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MORPHOMETRIC ANALYSIS AND CLASSIFICATION OF THE BAYS BETWEEN ŞİLE AND KEFKEN (TÜRKİYE) IN TERMS OF COASTAL GEOMORPHOLOGY

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Abstract: The morphometric characteristics of bays affected by geological and geomorphological processes provide information about the formation and development of coasts and their hydrodynamic functioning. This study examined the morphometric characteristics of bays between Şile and Kefken along Türkiye's Black Sea coast and developed a new bay classification model (*BCM*) as a systematic framework based on a comprehensive set of morphometric indicators. Satellite imagery, orthophotos, and topographic maps were used to determine bay boundaries and basic morphometric parameters in a Geographic Information Systems (GIS) environment. For each bay, shoreline length, coast width, maximum indentation, bay area, bay beach shoreline, bay beach area, and maximum bay beach indentation were measured. Five different morphometric indices were calculated based on the basic parameters: The Planform Index (*Ip*) of the bays, Embayment Morphometric Parameter (*ye*), Embayed Sinuosity Rate (*Si*), Circularity Rate Index (*Rc*), and the Bay Filling Index (*Bfi*). Additionally, five indices datasets were normalized to the range (0, 1), and their averages were used to establish the *BCM*. The average indentation of 142 bays identified between Şile and Kefken is 122.6 m, their width is 210.7 m, their shoreline length is 453.9 m, and their beach indentation is 21.8 m. The fact that the largest bay is approximately 3,889 times larger than the smallest bay demonstrates the high level of morphological diversity. *BCM* results revealed that 40% of the bays exhibited low circularity open-type features, while 19.1% exhibited high indentation and sinuosity closed-type features.

Keywords: bay classification; morphometric analysis; coastal geomorphology; Black Sea coast

1. Introduction

Gulfs or bays are coastal geomorphological units or landforms with different origins, formed where seawater penetrates inland, bounded on both sides of the bay entrance by coastal headlands or by an anthropogenic structure (Bird, 2008; Bowman et al., 2009; Hsu et al., 1989a). The bays exhibit coastal features formed and continually shaped by processes on rapidly changing coasts, such as sediment accumulation, transport, and erosion during the Holocene (Cao et al., 2021; De Muro et al., 2016; Loureiro et al., 2012). In this respect, bays can be related to all geomorphological processes caused by tectonics, karstification, fluvial processes,

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glaciers, waves, winds, and anthropogenic factors in terms of the morphogenetic region in which the bays are located and the characteristics specific to the bay (Fellowes et al., 2019; Usai et al., 2025). Additionally, bays have been primary areas of intense anthropogenic activity since ancient times, as they provide natural harbors and coastal shelter (Ojeda & Guillén, 2008). Another feature of bays is that the impact of high-energy waves can take different forms, causing waves to break far from the coast or for the current to flow toward different areas within the bay (Castelle & Coco, 2012; Daly et al., 2014; Finkl & Makowski, 2021; Gallop et al., 2020).

Morphometric analyses are important for understanding coastal dynamics, monitoring and modeling erosion and sedimentation processes, as well as establishing decision-support mechanisms for coastal management planning (Håkanson et al., 1986). Morphometric analyses in coastal areas include measuring the slope, steepness, shelf area, bathymetric characteristics, length of the shoreline, linear complexity (fractal dimension), coastal platform width, and morphological responses to sea level changes (Fellowes et al., 2019; Håkanson et al., 1986; Hsu et al., 1989b; Iglesias et al., 2009; Murphy et al., 2023; Payo et al., 2018). The fact that bays also have their own unique basic morphometric parameters and that these quantitative data are analyzed using different morphometric indices enables the modeling of coast with bays, the explanation of their geological and geomorphological evolution, the determination of their hydrodynamic structure, and the monitoring of coastal changes (Bowman et al., 2014; Castelle et al., 2020; Finkl, 2004; Håkanson & Eklund, 2007; Hsu et al., 1989a; Klein & Menezes, 2001; Swirad & Rees, 2015; Usai et al., 2025). The morphometric analysis and classification of bays can also contribute to their examination in terms of sustainable coastal management, beyond their hydrodynamic and geomorphological development (Corbridge & Hawley, 2020; Nunez et al., 2022; Usai et al., 2025; Uzun & Ocak, 2026).

The aim of this study is to quantitatively determine the morphometric characteristics of the bays located along the western Black Sea coast between Şile and Kefken and to develop a systematic classification model based on various morphometric indices. To this end, the morphological structure of the bays was evaluated using morphometric parameters, and a morphometry-based classification approach was proposed based on the findings.

2. Data and methods

2.1. Study area

The selected study area is the shoreline between Şile (Istanbul) and Kefken (Kocaeli) on the western coast of the Black Sea in northern Türkiye, which exhibits a longitudinal coastal type with locally quite different coastal morphologies. The main reasons for selecting this coast for bay morphometry and classification studies include its numerous bays of varying sizes, its paleokarst and eolian topography, and the influence of different lithological units on the shoreline (Ertek, 1995, 2014; A. Uzun, 2017; M. Uzun, 2015). The eastern boundary of the study area is formed by the eastern side of Kefken-Cebeci Bay, north of the Kandıra district in Kocaeli province. In contrast, the western boundary is formed by the Şile harbor breakwater (Figure 1).

A significant portion of the coast in the study area comprises Eocene and Cretaceous age limestones, conglomerates, and marls (Ertek, 1995, 2014). This situation has resulted in the coast comprising rocks with structurally distinct resistances, leading to changes in its geomorphological structure (Figure 1). Geomorphological units characteristic of karst topography are found along the coast and behind it, indicating that the coast also contains

paleokarst formations (Ertek, 2014). Cliffs, abrasion platforms, notches, beaches, coastal dunes, erosion notches, spits, and bioerosion landforms comprise the geomorphological elements in the study area (Ertek, 1995; A. Uzun, 2017; M. Uzun, 2015).

