



# Analyzing Coastal Vulnerability Using Analytic Hierarchy Process and Best–Worst Method: A Case Study of the Marmara Gulf Region

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Received: 17 December 2023 / Accepted: 25 April 2024  
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## Abstract

Coastal regions, integral to human economic and social frameworks, face increasing threats from disasters and climate change. This situation has made it necessary and a priority to study these areas at an international level. To be able to take precautions, protect, and manage coastal areas, it is essential to identify their coastal vulnerability. In this study, a coastal vulnerability analysis was conducted using best–worst method (BWM) in the Marmara Gulf Region, Türkiye. Moreover, comparison was made with the analytic hierarchy process (AHP) method in the subject of assessment of coastal vulnerability. According to the vulnerability map obtained with AHP, 17% of the region was determined to have a moderate vulnerability risk, 54% had a high risk, and 29% had a very high risk. On the other hand, the analysis results in BWM calculated the vulnerability percentages as follows: 18% moderate vulnerability, 57% high vulnerability, and 25% very high vulnerability. Visual and statistical comparisons revealed that the BWM method provides more consistent results and involves fewer pairwise comparisons than the AHP method. Thus, it offers ease of use and convenience to decision maker while maintaining relatively same level of weights for criteria. This study aims to lay the foundation for a dynamic system designed to assess coastal vulnerability, emphasizing usability for policymakers in decision-making and flexibility across various scenarios. Particularly, the adoption of the BWM provides notable benefits due to its direct approach and ability to yield more uniform and dependable evaluations, thereby efficiently addressing intricate decision-making challenges.

**Keywords** Coastal vulnerability · Climate change · Analytic hierarchy process · Best–worst method · Geographic information system

## 1 Introduction

Coastal areas are regions that act as junction points between land and sea, providing opportunities for all life forms, particularly for humans, to prosper. Thus, a great deal of the human population prefers coastal areas as their living spaces. In addition, coastal areas host a variety of economic, industrial, and touristic activities [1]. Due to these activities, these areas are experiencing intense urbanization. Approximately

40% of country residents live 60 km from coastal areas on average [2]. Also, coastal areas host a variety of ecosystems designed to preserve natural life in coastal regions, such as national parks and conservation areas.

The world is being greatly affected by climate change. In the past century, global surface temperatures have increased by 1.1 degrees due to human activities, particularly emissions of greenhouse gases [3]. The rise in sea level is a critical consequence of climate change, significantly impacting coastal regions by increasing their vulnerability and, in turn, threatening both their ecosystems and human populations [4]. Disasters such as erosion and rapid floods induced by sea level rises have started to pose threats to coastal areas, which hold critical importance for nations [5]. The living spaces of people and other species who live nearby ecosystems are under threat because of these disasters. In order for nations to protect coastal areas from disasters, take precautions, and manage coastal systems, the vulnerability of these areas to disasters must be determined [6]. Furthermore, the

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process of analyzing coastal vulnerability must be held on a regular basis because the factors that contribute to coastal vulnerability change over time. Therefore, it is crucial to monitor coastal changes continuously in order to take necessary precautions.

Coastal vulnerability can be defined as the sensitivity of coastal systems to sea level rise (induced by climate changes), numerous hazards, or other adverse effects, as well as the degree to which they are unable to cope with these hazards [7, 8]. The detection of coastal vulnerability is an analysis of critical importance for protecting these areas and taking precautions for possible future hazards. The primary goal of this analysis is to identify coastal areas that are at risk or could be potentially at risk from hazards that can develop due to several factors and to determine their levels of coastal vulnerability to these hazards [1].

A variety of methods have been established for evaluating the vulnerability of coastal regions to possible consequences of climate change. The initial studies on coastal vulnerability analysis began in the 1970s. Nowadays, the data provided by remote sensing satellites coupled with the data analysis capabilities offered by Geographic Information Systems (GIS) allow for analyses to be performed without the need for fieldwork [9]. One of the most commonly used methods for detecting coastal vulnerability is the Coastal Vulnerability Index (CVI). The CVI was initially developed by Gornitz et al. [10] in 1994. This initial study that utilized CVI in coastal vulnerability analysis accelerated research in this field. In the first coastal vulnerability studies, only physical criteria are taken into account. As studies increased, the impact of criterion priorities on results began to be discussed, and experts have identified that addressing coastal vulnerability only from a physical perspective is a deficiency that negatively affects the outcomes [11, 12]. Therefore, in the following years, social criteria have also begun to be included in coastal vulnerability analysis. Hedge and Reju [13] utilized population data as a social criterion in addition to physical criteria and conducted coastal vulnerability analysis through the CVI on the Mangalore coasts. Duriyapong and Nakhapakorn [14] incorporated social criteria, including land use and population density, alongside physical criteria in their analysis. The researcher concluded that social factors have a significant impact on coastal vulnerability [15–18]. Tragaki et al. [19] performed physical and social coastal vulnerability analysis for the coastlines of Peloponnese in Southern Greece, using both physical and social criteria. Görmüş and Ayat [1] conducted the first vulnerability assessment for the Black Sea region, specifically for the southwestern coasts of the Black Sea, utilizing both physical and social criteria. When the development process of coastal vulnerability analysis has been examined, initially, studies focused solely on physical criteria [20, 21]. Over time, studies have evolved from focusing solely on physical criteria to

adopting a multi-criteria analysis that incorporates both physical and social factors [22–24]. This transition underscores the complex nature of coastal vulnerability, necessitating a nuanced approach to its assessment. However, as the number of criteria considered in these analyses has grown, this increase has posed a separate problem. For example, criteria with minor and major impacts on the vulnerability of coastal areas were assigned equal weight. To enhance the accuracy of coastal vulnerability analysis, assigning weights to the evaluation criteria according to their significance in the coastal vulnerability context is important [25, 26]. Therefore, although the widely used CVI method is still employed in basic studies, it has begun to be replaced by multi-criteria decision-making (MCDM) methods that offer more comprehensive analysis options. Among these methods, the analytic hierarchy process (AHP), developed by Saaty [27], is one of the most commonly used in the field of coastal vulnerability [28–30]. The AHP method is widely used in the process of multi-criteria decision-making. In this method, comparisons among criteria are made by a group of decision-makers based on the principle of comparative judgment, which leads to pairwise comparison matrices. In this way, even when numerous criteria are used, the problems associated with equal weights can be eliminated, since the criteria weights are determined based on expert opinions. Various coastal vulnerability studies in the literature have been conducted using the AHP method. Özyurt et al. [26] performed a coastal vulnerability analysis across Mersin, the Göksu Delta and the province of Amasra, employing the AHP to weight criteria. They posited that not only identified hotspots, but the entire coastline requires vulnerability assessments. Furthermore, their findings suggest that the AHP method mitigates the variances stemming from user evaluations, thereby facilitating a more precise vulnerability assessment compared to parameter-based approaches such as the CVI. Chang et al. [31] conducted a coastal vulnerability assessment for the Miaoli coasts of Taiwan, employing three main criteria: engineering safety, ecology, and coastal landscape. They applied a combined methodology of AHP and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Through this integration of TOPSIS with AHP, they successfully ranked the vulnerability of the study area's segments from highest to lowest. Cozannet et al. [32] utilized AHP to weight physical criteria in their coastal vulnerability analyses of French coastlines. Their findings highlight the susceptibility of sand spits, estuaries, and low-lying areas adjacent to coastal lagoons across both studied areas. They determined that the AHP method provides a flexible and scalable framework that allows for the integration and consolidation of current knowledge and supporting long-term coastal zone planning. Mahapatra et al. [33] weighted physical and social criteria using the AHP method for the South Gujarat coasts in India. Utilizing these weights, they computed physical and

social CVI indices, thereby proposing an integrated approach to coastal vulnerability assessment. Their analysis revealed that 52.51% of the study area is categorized as having low to very low risk. In comparison, 13.47% of the coastal stretch is classified under the high to very high-risk category. Lin and Pussella [34] weighted physical and social criteria using the AHP method for the southwest coasts of Sri Lanka and conducted a coastal vulnerability analysis through weighted overlay analysis within a GIS environment. Their findings identified two critical hotspots requiring immediate intervention. Additionally, they concluded that coastal slope was the most significant factor contributing to coastal vulnerability in the study area. Baig et al. [35] weighted physical criteria obtained through remote sensing with the AHP method and conducted a coastal vulnerability analysis for the coasts of Vishakhapatnam in India. The results indicate that the study area encompasses a range of coastal vulnerability categories, including very low spanning 42.5 km, low covering 29.49 km, moderate across 23.46 km, high over 34.61 km, and very high extending 7.5 km. Rajakumari et al. [36] integrated criteria weighted with the AHP method into the CVI and conducted a coastal vulnerability analysis for the coasts of Brahmapur, India, using GIS and remote sensing techniques. The study's methodology involved the pairwise ranking of parameters to reflect their significance and contribution toward to coastal vulnerability. The findings from the vulnerability assessment revealed a distribution of risk across the coastline: very high risk along 22.2% of the coastline, high risk across 44.5%, moderate risk over 24.4%, and 9% classified as low-risk areas.

