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Research Article

Temporal Changes in Shoreline Dynamics along the Bakırçay River: Coastal Erosion and Accretion Trends

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Abstract

Coastal areas are among the most productive environments, providing ideal conditions for tourism, agricultural, commercial, and industrial activities. Nevertheless, both geological and anthropogenic factors significantly affect the morphology of coastal regions. To recognize these changes, shoreline change analyses play a crucial role in determining the erosion and accretion rates. The Bakırçay Delta, located in the northern Aegean coastal area of Türkiye, has suffered severe degradation in recent years owing to increased settlements and diverse economic activities, including mining, geothermal energy production, and agricultural activities on the coastline of the Bakırçay plain. Seasonally varying high discharges also have led to a higher transport of bed load depositions in the Bakırçay Delta. This study aimed to assess shoreline changes along the Bakırçay River Delta for the 1984-2022 period by using multi-temporal Landsat images and the Digital Shoreline Change Analysis System (DSAS). Possible human-induced factors causing the shoreline changes in the Bakırçay Delta were also discussed. Short- and long-term shoreline analyses of the Bakırçay Delta indicated that substantial shoreline changes have occurred in the northern part of the Bakırçay River. Long-term shoreline analyses showed that the highest shoreline accretion occurred along the Yeni Çandırlı Port, whereas the largest shoreline erosion rate was observed in the northern part of the Bakırçay River between 1984 and 2022. Overall, the Bakırçay Delta coast experienced significant shoreline changes mainly due to human-induced factors, which affected its morphology considerably.

Keywords: Bakırçay Delta, Coastal Erosion and Accretion, Digital Shoreline Analysis System (DSAS)

Introduction

Human populations have historically gravitated toward coastal zones because they offer proper conditions for the development of industrial, agricultural, recreational, and commercial activities (Ferreira et al., 2021). However, coastal areas offer both opportunities and challenges. Coastal cities account for over 40% of the world's population (Burak et al., 2004). Therefore, the world's multifunctional, dynamic coastal ecosystems are under severe stress owing to increasing population, urbanization, and climate change (Jangir et al., 2016; Nayak, 2004; Santos et al., 2021). There is worldwide concern regarding the influence of sea-level rise on coastal environments. Man-made pressure at coasts requires natural processes such as sediment dynamics. There are construction and defence barriers at coasts, including ports, infrastructure for industrial and recreational activities, interventions of river basin modifications, and regulation of watercourses for the supply of water resources for the use of water in agriculture and industrial processes. Again, the expansion of cities has involved coastal spaces and altered the morphology of structures such as beaches, dunes, deltas, and river estuaries, stimulating the phenomena of erosion, accumulation of sediments, and shoreline changes. Ports can also cause coastal erosion by altering the wave patterns. Eventually, all of these interventions can modify the morphology of the coasts. In the last century, coastal processes have undergone alterations, and consequently, there has been a degradation of ecosystems, with modifications of coasts, particularly with the increase in coastal erosion and related risks (Focardi and Pepi, 2023).

River deltas offer a resource-rich environment for many activities and provide environmentally dynamic ecosystems that accommodate more than 500 million people (Giosan, 2014; Karpouzoglou et al., 2019). River deltas are usually characterized by a unique landscape with low topography, rich and diverse ecosystems, and high agricultural productivity. Thus, they provide a wide range of ecosystem opportunities, including water supply, coastal defence, and recreational activities (Anthony, 2015). In recent years, many deltas have become environmentally vulnerable because of the variable sediment loads from rivers and other human-induced changes (Anthony et al., 2019). Delta shorelines, which are highly exposed to sediment loads, waves, and currents, exhibit complex accretion and erosion processes over a wide range of periods (Anthony, 2015). Coastal erosion is a very common phenomenon worldwide, and nearly 70% of sandy coasts are eroded (Gens, 2010). This remains a major issue for coastal zone management. Combined factors of climate variability, land-use changes, and increased human activity modify landscape dynamics in delta shorelines and consequently shape their local geomorphology. In addition to its environmental impact by causing a dwindling in coastal biodiversity, coastal erosion also threatens local socio-economic life by causing loss of land with high economic value and damage to coastal infrastructures especially in areas where tourism plays a key role in the economy (Alexandrakis et al., 2015; Petrakis et al., 2017; Menteş, et al., 2019). The equilibrium of coastal deltas can be disturbed by natural factors such as abnormal seasonal variations in wind speed and direction, or other human-induced factors such as building structures for new settlements, coastal structures such as harbours and fishery harbours, tourism activities, and sand and gravel withdrawals from the sea (Görmüş et al., 2014). All of these factors can easily tamper with sediment regimes in delta areas over the years.

Accurately defining and analysing shoreline position is critical for understanding and modelling coastal morphodynamics (Ferreira et al., 2021). Therefore, accurate models and multi-temporal satellite images are critical for decision-makers to define the best management strategy and reduce erosion in the study area (Ferreira et al., 2021; Gens, 2010). Remote sensing satellite images are used to effectively monitor shoreline changes and mapping (Chrisben Sam and Gurugnanam, 2022; Roy et al., 2018).

Coastal erosion problems in Türkiye are attributed to many factors but are usually associated with an increase in tourism activities that demand structural rural investments (Leventeli, 2011). In addition, the coastal habitation, presence of harbours, and improper construction activities are the main human-induced causative factors that affect coastal erosion in Türkiye (Leventeli, 2011; Yüksek et al., 1995) (Anil Ari et al., 2007; Berkun and Aras, 2012; Kuleli, 2010; Numanoğlu Genç et al., 2013; Yüksek et al., 1995) Görmüş et al. (2014) concluded that the harbour construction on the Karasu coast inflicted a far-reaching impact on the coastal erosion in Karasu town located on the Black Sea coastline of Türkiye.