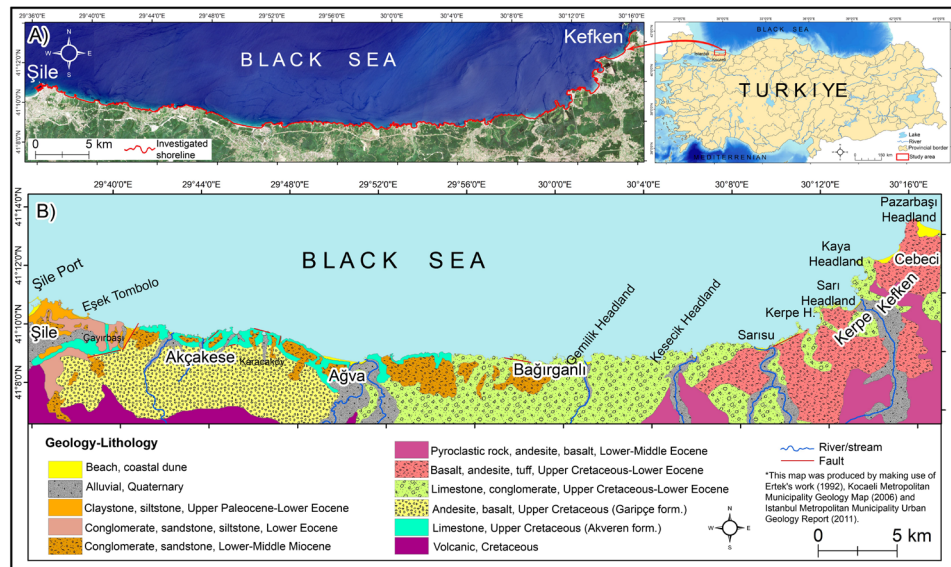


Figure 1. Panel A: Location of the study area in Türkiye and Sentinel-2 MSI satellite image of the shoreline acquired on July 22, 2025. Panel B: Geological map of coasts between Şile and Kefken.

Note. Adapted from “Kuzeybatı Anadolu kıyılarında jeomorfolojik araştırmalar (Şile-Kefken)” [Geomorphological researches in coasts of Northwest Anatolian (Between Şile-Kefken)] by T. A. Ertek, 2014, *Türk Coğrafya Dergisi*, 27, 139–153 (<https://dergipark.org.tr/en/pub/tcd/article/228220>). Copyright 1992/2014 by Turkish Geographical Review; from *İstanbul İl Alanının Jeolojisi* [Istanbul Metropolitan Municipality Urban Geology Report] by N. Özgül, 2011, Istanbul Metropolitan Municipality (<https://depremzemin.ibb.istanbul/uploads/prefix-ist-5000-jeoloji-rapor-66a3951b76d99.pdf>). Copyright 2011 by Istanbul Metropolitan Municipality; from *Kocaeli Metropolitan Municipality geology map*, by Kocaeli Metropolitan Municipality, 2006 (<https://rehber.kocaeli.bel.tr/portal/#40.7620078,29.9207242,13z>). In the public domain; from *Copernicus browser*, by Copernicus Data Space Ecosystem, 2025 (<https://dataspace.copernicus.eu/browser/>). In the public domain.

2.2. Dataset

One of the primary datasets used in this study is a Copernicus Sentinel-2 MSI satellite image dated August 16, 2025, with a spatial resolution of 10 m (Copernicus Data Space Ecosystem, 2025). The study also used satellite imagery with a spatial resolution of 1 m obtained from Google Earth Pro (2025), topographic data with a resolution of 10 m from the Directorate General for Mapping (2025), and the data collected during fieldwork.

The Digital Elevation Model of the study area, the geological map, and the natural appearance created from Sentinel-2 satellite image bands were used to generate the baseline data for the study. The study comprises the following steps: determining the boundaries of the shoreline and bays, applying morphometric analyses to the bays, evaluating and interpreting the resulting quantitative analyses, and classifying the bays based on their morphometric parameter data in terms of coastal geomorphology. In this regard, the

shorelines of the study area were generated in Google Earth Pro (1 m resolution), then transferred to ArcGIS in .kmz format and prepared for use by applying the necessary projection transformations. After the bay boundaries were determined, each bay was numbered from 1 to 142, east to west, in ArcGIS.

Following the delineation of bay boundaries, numerous studies were reviewed to determine the fundamental morphometric parameters of the bays (Bowman et al., 2014; Castelle et al., 2020; Fellowes et al., 2019; Håkanson & Eklund, 2007; Hsu et al., 1989a; Klein & Menezes, 2001; Swirad & Rees, 2015; Usai et al., 2025). Many previous studies have examined the morphometry of bays and the morphometric characteristics of beaches within them (Bowman et al., 2009; Fellowes et al., 2019; Short & Masselink, 1999; Usai et al., 2025). Calculations were performed separately for each bay using ArcGIS software. The parameters used are: R_o is the width-distance of bay between the headlands (m), a is the maximum indentation of the bay into the land (m), S_1 is the total shoreline length of the bay (m), A_e denotes the total area of the bay on the sea side within the defined boundaries (m^2), S_2 denotes the shoreline length of the beach formed in the bay (m), B_w denotes the maximum inland projection of the beach in the bay (m), and A_b denotes the total area of the beach in the bay (m^2) (Figure 2).