In recent years, one of the methods frequently used in the field of MCDM is the best–worst method (BWM). The BWM method, first introduced by Rezaei [37], has found its place in several application fields [38–41]. The BWM operates similarly to the AHP method; however, its most significant advantage over AHP is from the perspective of the decision-maker. In the BWM, the number of pairwise comparisons that a decision-maker needs to make for weighting criteria is less than the AHP method. For AHP, when “ $n$ ” is the number of criteria, a total of “ $n(n-1)/2$ ” pairwise comparisons are needed. In contrast, for BWM, this number is reduced to “ $2n-3$ .” As a result, the decision-maker expends less effort in making pairwise comparisons, and thus, the weights are more consistent compared to the AHP method. Additionally, in the AHP method, fractional numbers are used for pairwise comparisons, while in BWM, only whole numbers are used for comparisons. Thus, BWM allows the decision-maker to make easier comparisons [37]. Although BWM offers considerable benefits, its application in coastal vulnerability research still needs to be explored. Therefore, utilizing BWM for coastal vulnerability analysis could provide significant advancements in the field.

Another important topic is that despite Türkiye being surrounded by seas on three sides and many significant regions being located on the coastlines, only a limited number of studies have been conducted on coastal vulnerability to date. Moreover, no coastal vulnerability analysis has been conducted for the Marmara Gulf Region which is one of the most important coastal areas in Türkiye. Demirkesen et al. [42] assessed the vulnerability of all Turkish coasts to flooding due to sea level rise, using only the elevation criterion. Study results seek to offer a preliminary assessment of vulnerability due to sea level rise, aimed at assisting decision-makers and relevant stakeholders in formulating suitable public policies and land-use planning strategies. Özyurt and Engin [26] conducted a coastal vulnerability analysis related to sea level rise for the Göksu Delta, Amasra, and Göcek districts. Özyurt et al. [43] proposed a new methodology for determining coastal vulnerability and applied it to the Göksu Delta. The study determines that the Göksu Delta shows moderate to high vulnerability to sea level sea-level rise. Furthermore, by including parameters related to human influence, the methodology provides decision-makers with insights into managing the social dimensions of coastal vulnerability. Kahraman and Aydın [44] evaluated the coastal vulnerability from a morphological perspective in the coastal cities of Türkiye. The study revealed Kocaeli as the coastal city possessing the highest level of vulnerability in Türkiye. Atasoy Özdemir [45] evaluated the vulnerability of coastal zones within the Fethiye-Göcek conservation area. The study introduces a model for Fethiye-Göcek that incorporates both physical and human factors influencing coastal processes, considering climate-driven changes and other internal impacts. Görmüş and Ayat [1] investigated the coastal vulnerability of the Black Sea coasts using the CVI method. It was determined that the most significant factor increasing vulnerability along the coasts is their geomorphological structure. Additionally, Beaches are prevalent and serve as critical determinants of vulnerability due to their low elevation and gentle slopes. Aykut [46] examined the coastal vulnerability of Mersin and the Gulf of İskenderun with five different CVI methods. The findings suggest that methodologies incorporating socio-economic parameters yield more dependable vulnerability indices compared to those relying solely on physical parameters. Türkiye's extensive coastline necessitates taking precautions against disasters related to climate change in the present and future years. This situation is a significant risk management problem that needs to be addressed, especially by local and private administrations in coastal areas.

Considering the identified research gaps—namely (1) the lack of application of BWM in coastal vulnerability analysis and (2) the scarcity of coastal vulnerability studies within Türkiye's Marmara Gulf Region—the primary objective of this study is to conduct a coastal vulnerability analysis for the İzmit Gulf, Yalova Peninsula, and Gemlik Gulf located

in the Marmara Region by integrating MCDM methods and GIS to assess the coastal vulnerability of this region. In order to determine coastal vulnerability, physical (sea level change, elevation, slope, geomorphology, coastline change rate, geology, significant wave height) and social criteria (population density, land use) have been included in the study based on the relevant literature search. The pairwise comparisons used to calculate criteria weights have been made utilizing literature research. The criteria were weighted using both the AHP and BWM methods, and the resulting vulnerability maps were compared with each other. The outputs of the study are intended to provide a significant basis for decision-making authorities and relevant administrations in conducting risk management and future planning activities in the Gulfs of the Marmara Region. With this objective in mind, the study aims to address a critical gap in coastal vulnerability research by pioneering the application of the BWM in this field. The study endeavors to establish the groundwork for a dynamic system capable of identifying coastal vulnerability, tailored for ease of use in policymakers' decision-making processes and adaptable to different scenarios. Specifically, the utilization of BWM offers distinct advantages, including its straightforward application and the capacity to produce more consistent and reliable assessments by effectively handling complex decision-making problems.

The remainder of the study is organized as follows: The second section describes the data and the study area. The third section provides the methods that are used in the assessment. The fourth section explains how coastal vulnerability analysis was conducted in the study area. The fifth section presents and discusses the results provided by coastal vulnerability analysis. The last section concludes the main findings of the study and provides ideas for future works.

## 2 Study Area and Data Source

In this study, the Marmara Gulf Region, Türkiye, was chosen as study area. The region has the densest population in Türkiye, and the majority of the population lives in coastal areas. Additionally, the region hosts a variety of economic, industrial, social, and tourist activities. Considering its importance, the Marmara Gulf Region was chosen as the study area to enable the taking of necessary measures in case of a possible disaster and to ensure the protection and management of the existing coastal areas. The study covers a 440 km long coastline in the Marmara Gulf Region, including the provinces of Bursa, Yalova, Istanbul and Kocaeli. The entire Marmara coastline of Yalova, Kocaeli and Bursa provinces and the Marmara Sea coastline of the Anatolian Side of Istanbul, are included in the study area. Areas that are likely to be affected by coastal vulnerability, which include residential,

touristic, industrial, and ecologically significant zones, are part of the study area. The study area is depicted in Fig. 1.

In coastal vulnerability analysis studies, many criteria are included in the evaluation. The criteria are determined based on literature studies and expert opinions; the criteria, the sources of the data, their resolutions, and the methods of data acquisition are given in Table 1.

## 3 Methodology

A coastal vulnerability analysis was conducted in the Marmara Gulf Region using two different methods of MCDM. The criteria used in this study were selected based on an extensive examination of widely accepted research within the field [1, 2, 5–7, 10, 20, 23–26]. Special attention is given to their applicability and significance in relation to the unique attributes and vulnerabilities of the Sea of Marmara. In a GIS environment, maps representing various criteria were developed, and subsequently, these criteria were weighted using the AHP and BWM. The coastal vulnerability maps produced were then subjected to both visual and statistical evaluations. The subsequent sub-sections provide a detailed explanation of the criteria employed in the analysis of coastal vulnerability, as well as the multi-criteria decision-making methods utilized in this research.

### 3.1 Coastal Vulnerability Criteria

In coastal vulnerability studies, the usage of social criteria along with physical criteria adds factors related to human activities to the analysis. In this study, for representing the physical aspect of coastal vulnerability, criteria such as the sea-level change rate, coastline change rate, coastal type, elevation, slope, significant wave height, and geology were utilized, while for the socio-economic aspect, population density and land use criteria were employed. Additionally, criteria such as tidal range, storm surge, and tsunamis have been acknowledged in various studies as significantly impacting coastal vulnerability. However, the decision to exclude these criteria from our analysis was based on specific geographic and environmental characteristics of the Sea of Marmara. In the study area, the tidal range was determined to be 12 cm [48]. In literature, cases where the tidal range value is equal to or lower than 2.5 m are considered to have very low vulnerability [49]. Therefore, due to the tidal range being significantly below the established limits, this criterion was not included in this research. Moreover, the Sea of Marmara, an inland sea, is markedly less exposed to severe storm events compared to oceans, which substantially reduces the potential impact and relevance of storm surges within this context. Similarly, the lack of direct oceanic connection limits the occurrence and impact of tsunamis. While tsunamis