Türkiye has a total coastline of 8, 483 km, and the Aegean coastline accounts for nearly 40 per cent of it. The growth of the coastal population has exceeded the growth of the total Turkish population (5,2% vs. 4,5%) in recent years as the economic role of maritime areas has increased significantly. Along the Aegean coast, the orientation of mountains allows penetration of westerly precipitation systems for diverse agricultural activities in the fertile alluvial plains in the region. Consequently, the Aegean shoreline has been intensely inhabited by humans since historic times, allowing prime economic activities, tourism, agriculture, and other coastal uses. Bakırçay Basin, located in the northern Aegean Sea area, is distinguished by diverse economic activities, including agriculture, geothermal energy, tourism, and mining. The basin and its surrounding areas have also become favourable settlement areas, known as the Pergamon Microregion, during the last two thousand years due to its high potential for diverse economic activities, which has stimulated human impacts on the land use of the basin (Yang et al., 2021). The Pergamon Micro-Region became a favourable settlement area during the Hellenistic-Roman period (Laabs and Knitter, 2021), and the enhanced economic activities along with population growth made the coastal areas more vulnerable to land-use changes. However, major land-use changes in and around the Bakırçay Delta due to urban development have occurred at the expense of a reduction in agricultural areas (Kesgin and Nurlu, 2009). Mining activities, urbanization, and port construction, particularly in the delta section, have caused major changes in the morphology of the delta area. Moreover, during high discharge periods, the Bakırçay River deposits its bedloads into the delta area, which lies near sea level. As the delta is located at sea level, the Bakırçay River easily fills the delta with its full potential energy. Therefore, it is crucial to assess shoreline changes in the delta area resulting from both natural causes and human activities. In this study, shoreline changes in the Bakırçay Delta were evaluated using multi-temporal Landsat images both in short (1984−1990, 1990−2000, 2000−2010, 2010−2022) and long periods (1984−2022). Furthermore, natural and anthropogenic factors that cause shoreline changes along the delta coast were investigated and discussed.

Study Area

The study area is located in the northern part of the Aegean Sea between latitudes 38°56'21.27″' " and 38°54'57.47" N and longitudes 26°57'14.30" and 26°59'43.91" E (Fig. 1). The shoreline length of the study area approximately 4,5 km and is formed by the sediment deposition of the Bakırçay River, which originates in the Kocadağ and flows into the Aegean Sea. The Bakırçay River has a length of 129 km and its catchment area covers 3.356 km^2 in an E-W-oriented graben. The springs that feed the river downstream are Gelenbe Stream, Menteşe, Aksu, Yağçıllı, Ilıca, Kırkgeçit, Karadere, Gümüş, Bergama, Kestel, Boğazasar, Sınır, and Sarazmak creeks (Danacıoğlu, Ş. Tağıl, 2017). Coastal areas of the Bakırçay Basin are distinguished by littoral plains and deltas (Kuzucuoğlu et al. 2019). The foot slopes that form the transition to plain areas of the delta are fringed by colluvial deposits. The study area is under the influence of a typical Mediterranean climate, characterised by dry and warm summers and mild and wet winters. It is classified as “Csa” climate according to the Köppen-Geiger classification (Peel et al., 2007). Cash crops, primarily cotton and vegetables, are the dominant vegetation in the Bakırçay alluvial plain. The outskirts of the upper Bakırçay plain are mostly cultivated with olive trees, while the forest communities and shrub formations of the Mediterranean occupy higher elevations of the basin. The Bakırçay basin is under the influence of the north-easterly winds dominantly. The wind rose illustrating the prevailing wind direction on the coastline, is presented in Fig. 2, which uses wind data from a nearby city of Bergama located in close proximity to the Bakırçay Delta. As shown in Figure 2, the prevalent wind is in the north-northeast (NNE) direction, with a ratio of 44 per cent. In November and December, the prevailing wind takes the SW’ly direction. The Bakırçay Basin coastline is nearly perpendicular to the direction of the NNE, allowing effective winds across. The winds along the sea waves reach the delta coast perpendicular, triggering the formation of the bars extending parallel to the coast. The winds along the Bakırçay delta are quite strong reaching speeds up to 29 m/s especially in winter months, creating high waves.

