



Spatio-temporal analysis of shoreline changes and future forecasting: the case of Küçük Menderes Delta, Türkiye

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Abstract

A delta coastal area is one of the most important regions for human use owing to its scenic natural beauty and economic value. However, due to the constant interaction between the land and water environments in this region, it is also one of the most rapidly changing landforms in the world under the impact of natural processes as well as anthropogenic activities. Therefore, the determination and the constant monitoring of these changes spatiotemporally are of great significance in terms of the protection, planning, proper usage, effective management, and sustainability of the delta coast. In this study was aimed to determine the short-term and long-term shoreline changes that occurred between the years 1957 and 2020 along the coast of the Küçük Menderes Delta and its close surroundings. In addition, the underlying causes were explored, and the future of the shoreline position was forecasted. The shorelines were digitized using seven multi-temporal orthophoto maps based on the high water line indicator. The shoreline changes were analyzed using different statistical methods, namely, the Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR), and Linear Regression Rate (LRR), by employing the Digital Shoreline Analysis System (DSAS). The future position of the shoreline was estimated using the extended Kalman Filter in the DSAS. The analyses revealed that in a period of 63 years, the maximum accretion distance (NSM) and rates (EPR and LRR) were 248.99 m, 3.96 m/year, and 3.65 m/year, respectively, the maximum erosion distance (NSM) and rates (EPR and LRR) were -142.37 m, -2.27 m/year, and -2.19 m/year, respectively, and the delta coastal area had increased by 37.01 ha. It is forecasted that the delta coastal area will expand by 10.63 ha and 16.16 ha from 2020 to 2030 and 2040. If the current conditions that occurred in the last 63 years continue with similar effects, it was forecasted that by the years 2030 and 2040, significant changes would occur in the shoreline such as retreat into the existing facilities/usage areas and decrease of Eleman Wetland area, which would greatly alter the ecology, hydrography, and spatial usage of the delta region.

Keywords Shoreline change · Shoreline forecasting · Digital Shoreline Analysis System · Küçük Menderes Delta · Coastal area management

Introduction

Social developments after the Industrial Revolution have shaped the economic usage of coastal regions, which has led to the concentration of various activities that fulfill all the requirements of the society, such as industry, trade,

transportation, tourism, and housing, in these regions (Akdeniz and Inam 2021). The activities (industry, tourism, transportation, etc.) conducted to fulfill the requirements of the population concentrated in this limited region of coastal land have caused certain changes in the coastal areas. The most important of such changes are the shoreline changes.

A 'shoreline' is defined as the boundary between the land and a water body. The shoreline is one of the unique landforms present on the Earth and is recognized as one of the 27 most important 'Geographical Indicators' in the world by the Federal Geographic Data Committee (FGDC) (Li et al. 2001). The shoreline is one of the most dynamic regions in the coastal area as it is located in a zone where the water and land environments are in constant interaction (Gary and

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Klee 1999; Akdeniz and Inam 2021). Therefore, determining and monitoring the changes occurring on the shoreline position and geometry is extremely important for understanding the dynamic structure of the coast and developing effective policies and strategies within the scope of the Integrated Coastal Zone Management (ICZM) (Esteves et al. 2009; Rio et al. 2013).

Coastal managers, coastal scientists, and coastal engineers are all enthusiastic to know “where the shoreline was in the past, where is it located currently, and where would it be located in the future”. Therefore, studies on determining and monitoring the changes occurring in the shoreline position and geometry are crucial for identifying the coastal erosion and accretion processes, evaluating delta development, investigating the effects of coastal engineering structures on the coastal areas, understanding the dynamic structure of the coasts, and planning and developing the appropriate policies and strategies in accordance with ICZM. Delta coasts have a fragile and delicate ecosystem, due to which the most frequent shoreline changes occur in these geographical areas. Even if the slightest shoreline changes occur in a delta coast area, these will affect the entire delta, the lagoons within this area, and several biogeographic elements (Sütgibi 2009). Therefore, for the sustainability of delta coasts, it is important to determine and constantly monitor the delta shoreline changes, estimate the future shoreline position, prepare long-term coastal area plans accordingly, and undertake other necessary measures as well.

Changes in the shoreline may be caused due to both natural processes and anthropogenic activities. These changes could directly as well as indirectly affect the environs of the coastal area. Shoreline changes caused by natural processes typically take place over the long term and result from a combination of various geological, geomorphological, and climatological factors. These factors encompass wave erosion and accretion, sediment and material transport, storm events, ocean currents, fluctuations in sea levels due to global warming, and tectonic-induced continental movements. Shoreline changes caused due to anthropogenic activities include those that occur in consequence of intense human activities, such as human settlement, agriculture, tourism, transportation, and industry establishment in coastal areas (Avcı 2017). The dams constructed on the rivers that include a delta are among the main anthropological activities that negatively affect delta development (Del Rio et al. 2013; Bergillos and Ortega-Sanchez, 2017; Kale et al. 2019). The construction of dams prevents the transport of sediment, and cause development of the delta slowed and nearly stopped (Öztürk and Sesli 2015). All shoreline changes should be monitored “in designated regions, times, and under certain periods”. Coastal scientists, who are aware of the importance of shoreline changes, have conducted several studies

in various geographical regions and coastal areas with different characteristics across the world (Ricchetti et al. 2004; BaMasoud and Byrne 2011; Alberti et al. 2013; Niya et al. 2013; Dewi et al. 2016; Özpölat and Demir 2019; Zagorski et al. 2020; Ciritci and Türk 2020). These analyses would enable improved management of coastal resources, better protection of the coastal areas, and sustainable development along the coastal regions.