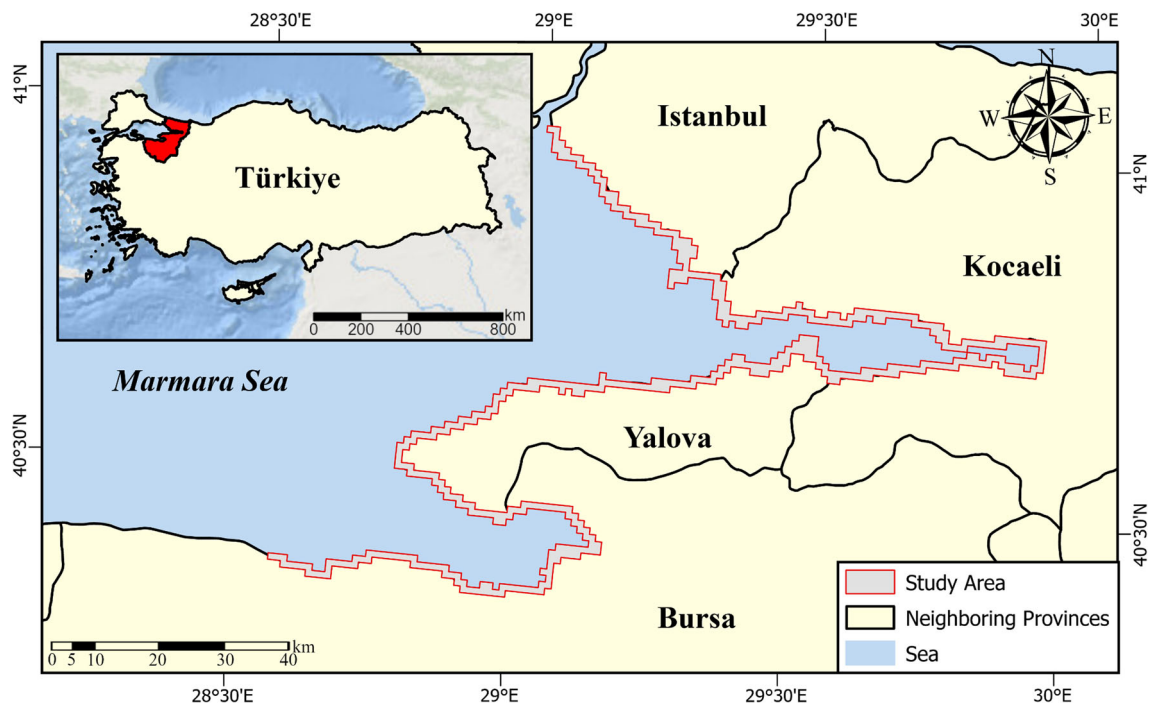


Fig. 1 Study area

Table 1 The criteria and sources of data used in the study

| Criterion  | Data Source                                  | Spatial Resolution | Acquisition Method                               |
|--|--|--------------------|--|
| Sea-level change rate (mm/year)                  | Turkish National Sea Level Monitoring System | –                  | Interpolation                                    |
| Coastline change rate (m/year)                   | Landsat 5 & Landsat 8 Images                 | 30 m               | Object-based classification and change detection |
| Significant wave height (m)                      | Global Ocean L3 Significant Wave Height Data | 7 km               | Interpolation                                    |
| Coastal type                                     | Google Maps and ArcGIS Maps                  | –                  | Digitalization                                   |
| Elevation (m)                                    | SRTM DEM                                     | 30 m               | –  |
| Slope (%)  | SRTM DEM                                     | 30 m               | Derived from DEM                                 |
| Geology  | IGME 5000                                    | –                  | Digitalization                                   |
| Population density (population/km <sup>2</sup> ) | Turkish Statistical Institute                | –                  | –  |
| Land use   | CORINE Land Cover                            | 100 m              | –  |

are a crucial factor in coastal vulnerability assessments globally, their inclusion in the Sea of Marmara is mitigated by the rarity of such events. The criteria utilized in this study are explained in the following paragraphs.

*Sea-level change rate* refers to the annual water level change that occurs in the seas. It is an important criterion used in coastal vulnerability studies [33, 50, 51]. Due to climate change, sea level is rising every year. The global sea level has

risen by approximately 83 mm between 1971 and 2010 [52]. Sea level rise increases erosion and can cause coastal areas to be submerged. Therefore, the sea level change rate is an important factor in coastal vulnerability. Thus, it is included in this study as a criterion.

*Coastline change rate* refers to the amount of annual change that occurs in a coastline. It is a criterion that occurs due to water level rise or erosion and indicates that the coast is

vulnerable in the region where it occurs. The coastline change rate is an important criterion commonly used in coastal vulnerability analysis [53–55]

*Significant wave height* refers to the average height of the highest one-third of waves. It is among the essential criteria affecting erosion on coastlines. As the heights of waves increase, erosion on the coastlines intensifies. Therefore, significant wave height is among the criteria included in coastal vulnerability analysis [1, 50, 55].

*Coastal type* refers to the artificial or natural landforms found in coastal areas. In several studies, the criterion is used to express the physical aspect of coastal vulnerability [1, 9]. Different types of coastlines exhibit varying vulnerabilities to coastal erosion and sea level rises. This criterion is included in the study to express the vulnerability of the given landform to these events.

*Elevation* refers to the height of a coastline. It is one of the criteria that influences how much land area will be submerged in case of water level rises along with the slope. Areas with an elevation of 1 m from the coastline are most likely to face permanent flooding, while areas up to 5 m high are also affected by waves caused by storms [56]. The elevation criterion is commonly employed in coastal vulnerability analysis [10, 57, 58], thus included in this study.

*Slope* refers to the steepness of a coastal area. It is an important physical criterion that determines how much the coast will retreat toward the land in case of sea level rises. When studies in the literature are examined, it is observed that the slope criterion has been used in coastal vulnerability analysis since the initial studies on coastal vulnerability [57–60]. Water levels rise more rapidly in low-sloped areas than in high-sloped areas. Therefore, the lower the slope, the higher the vulnerability of the relevant coast will be.

*Geology* refers to the rock type of coastal areas. It is a criterion that can be associated with the risk of erodibility. Rock types exhibit different resistances to erosion [56]. This resistance they show against erosion also affects coastal vulnerability. As the rock hardens, this resistance increases, and thus its vulnerability coefficients decrease.

*Population density* refers to the number of people per square kilometer. A significant portion of the human population lives in coastal areas, which are threatened by disasters such as sudden floods, tsunamis, and rising sea levels due to climate change. For this reason, population density, as one of the socio-economic criteria, is included in analyses in many studies [13, 61–63].

*Land use* refers to the various categories of utilization of coastal areas. It is a criterion included in studies to demonstrate how areas on the coast are utilized and the impact of this usage on vulnerability [55, 64]. Urbanization on the coast, the presence of tourist areas, industries, and shipyards, and actions such as afforestation change the structure of the coast and thus affect its vulnerability. Artificial structures, beaches,

and forests resulting from these changes exhibit a certain level of vulnerability. For example, urban areas and agricultural lands possess high vulnerability, while rocks and barren soils have low vulnerability. To demonstrate the impact of these effects on coastal vulnerability, the criterion of land use is employed in studies [55].

For the creation of coastal vulnerability maps, the multiplication of criteria maps by the weights derived from AHP and BWM methods is required. The criteria for assessing coastal vulnerability cover a range of impacts and are expressed in different formats such as numbers, text, and ratios. The literature suggests using coastal vulnerability coefficients to standardize these formats [1]. The vulnerability coefficients identified through a review of relevant literature are listed in Table 2. It is imperative to normalize the criteria using these coefficients to facilitate the construction of a coastal vulnerability map, ensuring that each criterion is assigned a value ranging from 1 to 5.

### 3.2 Analytical Hierarchy Process (AHP) Method

The AHP method, developed by Saaty [27], is a multi-criteria decision-making method. The first step in the method is to define a decision-making problem and establish the objective of this problem. Then, a hierarchical model is created to solve the decision-making problem. To establish this hierarchical model, criteria are selected based on the problem and objective. After establishing the hierarchical model, priorities among criteria are determined through pairwise comparisons. The pairwise comparisons are made through the scale given in Table 3.

After conducting the pairwise comparisons, “A” pairwise comparison matrix is formed (Eq. 1). In this matrix, “ $a_{ij}$ ” refers to the relative priority among the criteria. Then, the normalized pairwise comparison matrix is obtained by dividing each element by the sum of its column. In the normalized pairwise comparison matrix, the average of the elements in each row determines the priority, or in other words, the weight of the criterion corresponding to those rows.

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1j} \\ a_{21} & 1 & a_{23} & \cdots & a_{2j} \\ a_{31} & a_{32} & 1 & \cdots & a_{3j} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & a_{i3} & \cdots & 1 \end{bmatrix} \quad (1)$$

To use these weights obtained from the calculations in analyses, it is necessary to check the consistency of the pairwise comparison. If the consistency ratio (CR) is below 0.10, it is concluded that the pairwise comparisons made are consistent [27]. For the calculation of the CR, the largest eigenvector, “ $\lambda_{\max}$ ,” of the pairwise comparison matrix “A”

**Table 2** Coastal vulnerability coefficients of the criteria

|  | 1   | 2                       | 3                 | 4   | 5   |
|--|---|-------------------------|-------------------|---|---|
| Sea-level change rate (mm/year)                  | < 1   | 1.1–2.0                 | 2.1–3.5           | 3.6–5.0                                     | > 5.0   |
| Coastline change rate (m/year)                   | < 2.0   | 1.9–1.0                 | 0.9–(– 1.0)       | (– 1.1)–(– 2.0)                             | > – 2.0   |
| Significant wave height (m)                      | < 2.0   | 2.1–4.0                 | 4.1–5.0           | 5.1–6.0                                     | > 6.0   |
| Coastal type                                     | High cliff  | Medium cliff            | Low cliff         | Estuary, Cobble beach, Artificial structure | Changeable coast, Delta, Bay, Sandy beach, Lagoon, Floodplain |
| Elevation (m)                                    | > 30.0  | 30.0–21.0               | 20.9–11.0         | 10.9–6.0                                    | < 6.0   |
| Slope (%)  | > 30.0  | 30.0–21.0               | 20.9–12.5         | 12.4–7.5                                    | < 7.5   |
| Geology  | Plutonic rocks, Volcanic rocks  | Metamorphic rocks       | Sedimentary rocks | Undifferentiated sedimentary                | Volcanic ashes  |
| Population density (population/km <sup>2</sup> ) | < 50  | 50–100                  | 101–150           | 151–200                                     | > 200   |
| Land use   | Water bodies, Lakes, dams, Rivers, Low vegetation, Swamps, Bare soil, Rocks | Coastal sand or Cobbles | Forests           | Agricultural lands                          | Residential areas   |