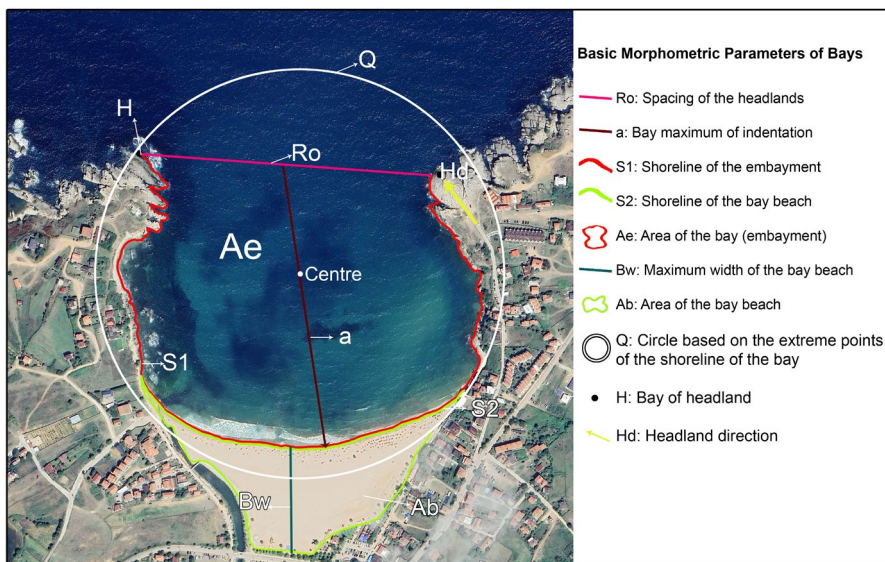


Figure 2. The boundaries of the bays and the representation of basic morphometric parameters.

In the next phase of the study, morphometric analyses were performed using the basic parameter data of the bays. Many studies on bay morphometry have been reviewed, and five indices frequently used in the literature have been employed (Babar, 2005; Bowman et al., 2009; Castelle et al., 2020; Fellowes et al., 2019; Håkanson & Eklund, 2007; Hsu et al., 1989a; Klein & Menezes, 2001; Miller, 1953; Spagnolo et al., 2008; Swirad & Rees, 2015; Usai et al., 2025). In this study, the Planform Index (I_p), Embayment Morphometric Parameter (γ_e), Embayed Sinuosity Rate (S_i), Circularity Rate Index (R_c), and Bay Filling Index (B_{fi}) indices were used. The equations for the specified indexes are shown in Table 1.

Table 1. Morphometric indexes and equations used in this study

Index	Equation	Reference
lp	$\frac{a}{R_o}$	Bowman et al. (2009), Hsu et al. (1989a)
γ_e	$\frac{a}{\sqrt{A_e}}$	Fellowes et al. (2019)
Si	$\frac{S1}{R_o}$	Babar (2005), Spagnolo et al. (2008)
Rc	$\frac{Ae}{\left(\frac{P}{\pi}\right)^2 \cdot \pi}$	Miller (1953)
Bfi	$\frac{S2}{S1}$	Bowman et al. (2009)

The Natural Breaks (Jenks) method was used to classify bay morphometric indexes. This method performs natural classification within a specified category by considering the maximum and minimum numerical values (Jenks, 1967).

This study differs from previous research by analyzing and classifying bays based on the combined effects of multiple bay morphometric variables (Castelle et al., 2020; Fellowes et al., 2019; Usai et al., 2025). To achieve this, a normalization process was first applied to compare and standardize the bay morphometric index results (Uzun &

Ocak, 2026). This process was implemented using the following equation:

$$No = \frac{1}{n} \sum_i^n \left(\frac{Bi - Bi_{min}}{Bi_{max} - Bi_{min}} \right) \quad (1)$$

In the equation, No denotes the result of the normalization process; Bi denotes the index value to be normalized; the minimum value within Bi_{min} , and the maximum value within Bi_{max} . The normalization result ranges from 0 to 1.

In this study, a Bay Classification Model (BCm) is proposed, using five bay morphometric values that have been normalized for comparison and analysis. The bay classification or bay degree equation is given below:

$$BCm = \frac{lp + \gamma_e + Si + Rc + Bfi}{(n = 5)} \quad (2)$$

In the equation, the results for the normalized morphometric index (lp , γ_e , Si , Rc , Bfi) for each bay are summed and divided by the total number of indices (n). Then, the BCm result values are classified into five categories using the natural refraction method. In this way, the degrees of bay formation in the study area are classified.

The relationships and interactions among the basic morphometric parameters of bays in the study area were assessed using the Pearson Correlation Coefficient. The bays in the study area were also examined with respect to the morphological structure of the headlands that bound them. For the analysis of headland orientation in bays, the headland classification developed by Fellowes et al. (2019), comprising six types, was used. Additionally, this study mentions anthropogenically formed headlands and six types of headlands.

3. Results

3.1. Basic morphometric characteristics of the bays between Şile and Kefken

A total of 142 bays have been identified between the Şile and Kefken coasts. The deepest indentation of the identified bays is 835.5 m, while the shallowest indentation is 21.8 m. The

average depth of the bays is 122.6 m. The majority of bays with the deepest indentations are in the eastern part of the study area (bays numbered 1–60). The average width of bays is 210.7 m, the average coastline length is 453.9 m (max 3,172.68 m, min 67.21 m), and the average bay area is 41,826.42 m². The highest indentation toward the land, the longest coastline, and the widest bay area were found in Bay No. 6 (Kumcağız Bay), while the longest bay width was found in Bay No. 1 (Cebeci Bay). It was found that there are 40 bays above the average indentation toward the land, 38 bays above the shoreline length, 26 bays above the average bay area, and 34 bays above the average width. The largest bay (No. 6) is 3,889 times larger than the smallest bay (No. 48). The orientation of bays (*a* value) largely coincides with the general coast at right angles. In this respect, the bays show a K-KB orientation distribution (with the direction facing the bay mouth taken as the general orientation). Bay indentation data show that the vast majority of bays exhibit diversity, and that smaller bays with lower values also show differences. It is also noteworthy that some bays have relatively higher values in terms of basic parameters and are concentrated in the eastern part of these bays (Figure 3).

