the application areas into sub-catchments and the positionings of the outlets, etc. are shown in Figure 8. The distribution of 4 alternatives to sub-catchments was determined according to the surface character and functional use of the area. For example, in the total size of the existing area, impervious surfaces, structures, sports and playgrounds, etc. were removed from the total size of the existing area, and areas with suitable rain garden qualities were determined for the remaining green areas. The results for the runoffs before and after the applications have been summarized in Tables 1 and 2. The results have been obtained for a random time series representing rainfall within 10 time units (Figure 9).

4. DISCUSSION AND CONCLUSION

In recent years, urbanization, changes in land surfaces in urban areas, and the increasing negative effects of global climate change on human life and the environment have made stormwater management one of the most important challenges

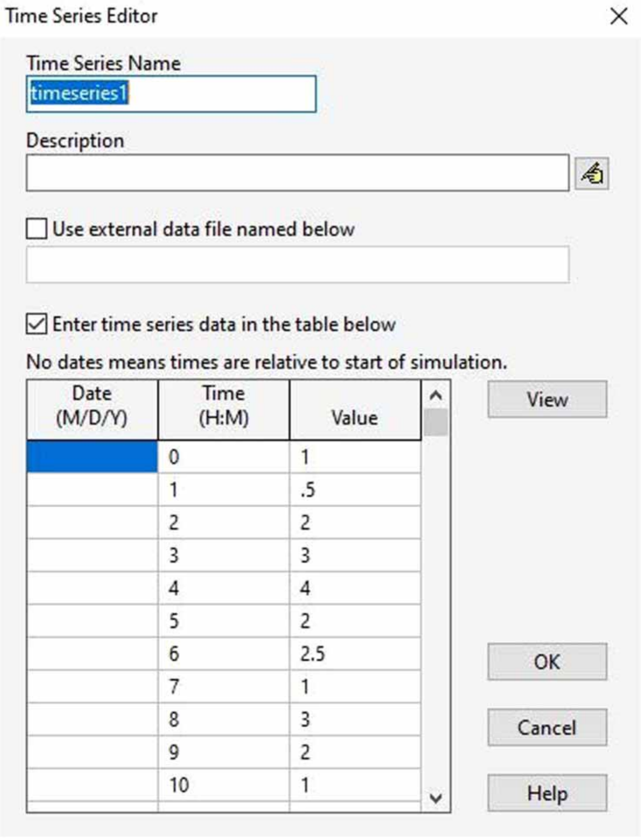
Figure 8 | The positioning of the outlets and sub-catchments in SWMM.

Table 1 | Runoff values of the Rize coastal park

Runoff	Mean	Peak
Current situation	0.2422 m^3	0.6583 m^3
Stormwater Management Method Applications – Simulation		
Bioretention areas	0.0731 m^3 (69% decrease)	0.1349 m^3
Rain gardens	0.1705 m^3 (29.5% decrease)	0.5502 m^3
Bioswales	0.1995 m^3 (17.5% decrease)	0.4425 m^3
Permeable pavements	0.2129 m^3 (12% decrease)	0.6581 m^3

Table 2 | Runoff values of the Güneysu-Rize highway

Runoff	Mean	Peak
Current Situation	0.2059 m^3	0.5121 m^3
Stormwater Management Method Applications – Simulation		
Bioretention areas	0.1913 m^3 (7% decrease)	0.4654 m^3
Rain gardens	0.1337 m^3 (35% decrease)	0.3249 m^3
Bioswales	0.0585 m^3 (71,5% decrease)	0.1094 m^3
Permeable pavements	0.0973 m^3 (53% decrease)	0.2308 m^3



Time Series Editor

Time Series Name: timeseries1

Description:

☐ Use external data file named below

☑ Enter time series data in the table below

No dates means times are relative to start of simulation.

Date (M/D/Y)	Time (H:M)	Value
	0	1
	1	.5
	2	2
	3	3
	4	4
	5	2
	6	2.5
	7	1
	8	3
	9	2
	10	1

Figure 9 | Time series used in SWMM simulation.

that humanity needs to address globally. The increase in heavy rainfall events has led to a rise in the number of disasters such as floods, waterlogging, and resulting landslides in cities and urban areas. Therefore, in recent years, rainwater management in urban areas has become a widely discussed and researched topic in the literature. Various subheadings such as surface runoff control, flood mitigation, non-point source pollution control, rainwater collection, and rainwater management strategies have seen over 1,000 articles published in journals indexed by 'Web of Science' in just the last 1.5 years.

Different strategies and practices for rainwater management have been developed in many different parts of the world. One of the most important points to consider is to determine the most appropriate application for each area, considering factors such as different climate conditions, soil structure, geographical features, and environmental factors for each area. In this context, in this study, we attempted to determine the most suitable stormwater management application for two different types of study area use in Rize, which has experienced many flood disasters, using the TOPSIS, one of the MCDM methods, which is one of the MCDM methods frequently used in environmental sciences. This preference can be justified by the fact that the TOPSIS method is widely used in environmental sciences, its mathematical infrastructure can be understood by those outside the field, and it has a structure compatible with the problem addressed in this study, thanks to the positive and negative ideal solutions it contains.

In this study, applications were made for two different types of study areas, namely the coastal park of Rize and the Rize-Güneysu highway, and it was tried to determine the most suitable method for each of the two typologies of green areas and impermeable surfaces. This is what distinguishes our study from other similar studies to be discussed with examples in the following sections.

Our study aimed to obtain outputs that could benefit the study area with the application of the most suitable rainwater management strategy specific to each typology of area such as green areas and impermeable surfaces, especially for Güneysu, a relatively vulnerable area that has been exposed to flood disasters many times.