**Table 3** Importance scale used in AHP [27]

| Importance scale | Linguistic variables   |
|------------------|------------------------|
| 1                | Equal importance       |
| 3                | Moderate importance    |
| 5                | Strong importance      |
| 7                | Very strong importance |
| 9                | Extreme importance     |
| 2, 4, 6, 8       | Intermediate values    |

must be computed (Eq. 2), and to calculate the largest eigen-vector, the values of “ $d_i$ ” must be computed (Eq. 3).

$$\lambda_{\max} = \frac{\sum_{i=1}^n \frac{d_i}{w_i}}{n} \tag{2}$$

$$[d_i]_{n \times i} = [a_{ij}]_{n \times n} * [w_i]_{n \times 1} \tag{3}$$

In Eqs. 2 and 3, “ $a_{ij}$ ” refers to the elements of the pairwise comparison matrix, “ $w_i$ ” denotes the weights of the corresponding criteria, and “ $n$ ” indicates the number of criteria. Finally, to calculate the CR (Eq. 4), it is necessary to know the value of the random index “RI” values, which vary depending on the number of criteria “ $n$ ,” are listed in Table 4.

$$CR = \frac{\lambda_{\max} - n}{(n - 1) * RI} \tag{4}$$

### 3.3 Best–Worst Method

BWM, like AHP, is one of the multi-criteria decision-making methods. The fundamental difference from the AHP method is that instead of comparing each criterion with all other criteria in pairwise comparisons, the best and worst criteria are selected and compared with the other criteria. Thus, while the AHP method involves “ $n(n-1)/2$ ” comparisons for  $n$  number of criteria, in the BWM, this number is reduced to “ $2n-3$ .” This reduction in the number of pairwise comparisons decreases the workload of the decision-maker [37]. The general process steps of BWM can be summarized in four stages: identifying the best and worst criteria, creating weight vectors for the best and worst criteria, conducting consistency analysis, and determining the most suitable weights for the criteria. Firstly, the selection of the best and worst criteria from the set of vulnerability criteria is conducted through an examination of existing literature and expert opinion. In the second step, the selected best criterion is compared with other criteria to determine its priority relative to them, and other criteria are compared with the worst criterion to establish their priorities relative to the worst criterion. Making pairwise comparisons in this way prevents fractional elements in the pairwise comparison matrix and minimizes the likelihood of the decision-maker making a gross error [37]. In the third step, weight vectors are created using these pairwise comparisons. In the final step, the values of the two vectors are used in the inequality system given in Eq. 5, and by solving

**Table 4** Random index values based on the number of criteria [27]

| n  | 1 | 2 | 3    | 4    | 5    | 6    | j    | 8    | 9    |
|----|---|---|------|------|------|------|------|------|------|
| RI | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

this system, the weights of the criteria are calculated.

$$\begin{aligned} & \min \xi, \\ & \left| \frac{W_B}{W_j} - a_{Bj} \right| \leq \xi, \\ & \left| \frac{W_j}{W_w} - a_{jw} \right| \leq \xi, \\ & \sum_j W_j = 1 \text{ ve } W_j \geq 0 \end{aligned} \quad (5)$$

In Eq. 5, “ $a_{Bj}$ ” represents the priority of the best criterion relative to the  $j$ -th criterion, “ $a_{jw}$ ” the priority of the  $j$ -th criterion relative to the worst criterion, “ $W_B$ ” the weight of the best criterion, “ $W_w$ ” the weight of the worst criterion, and “ $W_j$ ” the weight of the  $j$ -th criterion. Like the AHP method, it is also necessary to calculate the consistency ratio (CR) of the pairwise comparisons in BWM. In BWM, the calculation of the consistency ratio uses the Consistency Index (CI) values, which consist of the maximum possible values of the minimax optimization threshold  $\xi$  (Table 5).

The consistency ratio is calculated by dividing the  $\xi$  value by the consistency index (Eq. 6).

$$CR = \frac{\xi}{CI} \quad (6)$$

The consistency ratio takes values between 0 and 1. The upper limits for the consistency ratio are determined according to Table 6 [41]. Consistency ratios with values lower than the corresponding value indicate that the pairwise comparison is consistent. The lower the consistency ratio, the more consistent the pairwise comparison and the more reliable the results.

## 4 Detection of Coastal Vulnerability in the Marmara Gulf Region

In this study, a coastal vulnerability analysis was conducted using AHP and BWM methods in the Marmara Gulf Region, Türkiye, which is of critical importance to the country. The analysis was carried out in five stages. First, the criteria affecting coastal vulnerability in the study area were identified. Subsequently, these criteria were normalized in line with the coastal vulnerability coefficients identified through the literature review. Then, the weights of the criteria were calculated using AHP and BWM methods. Following this process, coastal vulnerability maps were generated using the calculated criteria weights. Finally, the results of the two methods

were compared visually and statistically. The workflow of the study is given in Fig. 2.

### 4.1 Weighting of the Criteria with the AHP and BWM

Firstly, the weights of the criteria were computed using the AHP method. The following steps were followed to utilize the AHP method.

- *Step 1* The pairwise comparison matrix for the coastal vulnerability criteria was created according to the literature review (Table 7).
- *Step 2* The normalized pairwise comparison matrix is computed by dividing each element of the pairwise comparison matrix by the sum of its column.
- *Step 3* The arithmetic mean of elements in each row was taken to compute criteria weights.
- *Step 4* The consistencies of the pairwise comparisons were checked (Eq. 4).
- Subsequently, the weights of the criteria were computed using the BWM. The following steps were followed to implement the BWM.
- *Step 1* The best and the worst criteria for detecting coastal vulnerability were identified.
- *Step 2* The selected best criterion was compared with other criteria (Table 8), and other criteria were compared with the worst criterion (Table 9).
- *Step 3* The weight vectors of coastal vulnerability criteria were created using these pairwise comparisons.
- *Step 4* The inequality system (Eq. 5) was solved to compute the weights of the coastal vulnerability criteria.

### 4.2 Evaluation of the Coastal Vulnerability

In the final stage, coastal vulnerability maps were created in the GIS environment using the weighted sum method, utilizing weights calculated by both methods. These maps were created based on the vulnerability levels given in Table 10. Firstly, the resulting maps from the two methods were visually compared, and the similarities and differences between the two maps were interpreted. Secondly, given that the coastal vulnerability coefficients derived from the two methods are qualitative outputs, they were analyzed using the Wilcoxon Signed-Rank test to determine if there exists a



**Table 5** Consistency index values for BWM [37]

| $a_{BW}$        | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    |
|-----------------|------|------|------|------|------|------|------|------|------|
| CI (max $\xi$ ) | 0.00 | 0.44 | 1.00 | 1.63 | 2.30 | 3.00 | 3.73 | 4.47 | 5.23 |

**Table 6** Consistency ratio for BWM

| Criteria $a_{BW}$ | 3      | 4      | 5      | 6      | 7      | 8      | 9      |
|-------------------|--------|--------|--------|--------|--------|--------|--------|
| 3                 | 0.2087 | 0.2087 | 0.2087 | 0.2087 | 0.2087 | 0.2087 | 0.2087 |
| 4                 | 0.1581 | 0.2352 | 0.2738 | 0.2928 | 0.3102 | 0.3154 | 0.3283 |
| 5                 | 0.2111 | 0.2848 | 0.3019 | 0.3309 | 0.3479 | 0.3611 | 0.3741 |
| 6                 | 0.2164 | 0.2922 | 0.3565 | 0.3924 | 0.4061 | 0.4168 | 0.4225 |
| 7                 | 0.2090 | 0.3313 | 0.3734 | 0.3931 | 0.4035 | 0.4108 | 0.4298 |
| 8                 | 0.2267 | 0.3409 | 0.4029 | 0.4230 | 0.4379 | 0.4543 | 0.4599 |
| 9                 | 0.2122 | 0.3653 | 0.4055 | 0.4225 | 0.4445 | 0.4587 | 0.4747 |

statistically significant difference between them for the two groups (AHP and BWM).

## 5 Results and Discussion

### 5.1 Weights of the Criteria

The weights calculated by both methods are presented in Table 11. Upon examination, it is observed that the weights for the coastline change rate, significant wave height, geology, and population density criteria are identical across both approaches. Moreover, a marginal discrepancy of 0.01 is observed in the weights for the sea level change rate, coastal type, slope, and land use criteria between the methods, whereas the elevation criterion displays a disparity of 0.02.

### 5.2 Evaluation of Coastal Vulnerability Maps of Individual Criteria

Coastal vulnerability levels for the sea-level change rate are given in Fig. 3b. In both methods, the criterion with the highest weight, namely the sea-level change rate, is categorized into only two classes for the Marmara Gulf Region. The sea level change increases as one moves westward in the study area. For the study area, the annual sea level change varies between 1 and 5 mm. Within this, 83% of the area experiences a change of 2 to 3.5 mm, while the remaining 17% undergoes a change of 3.5 to 5 mm annually. Increases in sea levels affect coastal vulnerability. The region of the Gemlik Gulf is highly vulnerable. The rest of the study area has a moderate level of vulnerability.