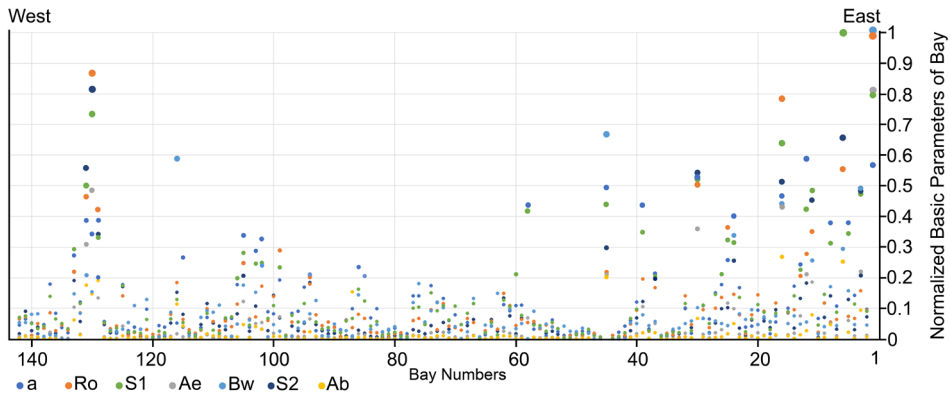


Figure 3. Normalized basic morphometric parameter results for the bays between Şile and Kefken.

The other key parameters of the bays along the coast between Şile and Kefken are the beach shoreline within each bay, the maximum distance from the land indentation of the beach, and the beach area. It was determined that 130 of the bays in the study area had beaches in terms of coastal geomorphology, while 12 bays did not have beaches. The bays without beaches are located between bays numbered 42 and 135. In this regard, it has been determined that beaches are present in all the bays, particularly in the eastern part of the study area. The average length of the S2 of beaches in the bays is 176.1 m. The longest beach is 2,155.2 m long and it is situated in the Bay No. 1. The average area of the beaches in bays *Ab* is 6,268.4 m², while the maximum value is 242,772.5 m² (Bay No. 1). The average value of the beach indentation in bay *Bw* is 21.8 m. The longest bay beach in the study area is Bay No. 1, with a length of 253.7 m. When evaluating the shoreline length, area, and maximum width of the beaches within the bay, it was determined that beach formation occurred over a wider area, particularly in the eastern section (Figure 3).

According to the correlation results, the weakest relationship was found between *a* and *Ab* ($R^2 = 0.284$). The highest correlation among the basic parameters is between indentation and bay shoreline length ($R^2 = 0.88$). High correlations were obtained, particularly between *Ro* and

$S2$ ($R^2 = 0.892$), $S1$ and Ae ($R^2 = 0.816$), $S1$ and $S2$ ($R^2 = 0.786$), and Ae and $S2$ ($R^2 = 0.815$). Quantitative data show that as the bay's indentation into the land increases, its width also increases at a rate (Figure 5).

3.2. Morphometric index analysis of the bays between Şile and Kefken

A morphometric index analysis was conducted to identify the morphometric characteristics of the coves between Şile and Kefken and to quantitatively assess their morphological differences. The parameters used and the results obtained for each parameter are detailed below:

- lp : It is calculated based on the ratio of the bay width between the headlands (Bowman et al., 2009; Fellowes et al., 2019; Usai et al., 2025). High index values indicate that the bay can be driven too far inland relative to their width. The study found that the average lp value for all the bays was 0.87. The maximum lp value is 3.56, the minimum is 0.17, and 51 of the bays have lp values above the average. Bays with above-average lp values and deep indentations relative to their width are concentrated between Kefken and Kerpe, along Bağırganlı coast, just east of Ağva, northwest of Akçakese along Şile coast (Figure 4). According to the categorical lp classification using the natural breaks method, 25% of the bays between Şile and Kefken are classified as Class 1 (C-1), 32% as Class 2 (C-2), 24% as Class 3 (C-3), 15% as Class 4 (C-4), and 4% as Class 5 (C-5).
- ye : It is calculated based on the ratio between the bay indentation and the square root of the bay area (Fellowes et al., 2019). High values indicate that the bay indentation is more pronounced and reflect the degree of bay formation to some extent. The mean ye value for the 142 bays in the study area was 1.05, with a maximum of 2.71 and a minimum of 0.44. The highest ye value is found in Bay No. 43. There are only 12 bays above the average value (Figure 4). This indicates that some bays in the study area are morphometrically distinct from others. According to the categorical classification based on natural breaks, 28% of the bays are in C-1, 26% in C-2, 21% in C-3, 17% in C-4, and 8% in C-5. The bays with the highest ye values were found between Ağva-Bağırganlı and along Kerpe coast.
- Si : It is calculated by dividing the length of the coastline by its width (Babar, 2005; Spagnolo et al., 2008). An index result close to 1 indicates that the bay's indentation toward the land is slight, while results relatively higher than 1 indicate that the bay creates an indentation at a greater distance toward the land. Additionally, the presence of a curved or circular structure within the bay correlates with a high Si value. The average Si value in the 142 bays between Şile and Kefken is 2.82, the maximum Si value is 11.49, and the minimum Si value is 1.23. The highest Si value was detected in Bay No. 58, and the lowest Si value was detected in Bay No. 116. Of the 142 bays, 47 (33%) have Si values above the average. A large portion of the bays with values above the average sinuosity rate are located east of Ağva (Figure 4). According to the categorical Si classification, 34% of the bays are in C-1, 30% in C-2, 24% in C-3, 6% in C-4, and 6% in C-5.
- Rc : It is calculated by comparing the bay area to a circle with the same perimeter (Miller, 1953; Swirad & Rees, 2015). The results reveal that the shape and dimensions of the bay were analyzed and that the elements controlling its geometry were identified (Miller, 1953; Swirad & Rees, 2015). Rc result values close to 0 indicate that the bay has a more angular geometry, while values relatively higher than 0 indicate that the bay has a high degree of roundness. The average circularity ratio value for the 142 bays between Şile and Kefken is 0.51, with a maximum Rc value of 0.77 and a minimum Rc value of 0.09. Bay 38 has the highest Rc value, while Bay 129 has the lowest Rc value. A total of 77 bays, or 54.2% of all the bays, have