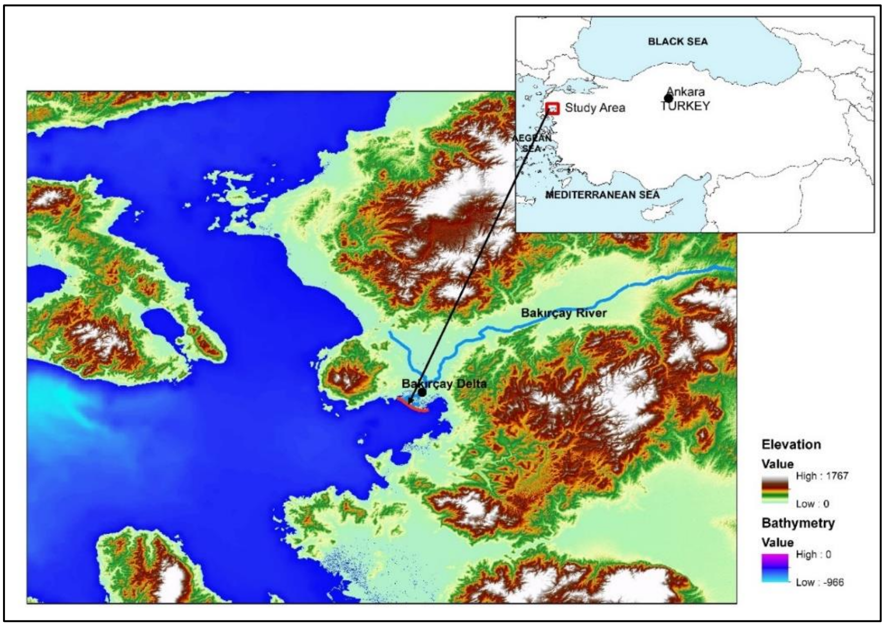

Fig 1. Location map of the study area

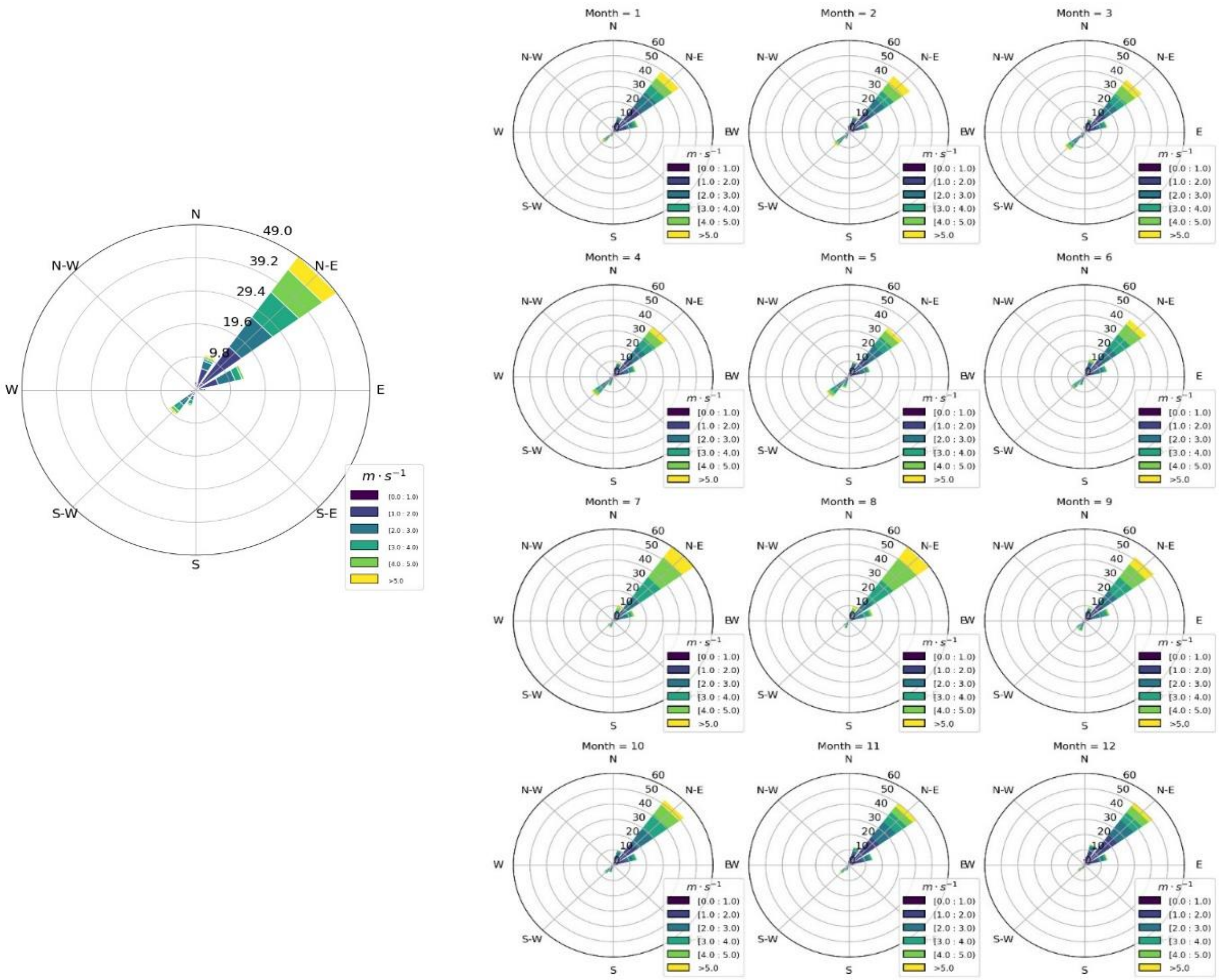

Fig 2. Annual and monthly prevailing wind directions on the Aegean city of Bergama

Data and Methodology

Multidisciplinary studies including remote sensing and geomatics techniques have proved to be quite successful in investigating changes in coastal environments (Klemas, 2011). Using multi-temporal satellite sensor images has become crucial in determining and evaluating the morphological changes that have occurred in the coastal lines in recent decades. Shoreline changes in the Bakırçay Delta were determined using multi-temporal satellite images. Landsat 4-5 TM (07/09/1984, 07/08/1990, 14/08)/2010), Landsat 4-5 ETM (09/07/2000) and Landsat 8 OLI (24/09/2022) images were used to determine the temporal and spatial changes in the shoreline of the Bakırçay Delta. The satellite images were obtained from the United States Geological Survey (USGS) website (http://www.earthexplorer.usgs.gov). The selected satellite images used in the study represented the dry seasons when lower shoreline positions with less cloud cover were visible.

Extraction and analyses of shoreline

The shoreline of the Bakırçay Delta was determined using the modified normalized difference water index (MNDWI). The MNDWI index effectively maps shorelines using short-wavelength infrared (SWIR) and green bands, and MNDWI employs the MIR and green bands to improve results and reduce "noise" along urbanized coasts (Darwish and Smith, 2023; Özpolat and Demir, 2019).

MNDWI formula is as follows:

$$MNDWI_{(Xu,\ 2006)} = Green - MIR/Green + MIR \qquad \text{Eq.1}$$

The spatial and temporal shoreline changes of the Bakırçay Delta were analyzed using DSAS version 5.1, supplied by the United States Geological Survey (USGS). DSAS generated 1259 transects at 5 m. intervals perpendicular to the shoreline between 1984 and 2022 (Fig. 3). Furthermore, Net Shoreline Movement (NSM), End Point Rate (EPR), and Linear Regression Rate (LRR) statistical methods were used to estimate shoreline changes in the Bakırçay Delta. The NSM statistic computes the distance between the oldest and youngest shorelines for each transect (Chrisben Sam and Gurugnanam, 2022; Himmelstoss et al., 2021).