The coastline change rate is one of the significant factors affecting coastal vulnerability. In calculations performed

using AHP and BWM, this factor weights 15% in both methods. In the study area, changes occurring along the coastlines vary annually between - 10 and + 10 m. It has been observed that the extensive buildup of coastal structures is the reason for these high variations in the coastline. The average annual coastline change in the study area was calculated as 1.11 m. When Fig. 3e is examined, there are classes in the study area that encompass each coastal vulnerability coefficient. The first class, representing a very low vulnerability, covers 40% of the study area. The coastlines of Istanbul province, the tip of the Yalova peninsula, and the coastlines of Bursa province have very low vulnerability in terms of coastline change. Very high vulnerability was identified on the northern shores of Yalova, the Gemlik Gulf, and the Gebze coastlines, and this area covers 39% of the study region. In these regions, high levels of erosion are causing coastal vulnerability. The remaining 21% of the region maintains stability in its coastline. Therefore, it is evenly distributed among the remaining three classes.

In the Sea of Marmara, wave heights vary between 0.7 and 2.6 m. Wave height is an important criterion that affects the amount of coastal erosion. Within the study area, waves have lower heights in bays compared to the open sea. Additionally, wave heights in the Sea of Marmara increase as one moves to the west. This increase can be observed in the coastal vulnerability map created for the significant wave height (Fig. 3a). In the study area, the wave height is divided into five classes according to the coefficients given in Table 3. Due to the Sea of Marmara being an inland sea with shallow depths, the wave heights are generally low. Because the study area consists of bays and is shallower compared to other parts of the Sea of Marmara, there is no region with a very high vulnerability for wave height (Fig. 3a). Class 1, which corresponds to very low coastal vulnerability, covers 56% of the study area. The entire Izmit Bay, the northern shores of Yalova province,

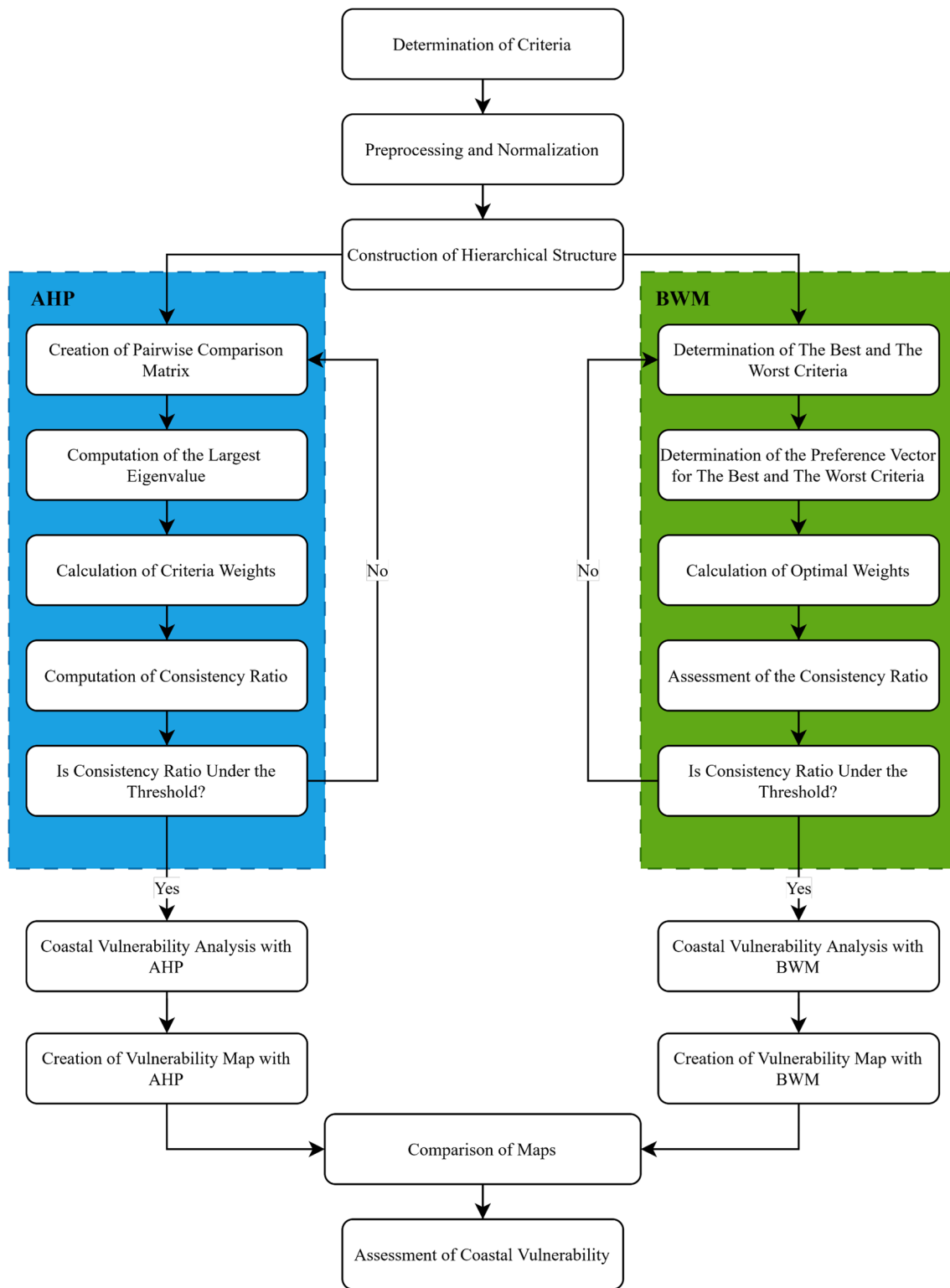


Fig. 2 Workflow of the study

**Table 7** Pairwise comparison matrix for AHP

| Criteria                | Sea-level change rate | Population density | Geology | Elevation | Coastline change rate | Land use | Coastal type | Slope | Significant wave height |
|-------------------------|-----------------------|--------------------|---------|-----------|-----------------------|----------|--------------|-------|-------------------------|
| Sea-level change rate   | 1                     | 4                  | 4       | 3         | 2                     | 7        | 4            | 3     | 3                       |
| Population density      | 0.25                  | 1                  | 1       | 2         | 0.5                   | 2        | 1            | 0.5   | 0.5                     |
| Geology                 | 0.25                  | 1                  | 1       | 1         | 0.5                   | 2        | 1            | 1     | 0.5                     |
| Elevation               | 0.33                  | 0.5                | 1       | 1         | 0.5                   | 2        | 2            | 1     | 1                       |
| Coastline change rate   | 0.5                   | 2                  | 2       | 2         | 1                     | 4        | 2            | 1     | 2                       |
| Land use                | 0.14                  | 0.5                | 0.5     | 0.5       | 0.25                  | 1        | 0.5          | 0.33  | 0.5                     |
| Coastal type            | 0.25                  | 1                  | 1       | 0.5       | 0.5                   | 2        | 1            | 0.5   | 1                       |
| Slope                   | 0.33                  | 2                  | 1       | 1         | 1                     | 3        | 2            | 1     | 1                       |
| Significant wave height | 0.33                  | 2                  | 2       | 1         | 0.5                   | 2        | 1            | 1     | 1                       |

**Table 8** The priority of the best criterion over other criteria

|                       | Sea-level change rate | Population density | Geology | Elevation | Coastline change rate | Land use | Coastal type | Slope | Significant wave height |
|-----------------------|-----------------------|--------------------|---------|-----------|-----------------------|----------|--------------|-------|-------------------------|
| Sea-level change rate | 1                     | 4                  | 4       | 3         | 2                     | 9        | 4            | 3     | 3                       |

**Table 9** The priority of the other criteria over the worst criteria

|                         | Land use |
|-------------------------|----------|
| Sea-level change rate   | 9        |
| Coastline change rate   | 5        |
| Significant wave height | 3        |
| Coastal type            | 3        |
| Elevation               | 4        |
| Slope                   | 4        |
| Geology                 | 3        |
| Population density      | 4        |
| Land use                | 1        |