circularity above the average R_c value. Bays with high circularity ratios are concentrated along the coasts of Kefken, Bağırçanlı bay (Figure 4). According to the categorical classification of the R_c value, 11% of the bays are in C-1, 28% are in C-2, 27% are in C-3, 17% are in C-4, and 17% are in C-5.

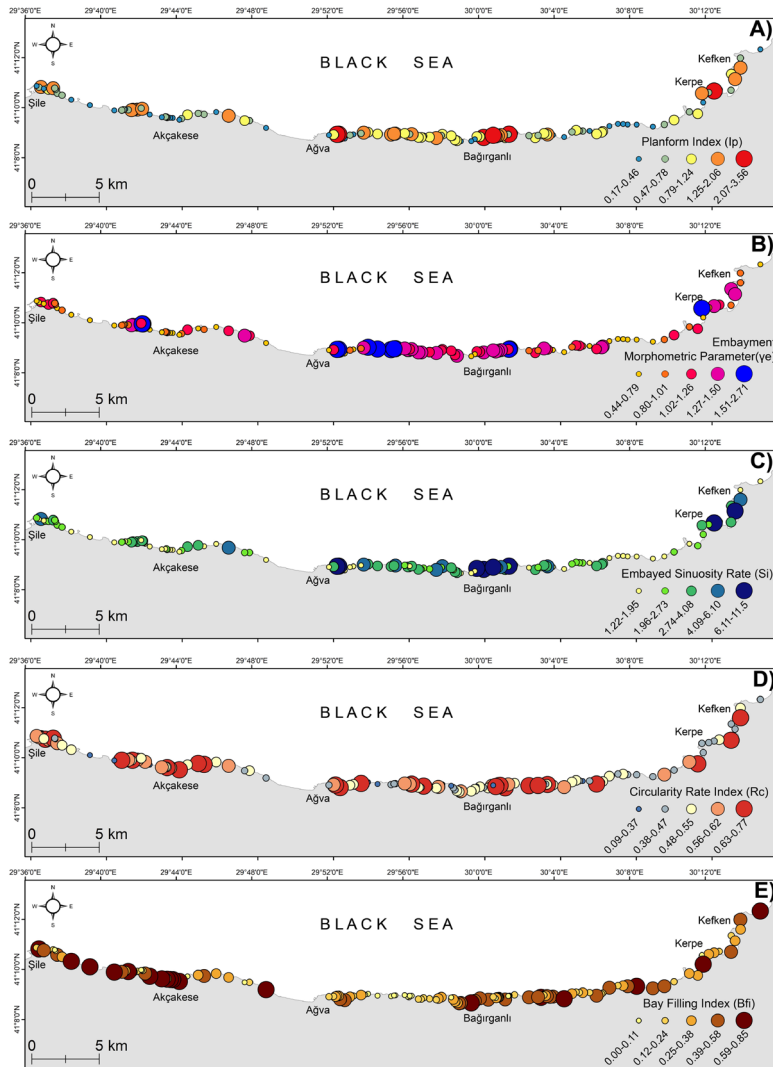


Figure 4. Distribution of morphometric index results for the bays between Şile and Kefken.

- *Bfi*: The ratio of the beach shoreline within the bay to the bay's total shoreline is used to calculate this (Bowman et al., 2009). The index results provide information on the bays' accumulation status, particularly regarding beach structure and coastal geomorphology. A *Bfi* result of 0 indicates that there is no beach in the bay, while a result close to 1 indicates that a beach has been formed in a large part of the bay. The average *Bfi* value for the bays between

Şile and Kefken was 0.30. The maximum value was found in Bay No. 1, at 0.84. Ten of the bays in the study area lack beaches, and their *Bfi* values are calculated as 0. (Figure 4). Forty percent of all bays exceed the average *Bfi* value. Bays with high *Bfi* values are concentrated along the coast between Şile–Akçakese, Bağıranlı, and Kerpe–Cebeci.

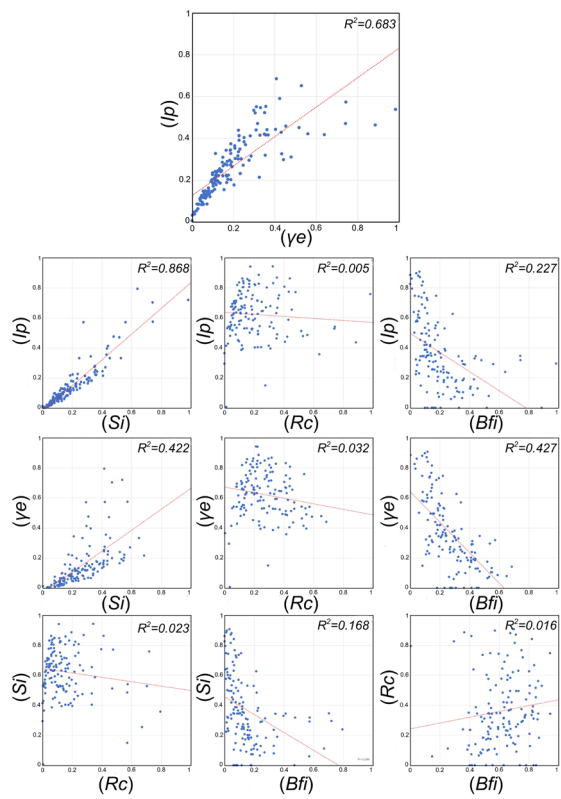


Figure 5. The correlation status between the morphometric indexes used in this study (based on normalized values).
Note. The red line indicates the trend between the indexes.