It is expressed as:

$$NSM = \{d_{2022} - d_{1984}\} \qquad \text{Eq..2}$$

The EPR statistic is calculated based on the distance of shoreline movement and the time elapsed between the oldest and most recent shorelines.
(Chrisben Sam and Gurugnanam, 2022; Himmelstoss et al., 2021) It is formulated as:

$$EPR = \left\{\frac{d_{2022} - d_{1984}}{t_{2022} - t_{1984}}\right\} \qquad \text{Eq.3}$$

Analysis and Results

Analysis of Sediment and Flow Data

The Bakırçay River flow and sediment values were obtained from the Ministry of Energy and Natural Resources gauging stations for 1998 and 2017 (Fig. 4 and 5). An analysis of the Bakırçay River's 19-year flow and sediment values indicated that the peak values were observed in 2001 and 2009 (Fig. 4). Furthermore, the Bakırçay sediment values decreased significantly from

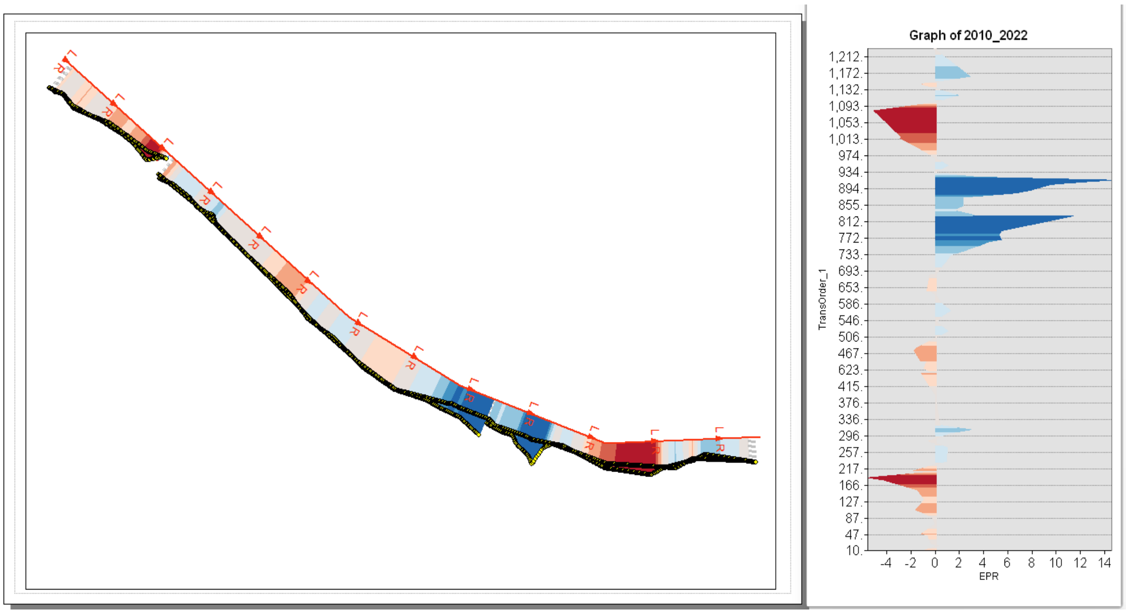

Fig 3. Shoreline change analyses of the Bakırçay Delta using the NSM statistic.

1998 to 2017 (Fig. 5). The Bakırçay River's average sediment value was 115.06 t/d in 1998, but it was reduced to 23.18 t/d in 2017. The flow of the Bakırçay River also significantly diminished. The average flow value in 1998 was 9.568 m^3/sec, but it was reduced to 6.304 m^3/sec in 2017. Moreover, the average flow and sediment values of Bakırçay River during 1998 and 2017 were 10,264 m^3/sec and 440,97 t/d respectively (Fig. 4). Dam construction on the Bakırçay River is considered to be the most significant contributing factor to the decrease of 19-year flow and sediment values. A total of five dams have been operational on the Bakırçay River, including Sevişler Dam (1981), Sarıbeyler Dam (1985), Kestel Dam (1988), Çaltıkoru Dam (2002), and Yortanlı Dam (2006).