**Table 10** Coastal vulnerability levels

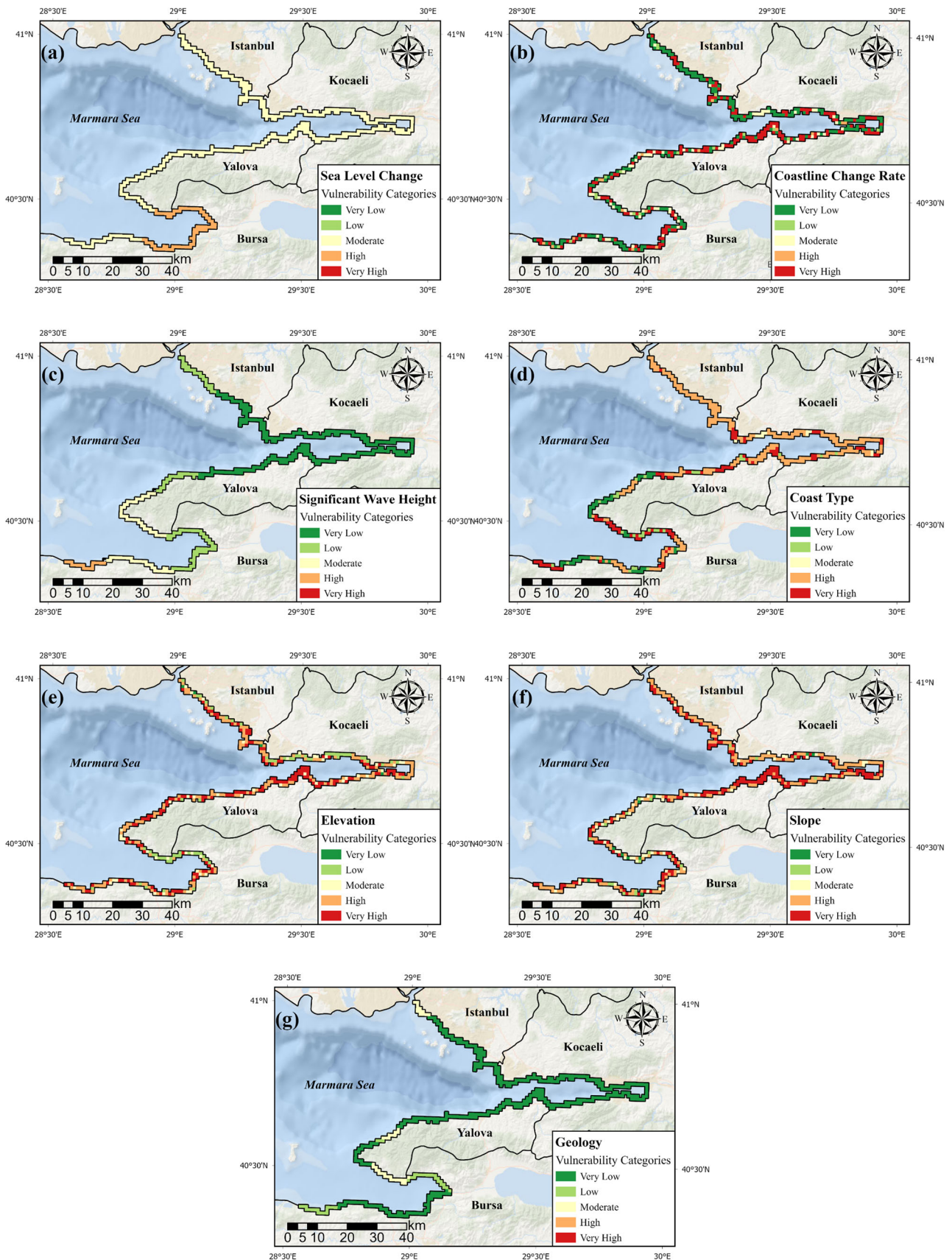
| Class Interval | Vulnerability Level     |
|----------------|-------------------------|
| 1.00–1.50      | Very low vulnerability  |
| 1.51–2.00      | Low vulnerability       |
| 2.01–3.00      | Moderate vulnerability  |
| 3.01–4.00      | High vulnerability      |
| 4.01–5.00      | Very high vulnerability |

**Table 11** Criteria weights calculated with the AHP and BWM

| Criteria                | AHP  | BWM  |
|-------------------------|------|------|
| Sea-level change rate   | 0.28 | 0.29 |
| Coastline change rate   | 0.15 | 0.15 |
| Significant wave height | 0.10 | 0.10 |
| Coastal type            | 0.08 | 0.07 |
| Elevation               | 0.10 | 0.08 |
| Slope                   | 0.10 | 0.11 |
| Geology                 | 0.08 | 0.08 |
| Population density      | 0.08 | 0.08 |
| Land use                | 0.03 | 0.04 |

and part of Istanbul’s coastlines are included in Class 1. It is observed that Gemlik Bay, a part of Yalova province, and the remaining coastlines of Istanbul province have a low vulnerability (Fig. 3a). These areas, included in Class 2, cover 23% of the study area. The tip of the Yalova peninsula, which has a moderate vulnerability, and the coasts of Bursa province to the south of this tip constitute 16% of the study area. The remaining coasts of Bursa province are included in the 4th class, which indicates high vulnerability.

The coastal vulnerability coefficients for the coastal type criterion can be seen in Fig. 3f. The study area includes artificial structures, cliffs, sandy beaches, pebble beaches,



**Fig. 3** Coastal vulnerability coefficient maps of physical criteria: **a** sea-level change rate, **b** coastline change rate, **c** significant wave height, **d** coastal type, **e** elevation, **f** slope, **g** geology

lagoons, and estuaries as coastal types. Artificial structures cover 57% of the study area's coastlines due to intensive urbanization and industrialization in the region. The coastlines of Istanbul and Kocaeli, along with the Gemlik Gulf, are regions where artificial structures are the dominant coastal type. Cliffs constitute 27% of the entire study area. Most of the coastlines in Yalova and Bursa provinces consist of cliffs. Sandy and cobble beaches cover 10% of the study area. The sandy beach coastal type is distributed throughout the Marmara Gulf Region. While there is a homogeneous distribution, Bursa and Yalova provinces have more beaches than Istanbul and Kocaeli provinces. The remaining 6% of the study area consists of lagoons and estuaries. While estuaries are distributed throughout the region, lagoons are located within the Yalova province. The impact of coastal types on vulnerability can be interpreted based on vulnerability coefficients given in Table 2. It can be observed that the majority of the coastal area is in the 4th class, with 57% (Fig. 3f). The reason for this is the presence of artificial structures and cobble beach coastal types in the region. After the 4th class, which represents high vulnerability coefficients, the 5th class is the most common in the region. This class, which includes sandy beaches, lagoons, and estuaries, covers 21% of the study area and is concentrated in Yalova province and the Gemlik Gulf. The cliff coastal type, which covers 27% of the study area, is distributed in classes 1, 2, and 3 based on the height of the cliffs.

The elevation in the study area varies between 0 and 100 m. The average elevation of the coastal areas included in the study is 18.5 m. The low elevation in the region negatively affects coastal vulnerability. When Fig. 3g is examined, which was generated based on the vulnerability coefficients (Table 2), it is observed that the majority of the study area falls into categories 4 and 5. The 5th class, corresponding to very high vulnerability, covers 36% of the total area, while the 4th class, representing high vulnerability, covers 37% of the total area. The remaining classes cover the total area as follows: 11% for the 3rd class, 15% for the 2nd class, and 1% for the 1st class. It is observed that areas resistant to coastal vulnerability in terms of elevation are located in the Gemlik Gulf and the Istanbul Peninsula. In contrast, the northern coastal areas of Yalova province and the coastal areas of Bursa province have high and very high vulnerability.

When the slope of the study area is examined, it is found that although there is variability throughout the region, there is generally a low slope. Coastal vulnerability increases as the slope decreases. 37% of the study area has a slope of less than 7%. Areas with a slope value of less than 13% cover 83% of the study region. According to the vulnerability coefficients given in Table 2, 80% of the study area has a high or very high vulnerability in terms of slope (Fig. 3c). Areas with low vulnerability in terms of slope criteria are found in the Yalova peninsula and Bursa coastal areas, where the

elevation is high. The northern coasts of Yalova province have a high vulnerability coefficient due to their low slope. For Istanbul province, the vulnerability coefficients vary between moderate and high, in other words, between classes 3 and 4.

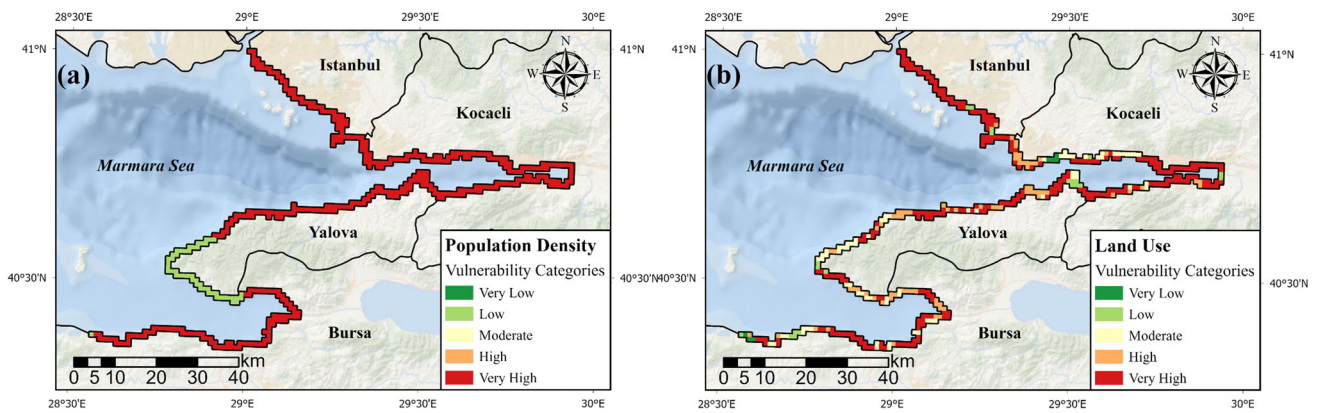
The coastal vulnerability map for the geology criterion can be seen in Fig. 3d. There are three different rock types in the region. Sedimentary rocks cover the largest area in the region (82%). In addition to sedimentary rocks, which fall into the second class in terms of vulnerability coefficient, plutonic and metamorphic rocks are also present in the region. Both rock types cover 18% of the region. Plutonic rocks fall into the first class, while metamorphic rocks are in the third class. Plutonic rocks, which have very low vulnerability, are found on the coasts of the Gemlik Gulf and Bursa province. Metamorphic rocks are found on the Yalova peninsula, while the remaining coastlines of Istanbul, Kocaeli and Bursa provinces, and the northern shores of Yalova province are composed of sedimentary rocks. Therefore, from a geological perspective, the study area generally has a low to very low level of vulnerability. Only 18% of the study area has a moderate level of vulnerability.