Based on the morphometric index results, the bays' geomorphological classification was first normalized. A correlation matrix was then created to examine relationships among bays by slope condition (Figure 5). According to the analysis, the highest correlation was observed between the *lp* and the *Si* ($R^2 = 0.868$). The other high correlation was found to be between *lp* and *ye* ($R^2 = 0.683$) (Figure 5). The reason for the high correlation between the specified indexes is related to the similarity of the basic parameters used and their consideration of bay geometry. The lowest correlations were found between *lp* and *Rc* ($R^2 = 0.005$), *Rc* and *Bfi* ($R^2 = 0.016$), and *Si* and *Rc* ($R^2 = 0.023$) (Figure 5). The findings show some similarities among the indexes but also yield quite different values. In this regard, although some bays in the study area are circular, the bay mouth opening may be broad or narrow. In addition, although some of the bays have numerous indentations, they are not circular but exhibit a rectangular morphology. This situation

suggests that coastal diaclasses, river valleys, or paleokarst topography may influence coastal geomorphology and bay morphology.

3.3. Classification model of the bays between Şile and Kefken

In this study, a different method was used to classify bays, distinct from those used in previous studies. In model classification, five morphometric index datasets were normalized to 0–1, and a bay degree classification, *BCm*, was established. The model's classification results data have been divided into five categorical classes using the natural break method. A result value close to 0 indicates a low bay degree, while a value close to 1 indicates a high bay degree. The bays in C-1 have a wide spacing between their headlands, a slight indentation, and a narrower beach morphology that is far from circular (Figures 6 and 7). The width between the headlands of the bays within C-4 and C-5 is narrow, the indentation is greater than the width, and beach formation is present in these bays, with a long shoreline.

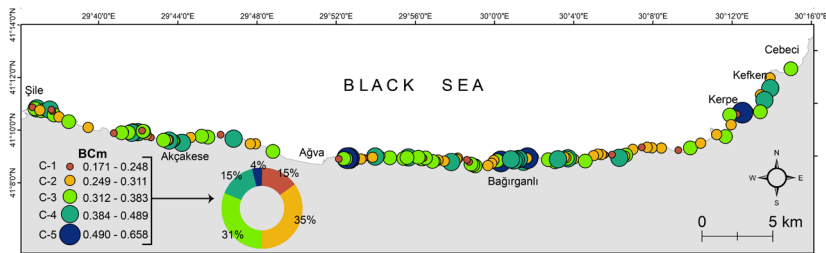


Figure 6. Distribution of the *BCm* between Şile and Kefken.

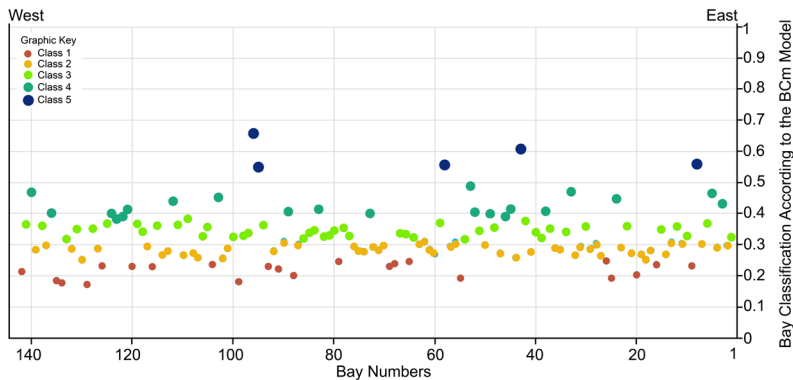


Figure 7. *BCm* graph of the bays between Şile and Kefken.

According to the *BCm* results based on morphometric indexes for bay classification, there are 22 bays in C-1 (15%), 50 bays in C-2 (35%), 44 bays in C-3 (31%), 21 bays in C-4 (15%), and five bays in C-5 (4%) in the study area (Figure 6). According to the *BCm*, the bays with the highest bay degree values, numbered 96, 43, 8, 58, and 95, are located on the eastern coast of Ağva and the coasts of Kerpe and Bağıranlı. The main feature of these bays is that they have a large indentation relative to their width, form a longitudinal structure into the land, and contain beaches of a specific size. According to the *BCm*, bays classified as C-4, with high

bay degree also exhibit greater indentation toward the land and resemble a circle. The bays in C-4 are distributed primarily between bays 20–60 and 100–140 (Figure 10). The bays in C-3 and C-2, on the other hand, show spatial clustering. The bays in these two categories are scattered along the coasts between Şile and Kefken. The average *BCm* value for all the bays in the study area was 0.324, with the maximum value calculated as 0.658 (Bay No. 96) and the minimum value as 0.171 (Bay No. 129). Only 38 bays (27%) in the study area exceed the average *BCm* value. Many indented land bays with narrower bays, particularly those formed by less resistant lithology, are classified as C-1 and C-2.