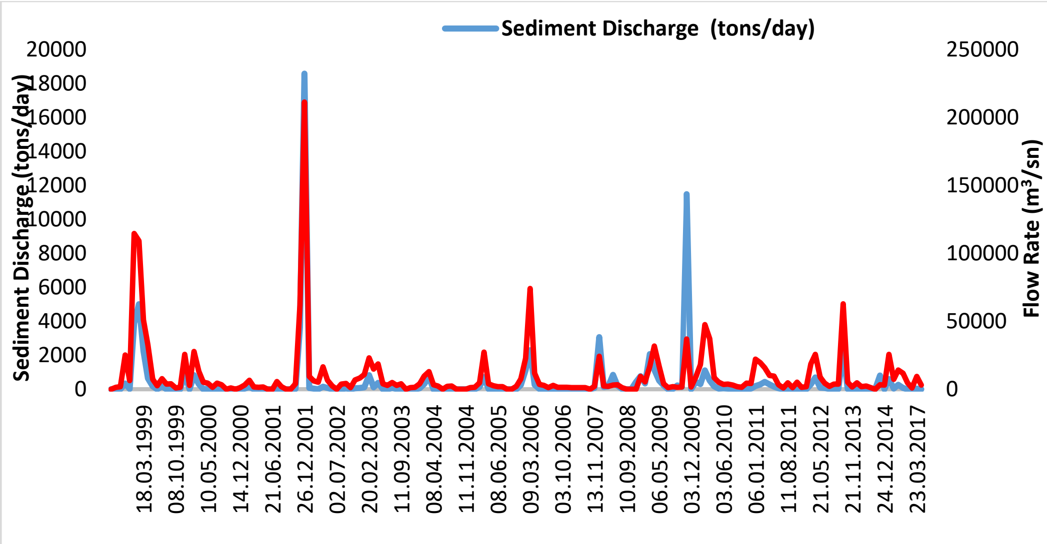

Fig 4. Variabilities in flow rate and sediment discharge of Bakırçay River

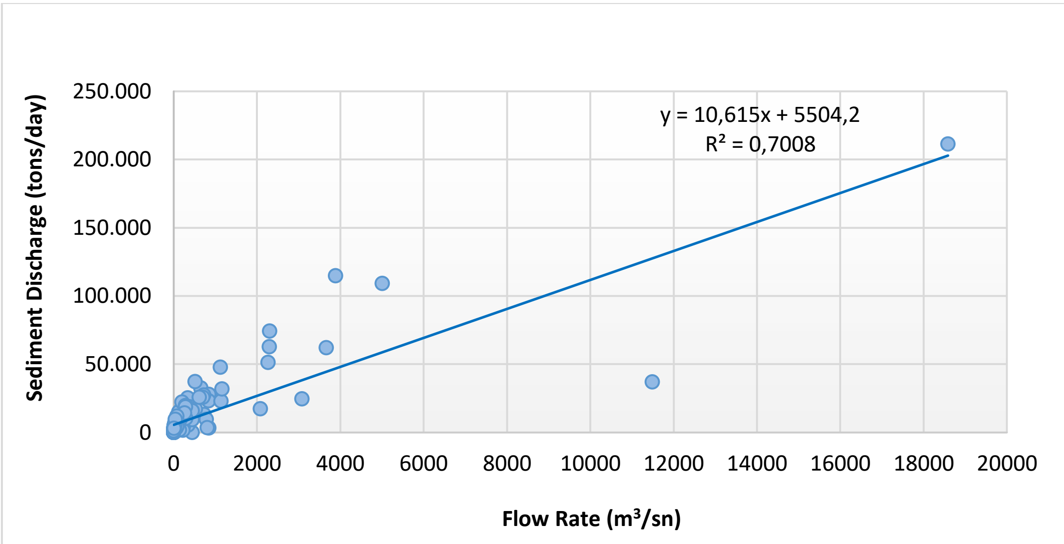

Fig 5. Relationship between sediment discharge and flow rate of Bakırçay River between 1998 and 2017

Short and long periods of shoreline change along the Bakırçay River Delta

The spatial and temporal shoreline changes along the Bakırçay River Delta were analysed over both short and long periods. The long period of shoreline change in the Bakırçay Delta was assessed using EPR, NSM, and LRR statistics of the DSAS tool, whereas short periods of shoreline change were evaluated using the EPR and NSM statistics only.

Short periods of shoreline change in Bakırçay Delta

An analysis of the short periods of shoreline change along the Bakırçay River Delta showed that the maximum shoreline erosion occurred between 2000 and 2010, with an NSM value of -106.08 m, and the maximum shoreline accretion occurred between 2010 and 2022, with an NSM value of 176.8 m (Figure 6).

Furthermore, the second-highest erosion was observed in 1990 and 2000, with an EPR rate of -9.6 m/yr^{-1}, while the second-highest accretion was observed in 1984 and 1990, with an EPR rate of 16.6 m/yr^{-1} (Table 1). In the short periods of shoreline analysis, most of the shoreline erosion was observed along the Bakırçay River mouth (Fig. 7 and 8). Additionally, the rate of shoreline accretion was low in the early periods but has increased recently (Fig. 6).

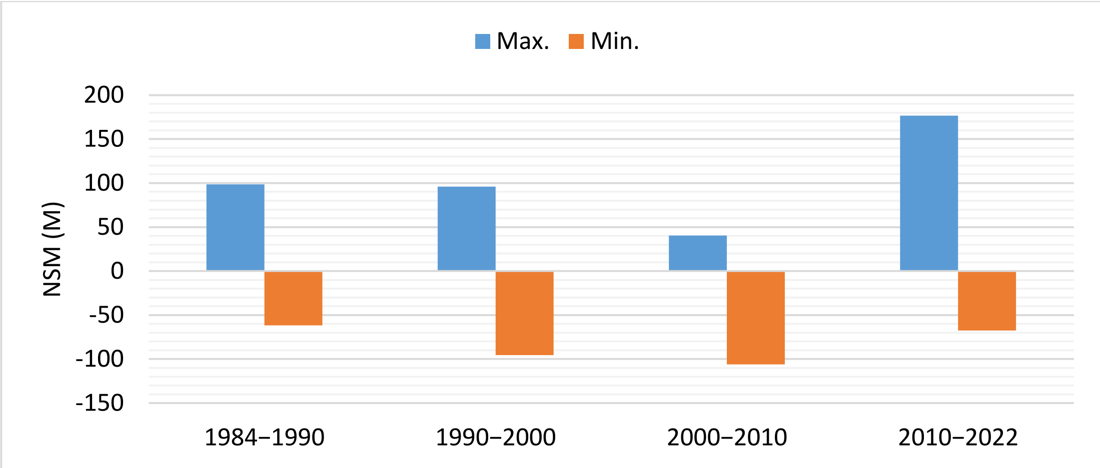

Fig. 6. Short periods of shoreline change in Bakırçay Delta

Table 1. Statistical results of NSM and EPR along the study area

Statistic	1984−1990	1990−2000	2000−2010	2010−2022
EPR				
Average	1.8	0.1	-1.7	0.5
Max.	16.6	9.6	4.02	14.6
Min.	-10.4	-9.6	-10.5	-5.5
Standard deviation	3.2	3.2	3.2	2.9
NSM				
Average	10.6	1.3	-18.05	6.3
Max.	98.4	96.1	40.5	176.8
Min.	-61.8	-95.4	-106.08	-67.5
Standard deviation	19.3	32.2	32.4	35.4