The population density in the study region is high due to the richness of its settlements. 89% of the region has a very high coastal vulnerability (Fig. 4b). The only area with a low coastal vulnerability coefficient is the tip of the Yalova Peninsula, which has few settlements. The northern-facing coasts of Bursa, Istanbul, Kocaeli, and Yalova provinces have a very high vulnerability coefficient. The most densely populated area in the region is the Anatolian side of Istanbul. Thus, the Anatolian side of Istanbul has a very high vulnerability.

The study area hosts a dense industrial and residential zone. The coastal vulnerability of these places, where people live and conduct their work, is high. In these areas with dense populations, the rise in water levels poses a threat to the safety of life and property for many people. The residential and industrial areas in the study region are included in the 5th class, as indicated in Table 2. This class, which has a very high vulnerability, constitutes 60% of the region (Fig. 4a). The 4th class, which represents high vulnerability covers, 17% of the study area. These regions consist of agricultural lands. The 3rd class, which represents moderate vulnerability, represents forested areas and constitutes 16% of the study area. The remaining areas with low and very low vulnerability cover 7% of the study area.

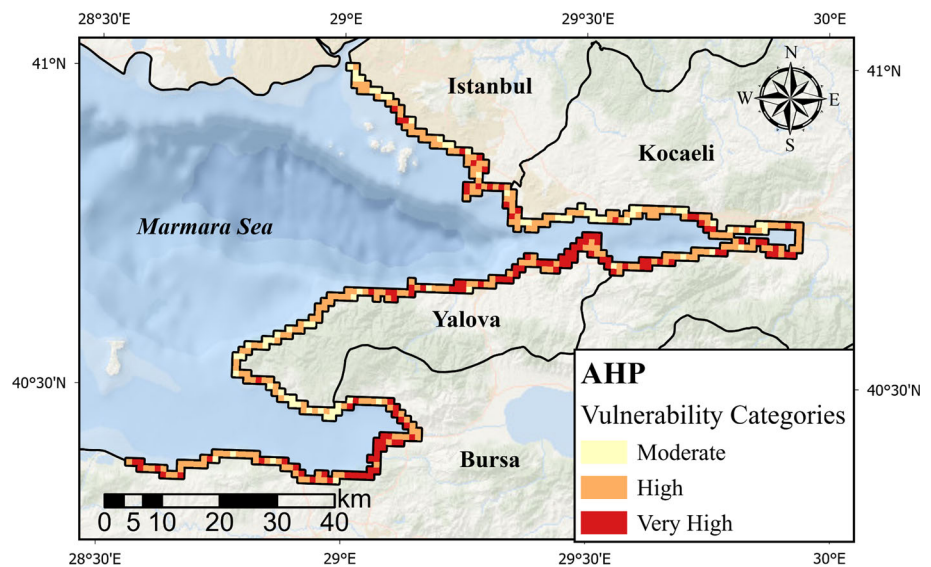
### 5.3 Coastal Vulnerability Levels Obtained with the AHP

The coastal vulnerability map obtained by using the weights calculated with the AHP method in the weighted sum method is given in Fig. 5. When the coastal vulnerability map of the study area is examined, it is observed that there are no regions with very low or low vulnerability. The reason for



**Fig. 4** Coastal vulnerability coefficient maps of social criteria: **a** population density, **b** land use

**Fig. 5** Coastal vulnerability map obtained with the AHP



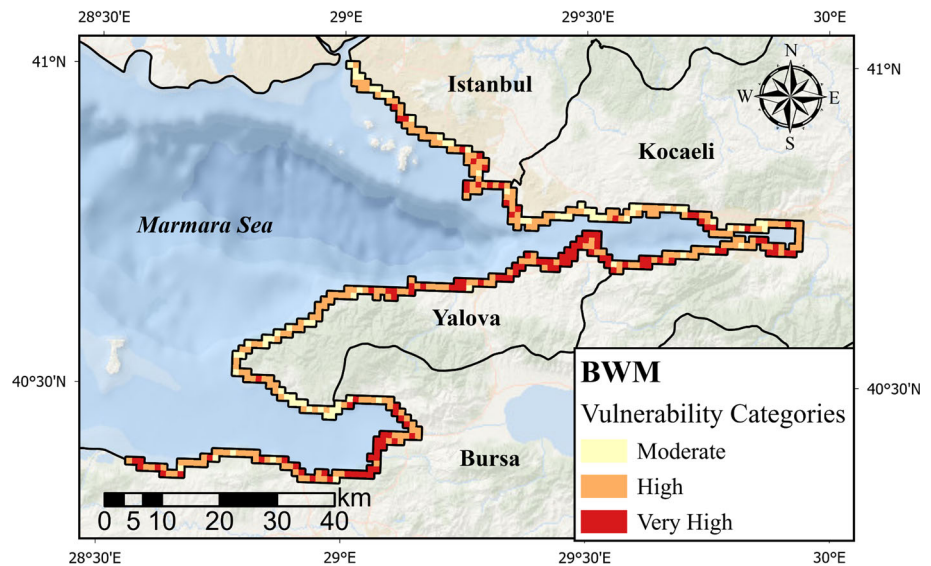
this is the presence of high vulnerability coefficients in the region (Table 2) for criteria such as sea-level change rate, coastal type, slope, elevation, population density, and land use. The sum of the weights of these criteria reaches a total of 0.74 out of 1. 17% of the study area has a moderate coastal vulnerability. These areas include the Kadıköy and Göztepe districts of Istanbul, as well as the outer sections of Gebze and the Yalova Peninsula. The province of Bursa, which has high coastal vulnerability along with the remaining coasts of the province of Istanbul and the northwestern coasts of the province of Yalova, constitutes 54% of the study area. Areas with very high vulnerability cover 29% of the study area. Although regions with very high vulnerability are scattered throughout the study area, they are concentrated around the Gulf of Gemlik and the north-facing coasts of Yalova. Within the borders of Yalova province, the settlements of Altınova, Central Yalova, and Çınarcık, and within the borders of Bursa province, the settlements of Gemlik and Mudanya are areas with very high vulnerability. In these regions, low elevation

and slope are among the reasons for high vulnerability. Additionally, the settlements in these areas are established close to the coast, which is also a reason for high vulnerability. Another important reason is the significant changes in the coastline in these areas with high vulnerability. Lastly, the coasts in this region consist of artificial structures with high vulnerability coefficients and sandy beaches with very high vulnerability coefficients. Although the individual weights of each criterion are not high, the coastal vulnerability in these regions is very high due to multiple criteria having very high coastal vulnerability values.

#### 5.4 Coastal Vulnerability Levels Obtained with the BWM

The coastal vulnerability map produced with BWM is presented in Fig. 6. The coastal vulnerability values calculated with BWM, like AHP, do not include the low and very low vulnerability classes. 18% of the study area has moderate

**Fig. 6** Coastal vulnerability map obtained with the BWM



vulnerability, 57% has high vulnerability, and 25% has very high vulnerability. Regions with very high vulnerability are concentrated around the Gulf of Gemlik and the north-facing coasts of Yalova. Areas with high vulnerability, similar to the AHP method, are the province of Bursa, the coasts of Istanbul province excluding Üsküdar and Göztepe, and the north-western coasts of Yalova province. Üsküdar and Göztepe districts, the tips of the Yalova peninsula, and Gebze have moderate coastal vulnerability. Using BWM, fewer pairwise comparisons were conducted, and similar results to AHP were observed.

### 5.5 Comparison of Two Methods

The results of the Wilcoxon Signed-Rank test, which examines whether there is a statistically significant difference between the paired coastal vulnerability coefficient differences obtained by the two methods, are provided in Table 12. When Table 12 is examined, it is observed that there is no statistically significant difference between the coastal vulnerability coefficients calculated with the AHP and BWM ( $Z = -0.333$   $p = 0.739$ ). Based on this result, it can be concluded that the coastal vulnerability coefficients obtained with the usage of the AHP and BWM are quite similar. Thus, BWM achieves similar results to AHP with fewer pairwise comparisons.