The orientation of the headlands is one of the main factors affecting bay classes, beach structure, and other morphometric characteristics. In this study, the headland classification developed by Fellowes et al. (2019) was used (Figure 8A). It covers six headland types. However, in this study, anthropogenically created bays have been evaluated as separate types. According to the analysis, three bays formed anthropogenically have been identified on both sides of the headland along the coast between Şile and Kefken (bays numbered 5, 58, and 142). Two percent of the bays in the study area are anthropogenic, 14% are Headland 1 (H1), 10% are Headland 2 (H2), 16% are Headland 3 (H3), 24% are Headland 4 (H4), 21% are Headland 5 (H5), and 13% are Headland 6 (H6) (Figure 8C). No dominant clustering distribution based on the orientation class of the bays between Şile and Kefken was detected (Figure 8B). Although there are different headland classes in some places, bays with H1 and H2 headland orientations are concentrated between Ağva and Şile, and bays with H4, H5, and H6 headland orientations are concentrated between Ağva, Bağırçanlı, and Sarısu (Figure 8B).

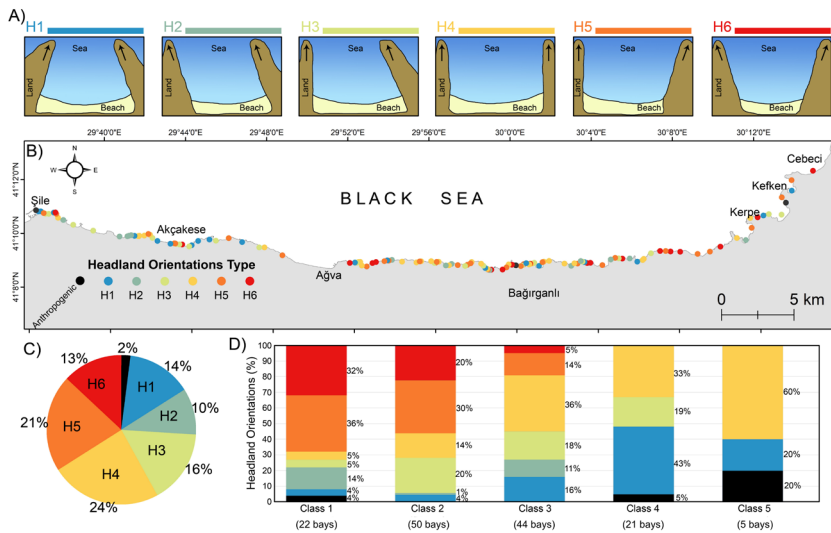


Figure 8. Panel A: Classification of headland orientations. Figures are redrawn from “Morphometric classification of swell-dominated embayed beaches” by T. E. Fellowes, A. Vila-Concejo, and S. L. Gallop, 2019, *Marine Geology*, 411, p. 83 (<https://doi.org/10.1016/j.margeo.2019.02.004>). Copyright 2019 by Marine Geology. Panel B: Orientation of headlands between Şile and Kefken. Panel C: Proportions of headland orientations by type in the study area. Panel D: Proportional values of headland orientations according to *BCm* categorical classes.

This study examines the relationship between *BCm* categorical results and headland orientation classification. In this regard, a large portion of the bays within C-4 and C-5 have H1 and H4 headland orientations (Figure 8). Bays that have settled in rift due to their lithological structure are classified as H4 type, while bays with a closed mouth structure oriented toward the headland are classified as H1 type. More than half of the bays within C-1 and C-2, which have shallow indentations and wide bays, have an H5 and H6 headland orientation (Figure 9).



Figure 9. Classification of some bays between Şile and Kefken according to the *BCm*.

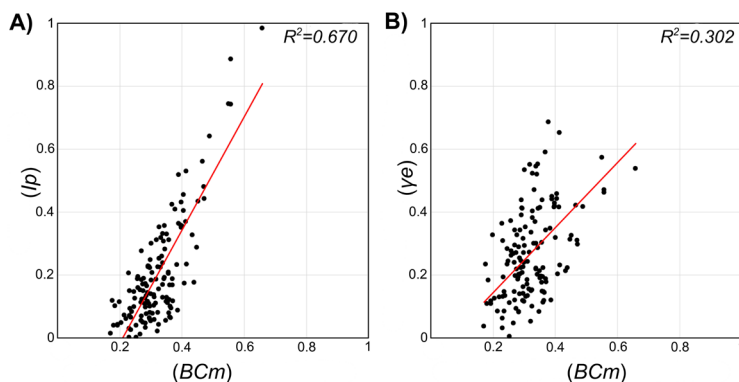


Figure 10. Correlation graphs between lp and ye using the BCm .

4. Discussion

The results regarding the degree of embayment in this study reveal that the geological structure is the primary factor controlling the hydrodynamic and morphological processes, especially in bay beaches (Castelle & Coco, 2012; Fellowes et al., 2019; Loureiro et al., 2012). However, the bays' own morphometric parameters also influence the geomorphological cycle. In this study, the correlation coefficients among the basic morphometric parameters ranged from 0.284 to 0.892. High correlations among specific parameters support the findings of many previous studies (Fellowes et al., 2019; Hsu et al., 1989a, 1989b; Short & Masselink, 1999; Swirad & Rees, 2015). In index analyses, high correlations were found between indices that use similar basic morphometric data. The results indicate that planform, circularity, sinuosity, and bay indentation are more effective in characterizing the geomorphological features of bays (Fellowes et al., 2019; Hsu et al., 1989a).

Furthermore, this study proposes a modeling approach based on fundamental parameters that affect bays and on previously established indices. The BCm results for the Şile–Kefken area have been divided into five categorical classes using the natural breaks method. It was determined that the width between the headlands of bays in class C-1 is large and the indentation is slight. In contrast, the indentation, bay area, circularity, and sinuosity of bays in classes C-4 and C-5 are large, and the width between the headlands is small. This situation corresponds, to some extent, to the previously conducted lp and ye analyses (Usai et al., 2025). The correlation results between BCm and lp (0.67) and BCm and ye (0.30) also support this situation (Figure 9).