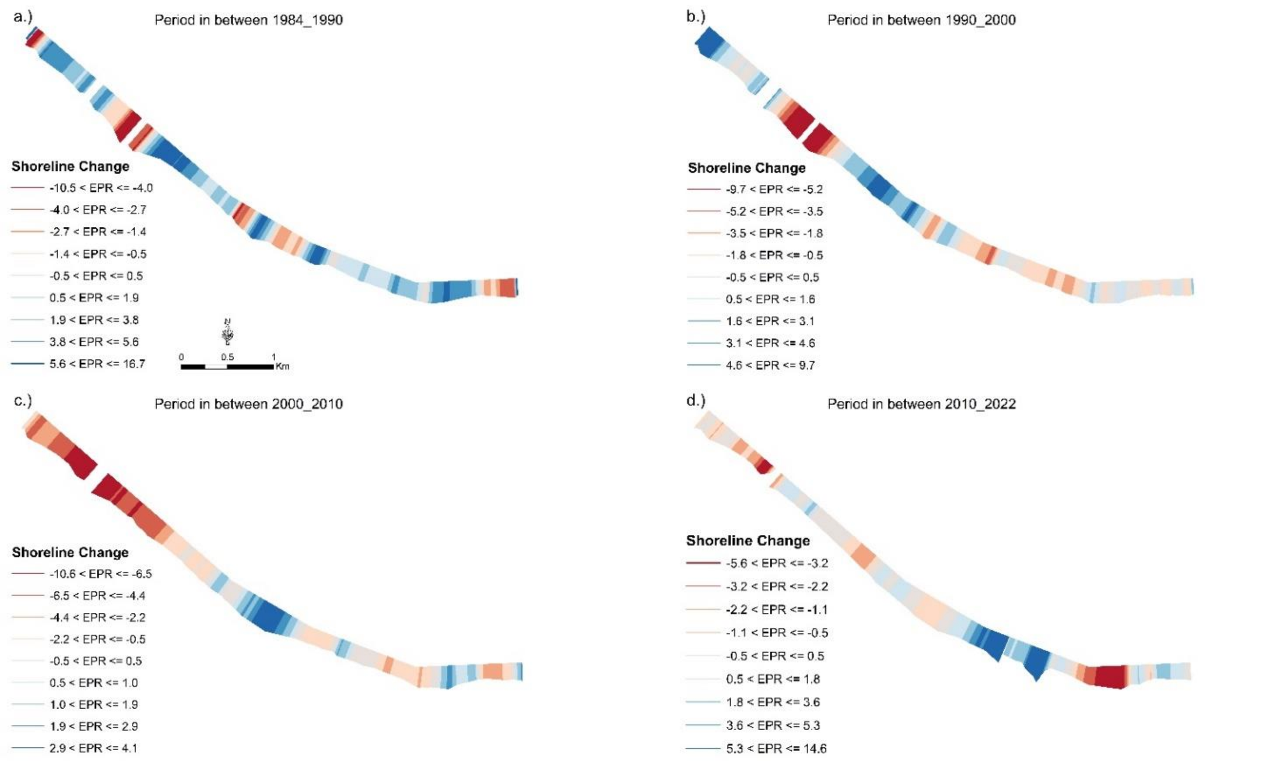

Fig. 7. Endpoint rate (EPR) of the shoreline changes calculated for the four different periods: (a) 1984−1990, (b) 1990−2000, (c) 2000−2010, and (d) 2010−2022

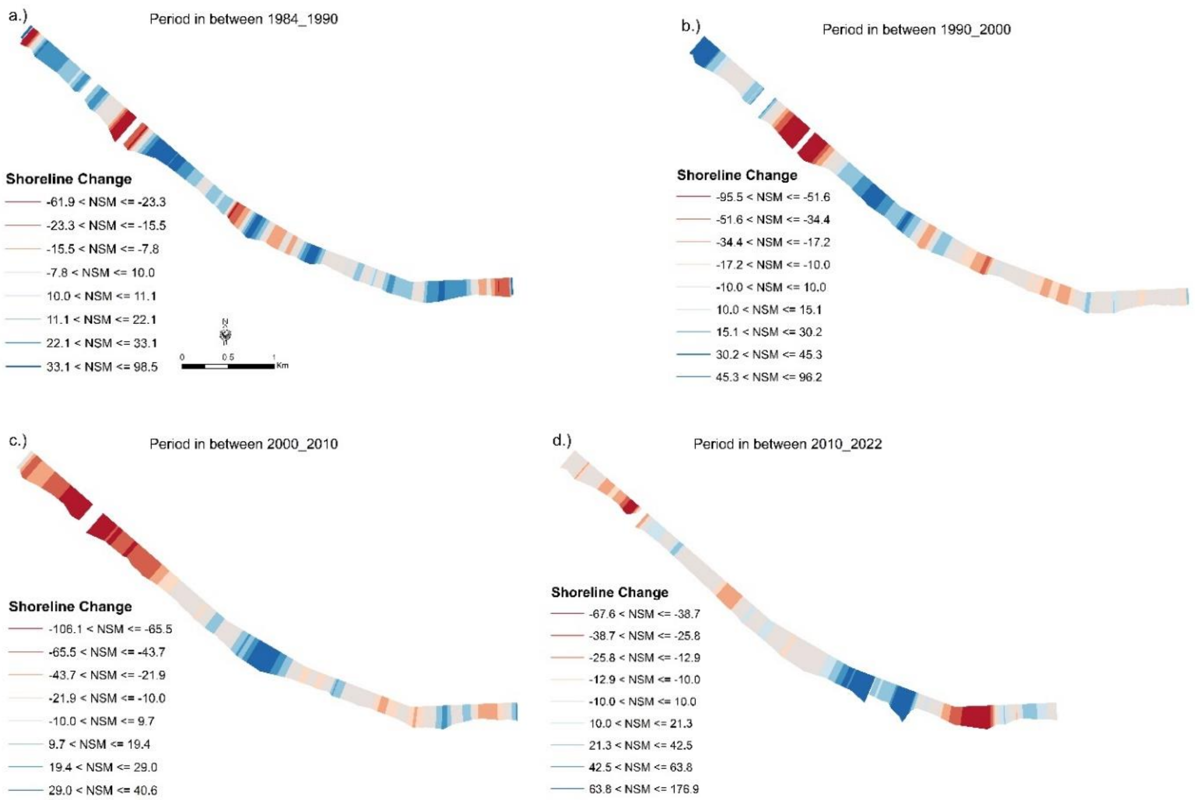

Fig. 8. Net shoreline movement (NSM) of the shoreline changes calculated for the four different periods: (a) 1984−1990, (b) 1990−2000, (c) 2000−2010, and (d) 2010−2022