Given the increasing effects of global climate change, it is seen that the issue of stormwater management has become one of the most important planning priorities of Rize, and traditional methods have been insufficient. Brierley & Fryirs (2009) pointed out that traditional methods aim to drain rainwater away from urban areas, aiming to prevent floods, and that this system is a single-function approach that ignores the natural hydrological and geomorphic processes necessary for a healthy watershed-ecosystem functioning. In their studies, Sheikh & Izanloo (2021) presented low-impact development alternatives instead of traditional methods for rainwater management in Bojnord, Iran, and aimed to find the most suitable LID method by using 6 different MCDM methods, namely TOPSIS, VICOR, SAW, MEW, ELECTRE III, and NFM, for each typology. In contrast to this study, after determining the appropriate strategies for our study area with MCDM methods, we found that the impacts of urban flood scenarios can be mitigated by reducing the amount of surface runoff with the recommendations we made with SWMM simulations. In their studies, Tabatabaee *et al.* (2019) attempted to reveal the benefits, opportunities, costs, and risks of green roofs, a rainwater management application, using the fuzzy delphi (EFDM) and fuzzy DEMATEL (FDEMATEL) methods. Bibi (2022) in his study, conducted in Dodola town, Ethiopia, aims to examine the effects of land-use and climate change on peak runoff and flood volumes by assessing the effectiveness of low-impact development practices using SWMM 5.1. Bibi *et al.* (2023) in their study conducted in Robe town, Ethiopia, using PCSWMM, aimed to assess the impact of climate change and land-use change on urban flooding. It developed four simulation scenarios to analyze flooding volume and the effectiveness of low-impact development practices like rain barrels and rain gardens in mitigating flooding. Results indicated increased peak flow and flooding volume due to land-use changes and climate change, highlighting the importance of adopting low-impact development strategies to reduce flooding effects in the region. Unlike these studies, we used the TOPSIS method to find out which stormwater management practices should be used for the requirements of our study areas, and then, similar to this study, we used SWMM simulations to demonstrate the contribution of the results we obtained to urban stormwater management and the reduction of runoff.

In this study, the TOPSIS method has been used to determine the appropriate stormwater management methods for two different area types in Rize. Rize Coastal Park and Güneysu-Rize highway have been selected as application areas to analyze the use of the TOPSIS method. The criteria used for the assessment and the criteria weights have been determined by consulting area experts for their expert opinions. Results show that Bioretention areas are the most appropriate stormwater management method for Rize coastal park whereas Bioswales are the most appropriate method for the Güneysu-Rize highway. Various alternative scenarios have also been investigated for these areas. The effects of the changes in criteria values such as cost or rain precipitation or changes in criteria weights have been analyzed as alternative scenarios. The results for all the cases have been graphically presented and a comparison of the changes in the most appropriate methods has been made. The results have also been verified in SWMM. The application areas have been modeled in SWMM with parameters matching the decision matrices. SWMM results show Bioretention areas provide a 69% decrease in surface runoff whereas the other strategies' values are 29.5% for Rain Gardens, 17.5% for Bioswales and 12% for Permeable pavements for Rize coastal park. In accordance with the similarity coefficients for the TOPSIS method, the decrease in runoff for Bioretention areas in SWMM simulations is significantly better compared to the other strategies. For the Güneysu-Rize highway, Bioswales provide a 71.5% decrease in surface runoff, Permeable Pavements are at 53%, Rain Gardens are at 35% and Bioretention Areas provide a 7% decrease in surface runoff. Similar to the first application, the similarity coefficients for the TOPSIS method and runoff decreases in SWMM simulations are in accordance with the Güneysu-Rize highway. Note that the calculations have been done for mean runoff values. SWMM simulations have been done for the original scenarios of the application areas and can be further studied to include alternative cases as well.

The data shows that the use of bioswales in the median strips and sides of highways and roads, the use of bioretention areas and rain gardens in urban parks and green areas, and the use of permeable pavements in town squares and pavements would be an important contribution to decrease surface runoff in the city. This is a crucial component to controlling surface flows in urban areas and reducing material damage and casualties in floods. The use of these strategies would also increase the amount of qualified green areas, further increasing the contribution in terms of greater biodiversity, carbon storage, oxygen production etc. Hence, this study provides mathematical proof and verification from simulations for the possible contributions a city can experience from the use of these strategies. The study can be improved using different approaches. The use of TOPSIS together with other MCDM methods, TR55 or other surface flow simulation software can be used instead of SWMM could provide a new perspective for the analysis of the results. The use of new distance definitions within TOPSIS or the modifications of the method such as DPL-TOPSIS, and PF-TOPSIS could also be alternative approaches. The use of other number systems such as fuzzy numbers, intuitionistic fuzzy numbers or neutrosophic numbers would also result in new calculations and a deeper analysis. Various other applications could be added for new types of areas in Rize or other cities in the region. Many alternative scenarios for the problems under investigation could be easily analyzed using this approach. These applications can be generalized to other areas of the world as well. This study aims to set an example of an accessible and rigorous methodology for finding the most appropriate stormwater management strategies for many types of areas worldwide.

AUTHOR CONTRIBUTIONS

F.B. and C.A. proposed the concept; designed the study; did literature search; C.A. supervised the study and did critical review; F.B. collected the materials and data and processed the study; and did analysis and/or interpretation; and wrote the mannuscript. All authors read and approved the final manuscript.

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None of the authors of this article conducted any studies involving animals.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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