Fifteen percent of the bays between Şile and Kefken are classified as C-1, 35% as C-2, 31% as C-3, 15% as C-4, and 4% as C-5. It has been determined that the bays between Şile and Kefken, classified as C-1 and C-2 under the BCm framework, have a greater width between their headlands and fewer indentations (Figure 8). However, it is noteworthy that the bays covered by C-4 and C-5 have a greater indentation relative to the width of the bay between the headlands, form a circular structure, and have excessive sinuosities. C-4 and C-5 type bays, which were previously classified differently in this study, are generally classified as very well or well embayed from a morphological perspective (Usai et al., 2025). In these bays, the influence

of geological factors is increasing due to headland shading, and beach morphodynamics are being affected (Castelle & Coco, 2012; Klein & Menezes, 2001).

It has been concluded that the circular structure of this type of bay and the orientation of the headlands (Fellowes et al., 2019) cause the depth of the bay indentation to affect wave propagation, and that the sediment load in the erosion-deposition balance of bay beaches is related to the asymmetry direction (Daly et al., 2014). It is suggested that wave energy may be excessive in bays classified as C-1 and C-2 due to their openness to the sea. Therefore, if these bays are narrow, the beach formation is relatively narrow, and if they are wide, the beach formation is quite wide. This situation also reveals the geomorphic processes associated with the bay indentation and area.

The distribution of basic morphometric parameters and *BCm* results indicates that some bays exhibit distinct morphologies. The karst topography in certain parts of the study area has been particularly influential in shaping these bays. The dolines observed on the land surface in some parts of the coast also confirm this situation. Furthermore, Ertek (1995, 2014) demonstrated in his studies that the ancient poljes, uvalas, or dolines along Kefken and Kerpe coasts have acquired their present bay shape due to rising sea levels (Ertek, 1995, 2014). The situation described is particularly observed between bays numbered 1–60 in this study. In the study, bays with high planform values, distributed across different classes, were formed by the shaping of a developed rift in limestone through geomorphological processes and hydrodynamic factors. The development of these bays is particularly related to the erosion of marls, which are less resistant to erosion than limestones. The areas within the study site where the effects of paleokarst topography are evident have also been instrumental in the emergence of C-4 and C-5 class bays. Furthermore, bays such as Kefken and Kerpe, which have an ancient polje base, contain many smaller bays, allowing the multiple-bay feature to be observed in the study area (Figures 9 and 10). The multiple-bay type refers specifically to the curved and adjacent bays within an enormous bay/gulf that had a polje base during the Eocene-Miocene and were later formed by sea-level rise (bays numbered 11, 12, and 13). This situation indicates that the characteristics of the bays in the study area are related to the geological structure and that this also affects their geographical distribution. Anthropogenic factors were identified to varying degrees across the study area, occurring partially in some bays and encompassing the entirety of others (Bay No. 58). In this context, specific human-induced interventions along the coast alter wave refraction, causing the shoreline to curve; as a result, the coastal strip gradually becomes bent and takes on a distorted appearance, deviating from its natural form (Iglesias et al., 2009). This situation both alters the bay's morphometric parameters and affects the type of coast, beach formation, and hydrodynamic processes.

The findings indicate that the coast between Şile and Kefken is bay-type, consistent with the work of Ertek (1995, 2014). The general coastal appearance of the study area reflects a Pacific coast type; however, bays have developed in many sections of the coast due to geological, geomorphological, hydrodynamic, and anthropogenic factors. Within the scope of this study, 142 of these bays were examined in detail using morphometric methods. The presence of beaches in 90% of the bays studied indicates that the coast is not only of the high-narrow cliff type but also heterogeneous, combining wide and low coastal features.

5. Conclusion

In this study, 142 bays located along the Şile–Kefken coast were examined using seven different fundamental morphometric analyses, and a *BCm* proposal was presented based on five different bay morphometric indices. The fact that the largest bay is approximately 3,889 times larger than the smallest bay indicates that bay morphologies in the study area exhibit considerable heterogeneity in morphometry and distribution. In the study index, the results indicate that the coast generally has moderately indented-circular structures, but there are bays with higher circularity and indentation ratios, particularly in the eastern section (around Kefken–Kerpe–Bağıranlı). Furthermore, the presence of beaches in 90% of the bays demonstrates that the coasts are not composed solely of high, narrow cliffs; they also include wide, low-lying coastal forms.

The *BCm* analysis developed in this study has enabled systematic classification of bays based on morphometric criteria. According to the findings, 40% of the bays are of the “open type”, with low circularity and wide bay openings. In comparison, only 19.1% exhibit a more closed morphology, characterized by high circularity and deep indentation values. Thirty-one percent of the bays show average values and are located between open and closed bay morphology. The bays between Bozkoca, Kumcağız, Bağıranlı, and Kefken–Kerpe stand out with their high *BCm* values. The results reveal that the Kefken–Şile coastline exhibits considerable morphodynamic diversity and that lithological structure, paleokarstic topography, and wave-current regimes are decisive in the region’s coastal evolution.

The *BCm* equation proposed in this study examines bays across different morphometric index values and provides important data for managing bay-containing coastlines by classifying quantitative results. However, this study still has some limitations. In particular, it is possible for *BCm* results to show extreme values in bays created by artificial coastlines or the construction of piers and marinas. Therefore, it is recommended that future studies also compare artificial and natural bays. The most important advantage of *BCm*, and the results it reveals, is its ability to establish a connection between the morphological and morphometric characteristics of bays and the factors that influence them. This situation has been correlated with lithology and paleocoast in the study area. In general, this research provides important data for the sustainable management and protection of coasts. Furthermore, the morphometric approach used provides a methodological contribution for the comparative analysis of different coastal areas.

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