Table 2. NSM, EPR and LRR Statistical results of Bakırçay Delta from 1984 to 2022

Statistic	1984−2022
EPR	
Average	-0.04
Max.	5.2
Min.	-4.5
Standard deviation	1.7
NSM	
Average	1.8
Max.	197
Min.	-172
Standard deviation	66.1
LRR	
Average	0.2
Max.	5.5
Min.	-4.04
Standard deviation	1.8

The long-period shoreline change analyses in Bakırçay Delta

An assessment of the long-period shoreline change analyses reveals that the maximum shoreline accretion was 197 m for NSM, 5.2 m/yr^{-1} for EPR, and 5.5 m/yr^{-1} for LRR between 1984 and 2022, while the maximum shoreline erosion was -172 m for NSM, -4.5 m/yr^{-1} for EPR, and -4.04 m/yr^{-1} for LRR (Table 2). Furthermore, the largest shoreline erosion rate was observed in the northern part of the Bakırçay River mouth, while the highest shoreline accretion was observed in the northern and southern parts of the Yeni Çandırlı port during the 38 years (Fig. 9, 10 and 11).

Discussions

The spatial and temporal analysis of the shoreline changes along the Bakırçay River Delta revealed that it experienced considerable shoreline changes over both short and long periods, which eventually affected the morphology and ecology of the coast. For example, short-term shoreline analyses have shown that specific parts of the delta have been subjected to erosion and accretion during various periods. The only area that experienced shoreline erosion during all short periods was the mouth of the Bakırçay River and its surroundings. Moreover, the short-term shoreline statistics of the Bakırçay Delta indicated that the highest shoreline erosion rate occurred between 2000 and 2010, with an NSM value of -106.08 m, while the highest shoreline accretion was experienced between 2010 and 2022, with an NSM value of 176.8 m. The short-term shoreline change along the Bakırçay River Delta is significantly related to the sediment value of the Bakırçay River, according to data from the Republic of Türkiye Ministry of Energy and Natural Resources, spanning the years 1998 and 2017.

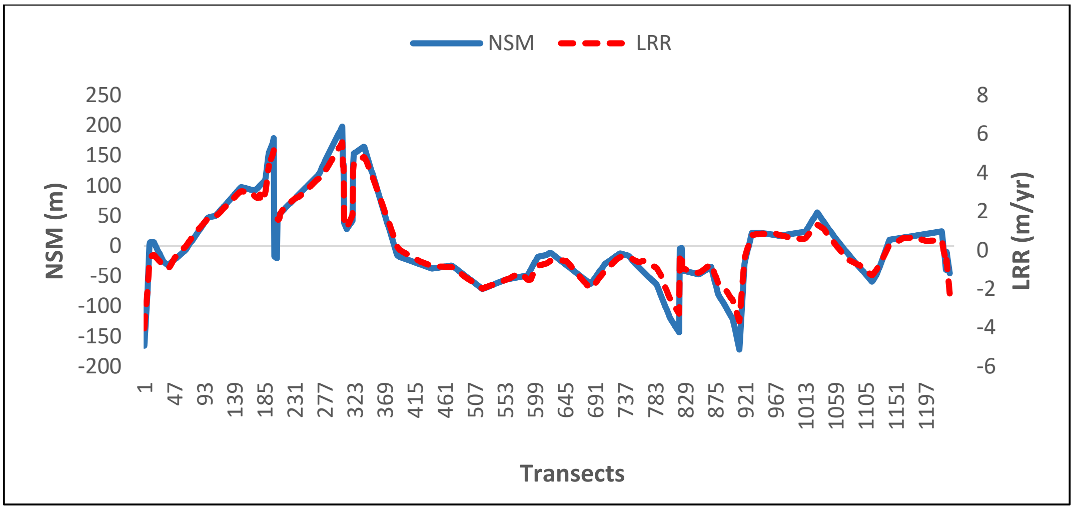

Fig. 9. Long-period shoreline change analyses of the Bakırçay Delta according to the NSM and LRR statistics of the DSAS tool.

Fig. 10. High rate of erosion in the northern section of Bakırçay River

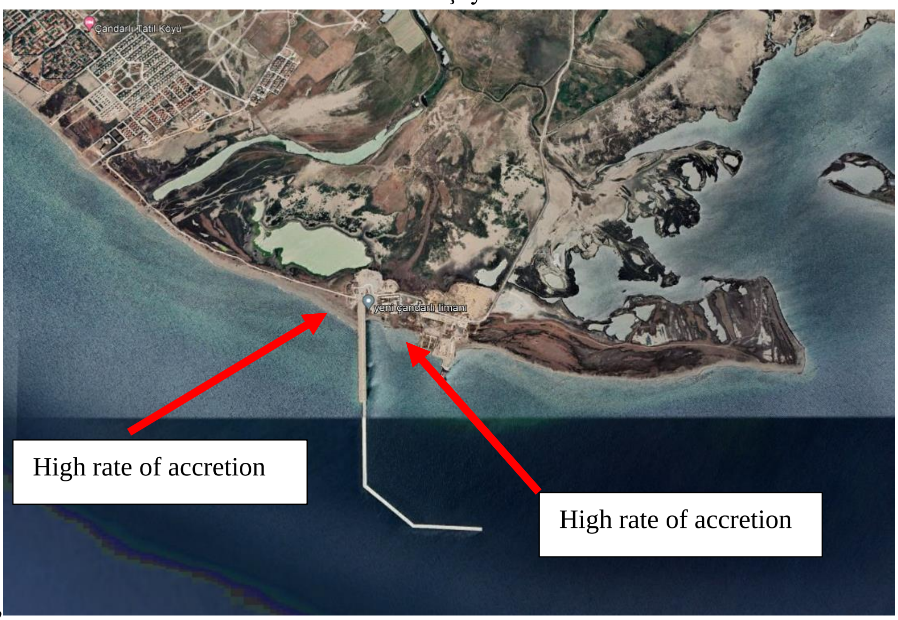

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Fig. 11. High rate of accretion in the northern part of Yeni Çandırlı Port.