In addition to the statistical test, the difference map obtained by subtracting the result maps obtained with both methods using band arithmetic is given in Fig. 7. There is a difference of only 2% of the entire study area between the two methods. In the remaining 98% of the area, there is no difference between the coastal vulnerability values obtained by the two methods, and the results are observed to be the same (Fig. 7). The main reason for this discrepancy is the

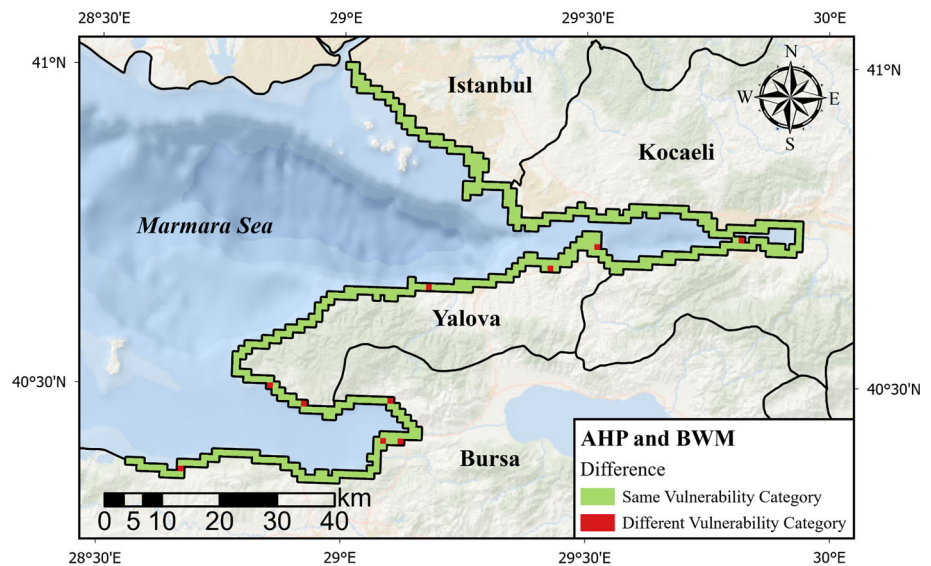
inconsistency in the weight calculation in the AHP method compared to BWM.

Subsequently, the AHP and BWM methods were analyzed in terms of computational efficiency, time efficiency, internal consistency, and ease of use. Additionally, their applicability was assessed with the aid of statistical tests, and a comprehensive comparison was concluded by reviewing literature studies that employed both methods.

When considering computational efficiency, AHP involves a greater number of pairwise comparisons. AHP requires " $n(n-1)/2$ " pairwise comparisons for ' $n$ ' criteria, whereas BWM requires only " $2n-3$ " comparisons. In this study, where  $n = 9$ , 36 comparisons were made for AHP and 15 for BWM, demonstrating BWM's lower computational burden. Timewise, the longest phase in both methods is conducting pairwise comparisons. Even though solving the BWM model involves more complex calculations than AHP, advancements in technology negate significant time differences, making the fewer comparisons required by BWM a time-saving advantage. A study by Rezaei in 2015 examined the internal consistency of both methods, finding BWM to be more internally consistent than AHP [37]. Furthermore, BWM's fewer pairwise comparisons simplify the decision-making process for users. Unlike AHP, BWM does not utilize decimal numbers during comparisons; it only uses integers, reducing potential errors and inconsistencies. Lastly, studies within the literature that compared the BWM with the AHP method, particularly those incorporating GIS, were examined. Tan et al. (2023), while assessing ecological suitability, found that, in comparison with the AHP model, the BWM model showed greater stability and precision, indicating its potential to enhance the model's accuracy and the reliability of evaluation outcomes [65]. In a comparative evaluation focusing on GIS-based BWM for emergency

**Table 12** The results of the Wilcoxon Signed-Rank test

| Groups | N   | Median | Z      | p     |
|--------|-----|--------|--------|-------|
| AHP    | 438 | 4.00   | -0.333 | 0.739 |
| BWM    | 438 | 4.00   |        |       |

**Fig. 7** Band difference map of AHP and BWM

facility planning, the BWM model was compared against the AHP method by examining pairwise comparisons, computed weights, and rankings derived from these weights. It was determined that the BWM model is considerably simpler and faster for computing weights, as it requires fewer comparisons than AHP. The final weights, rankings from weights, and mean rankings obtained through BWM were found to be consistent and reliable in comparison to AHP [66]. A study on flood-based critical sub-watershed mapping demonstrated through a comparative analysis that BWM yielded results consistent with field evidence, proving it to be the most effective method [67]. In another research about determining the potential zone of Pasir Batu mining, it was concluded that the BWM method facilitates more structured comparisons, making the process more straightforward and more comprehensible, and thus leading to more consistent comparisons and, consequently, more reliable weights [68]. There is no significant difference between AHP and BWM in terms of coastal vulnerability levels, and the BWM method stands out for the advantages it provides to the decision-maker during pairwise comparisons and ease of use.

## 6 Conclusions

For many years, coastal areas have been recognized as living spaces around the world, and numerous studies have been conducted to protect these areas. Especially, natural hazards

and potential damages caused by climate change are significant issues that negatively affect coastal areas. For nations to successfully protect coastal areas against hazards, implement measures, and manage these processes effectively, identifying the coastal vulnerability of these regions is of great importance. Furthermore, since the factors causing coastal vulnerability dynamically vary, the process of coastal vulnerability analysis is an important one that needs to be repeated over time.

Despite Türkiye being surrounded by seas on three sides and many important regions located on the coasts, there have been only a limited number of studies on coastal vulnerability up to the present day. In the Marmara Gulf Region, an area of significant importance in Türkiye due to its population density and geopolitical position, an extensive coastal vulnerability analysis has not been conducted. Additionally, the BWM method, frequently used for solving multi-criteria decision-making problems in various study areas, has not yet been used in coastal vulnerability analysis studies. In this study, considering the aforementioned gaps in the literature, a coastal vulnerability analysis for the coasts of the Izmit Gulf, Yalova Peninsula, and Gemlik Gulf in the Marmara Region was conducted using AHP and BWM methods. Based on an extensive literature review, coastal type, coastline change rate, elevation, sea-level change rate, significant wave height, geology, population density, and land use criteria were included in the study. These criteria were normalized in line with the coastal vulnerability coefficients identified



through literature review and expert opinion. Subsequently, the weights of the criteria were determined using AHP and BWM, and coastal vulnerability maps were created. Finally, the results obtained from both methods were analyzed visually and statistically, and the methods were compared with each other. According to the vulnerability map obtained with AHP, 17% of the study area is under moderate vulnerability risk, 54% under high vulnerability risk, while the remaining 29% is under very high vulnerability risk. According to the vulnerability map obtained with BWM, it is observed that 18% of the study area has a moderate vulnerability, 57% has a high vulnerability, and 25% has a very high coastal vulnerability. The areas with high vulnerability are located on the northern coasts of Yalova and in the Gulf of Gemlik. High vulnerability coasts include the province of Bursa, the coasts of Istanbul excluding Üsküdar and Göztepe, and the northwestern coasts of the province of Yalova. The vulnerability values obtained from both methods yielded very similar results. Furthermore, the Wilcoxon Signed-Rank test was conducted to evaluate if there is a statistically significant difference between the two methods. The results of the test indicate that there is no statistically significant difference between the methods ( $Z = -0.333$ ,  $p = 0.739$ ).

The comparisons between AHP and BWM demonstrate BWM's notable advantages in computational and time efficiency, internal consistency, and ease of use. BWM's streamlined approach offers a quicker and more intuitive evaluation process, presenting a valuable tool for decision-making and coastal vulnerability assessments. Literature research about the comparison of two methods, especially in GIS applications, corroborates these findings. Studies indicate that BWM, compared to AHP, provides greater stability, precision, and structured comparisons, making it an equally suitable method for decision-making in coastal vulnerability contexts. This analysis enriches our understanding of BWM's applicability and strengthens its position as a preferred choice for efficient and reliable decision-making processes.

This study makes a significant contribution to the field of coastal vulnerability assessment by conducting a comparative analysis of the AHP and BWM, with a particular focus on the novel application of BWM in coastal vulnerability context. Our findings demonstrate that BWM not only parallels AHP in terms of outcome reliability but also offers enhanced efficiency through reduced pairwise comparisons. This efficiency, coupled with the method's ease of use and internal consistency, positions BWM as a formidable tool for policymakers and coastal managers, facilitating informed decision-making for coastal protection and hazard mitigation strategies. By bridging a methodological gap in the literature and providing a rigorous empirical comparison, this research enriches the academic discourse on coastal vulnerability assessment and underscores the global importance of adopting innovative and reliable methodologies in the face

of climate change. Our study offers practical insights for the development of sustainable management practices crucial for protecting coastal ecosystems and human populations against environmental hazards.

Future research directions could explore the application of BWM across diverse geographical settings and its integration with other decision-making frameworks, further solidifying its utility and adaptability in coastal vulnerability studies. Moreover, the selection of criteria plays a critical role in the accuracy of coastal vulnerability analyses. As the suite of considered criteria broadens, the sensitivity and specificity of the analysis improve. Future studies might gain from incorporating economic and ecological criteria into coastal vulnerability assessments, potentially leading to more comprehensive and nuanced analyses. Consequently, it is advisable to expand the inclusion of social criteria and integrate indicators that more accurately reflect the demographic composition, aiming to refine the assessment of coastal vulnerability.

**Author Contributions** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Tümay Arda and Onur Can Bayrak. The first draft of the manuscript was written by Melis Uzar and Tümay Arda, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Funding** Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

## Declarations

**Conflict of interest** All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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