As the highest sediment values of the Bakırçay River were observed on December 26, 2001, and November 5, 2009, it was determined that the highest shoreline accumulation in the Bakırçay Delta occurred between 2010 and 2022. A long-term shoreline analysis along the Bakırçay River Delta showed that the northern parts of the Bakırçay River mouth experienced the highest rate of shoreline erosion between 1984 and 2022, whereas shoreline accretion was observed in the northern and southern parts of the Yeni Çandırlı Port. In 1984 and 2022, the highest shoreline accretion was 197 m for NSM, 5.2 m/yr^{-1} for EPR and 5.5 m/yr^{-1} for LRR statistics whereas, the highest shoreline erosion was -172 m for NSM, -4.5 m/yr^{-1} for EPR, and -4.04 m/yr^{-1} for LRR statistics.

The findings of this study demonstrate that the Bakırçay Delta has undergone significant shoreline changes over both short and long periods, driven by a combination of natural forces and human-induced processes. This dynamic and evolving nature of the delta mirrors the patterns observed along other deltas and coastal regions of the Aegean Sea, reinforcing broader trends of coastal erosion in Türkiye (Akdeniz and İnam, 2023; Irtem et al., 2000; Lütfi Süzen and Rojay, 2005; Şermin Tağıl; İsa Cürabal, 2005). For example, studies by Irtem et al. (2000), and Tağıl and Cürabal (2005) revealed significant shoreline changes due to both natural dynamics and anthropogenic pressures on the Altınova coast located in northern Aegean Sea. Moreover, Akdeniz and İnan (2023) analyzed the shoreline changes of the Küçük Menderes delta over a 63-year period, revealing that the maximum accretion distance, as indicated by the Net Shoreline Movement (NSM), was 142.37 m, while the maximum erosion distance (NSM) reached −142.37 m. Another significant study along the Aegean Coast was conducted by Süzen and Rojay (2005) on the Büyük Menderes Coast. The findings revealed that significant geomorphological changes occurred along the coastal face of the Büyük Menderes River over the observed period (1956 to 2004).

As a result, the cumulative findings underscore a critical trend as much of the Aegean coastline is experiencing continuous erosion, with river deltas and sandy beaches being especially susceptible. The Bakırçay River Delta is a clear example of this vulnerability. The study reveals that the delta is undergoing significant erosion, exacerbated by both natural processes and human-induced changes. These challenges highlight the urgent need for effective coastal management and mitigation strategies to prevent further degradation in areas like the Bakırçay Delta. Moving forward, the discussion must emphasize the importance of implementing ICZM approaches to protect these vulnerable deltas. A sustainable management plan that considers both natural coastal dynamics and human intervention can protect the ecological and economic value of deltas like Bakırçay.

Conclusion

This study investigated the spatial and temporal shoreline changes in the Bakırçay Delta as well as the effects of natural and human-induced factors causing shoreline changes. Multi-temporal Landsat images and the Digital Shoreline Analysis System (DSAS) were used to evaluate shoreline changes in the Bakırçay Delta. The findings indicate that the highest shoreline accretion occurred near Yeni Çandırlı Port, and the highest shoreline erosion occurred in the northern part of the Bakırçay River between 1984 and 2022. A short-term shoreline analysis of the Bakırçay Delta showed that the vicinity of the Bakırçay River mouth was exposed to shoreline erosion during all periods. Additionally, the highest shoreline erosion in the short periods of shoreline analyses was recorded in 2000 and 2010 years with the EPR rate of -4.02 m/yr^{-1} and the highest shoreline accretion rate was observed in 2010 and 2022 with the EPR rate of 14.6 m/yr^{-1}. Additionally, the short periods of shoreline change in the Bakırçay Delta indicate a significant relationship between the maximum shoreline accretion period and peak sediment velocity years. In addition, the short-term shoreline change of the Bakırçay Delta showed a significant relationship between the maximum shoreline accumulation time and peak sediment years. In conclusion, the coast of the Bakırçay Delta is influenced by both natural and human-induced factors, causing significant shoreline and coastal morphology changes. Therefore, it is important to determine the extent of the variability in shoreline changes and define triggering factors that are extremely important for the sustainability of the diverse resources of the area. It is our view that the hydrodynamics of coastal processes in Türkiye are still poorly understood, and more research is needed on sediment dynamics along the coastal zones of the country to depict the vulnerable areas. Moreover, to achieve sustainable development of the vulnerable coastal zones a more strategic and proactive approach is needed. Coastal resilience along the Turkish coast can be improved by restoring the sediment balance and allocating the space necessary to adapt to natural erosion and coastal sediment processes. Coastal monitoring is a critical solution to be achieved using traditional methods of water quality monitoring, such as the evaluation of the extent of sediment inputs, sediment balances, and sea-level measurements using tide gauges, the latter of which has been used for over a century. These approaches can be combined with modern observation techniques, such as satellite altimetry, which represents fundamental support in studies aimed at monitoring land-use changes at the coastal area level. Remote data acquisition and processing can extend applications to a large number of users and managers involved in problems concerning the coastal environments.

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