The Küçük Menderes Delta investigated in this study is one of the most important ecosystems of the Aegean Region. This delta contains lagoons and wetland areas rich in flora and fauna, abundant water resources, and fertile agricultural lands along the coast of the delta, all of which have significantly increased its ecological value. In addition to its ecological richness, the Küçük Menderes Delta is also home to the ancient city of Ephesus, which has been placed on the protection list of the United Nations Educational, Scientific, and Cultural Organisation (UNESCO). Ephesus was once a seaport city. Ephesus was later filled with alluviums carried by the Küçük Menderes River and so was disconnected from the sea, in view of which it was used as one of the first examples of temporal shoreline change. Therefore, it has become further evident that examining the effects of shoreline changes in the Küçük Menderes Delta region is crucial. In this context, this study was aimed to investigate the shoreline changes that have occurred in the Küçük Menderes Delta coast region and its immediate surroundings during a period of 63 years. In addition, the future position of this shoreline was estimated.

Study area

Position

The Küçük Menderes Delta is situated in the western region of Türkiye, between the Lower Gediz Region in the north of the Aegean Region and the Büyük Menderes Region in the south, within the borders of the Selçuk district of Izmir province (Fig. 1). The study area was located between 37°54'00–38°00'05 N latitudes and 27°13'55–27°20'50 E longitudes. The delta neighbors the Menderes and Torbalı districts in the north, the Kuşadası and Söke districts in the south, the Aegean Sea in the west, and the Tire and Germencik districts in the east. Küçük Menderes Delta is an alluvial-fill area, which is 11 km long and 5 km wide (Erinç 1955). The slope of the delta area is extremely low, with the elevation from the coast to the Belevi Lake equal to only 5 m.

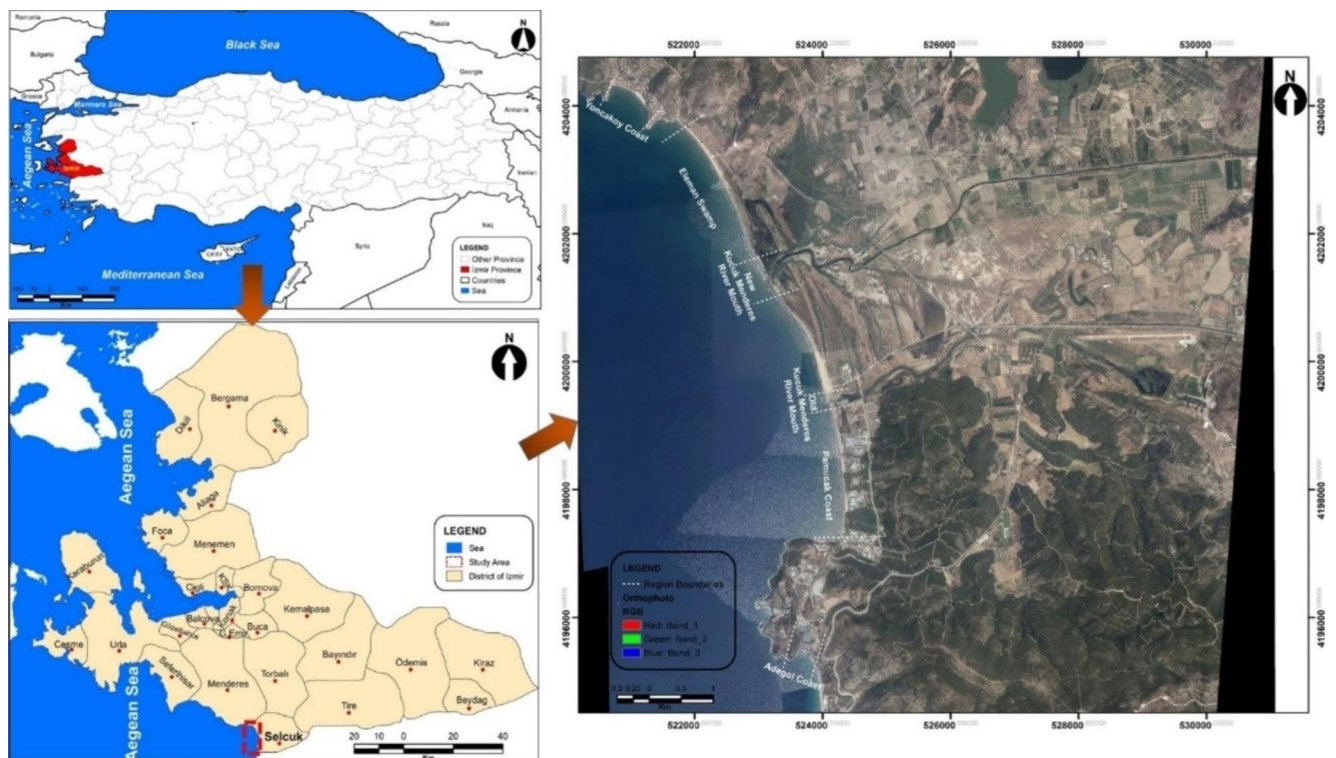


Fig. 1 Study Area

Geological characteristics

The geology of Western Anatolia comprises the Menderes Massif, which is constituted of crystalline stones, such as gneiss, marble, and mica schist. The Menderes Massif has been lifted by recent earth movements and broken into large blocks by oblique and strike-slip faults since the Miocene period. As a consequence, east–west trending grabens have been formed due to the tectonic evolution from Neogene to Quaternary (Kayan and Kraft 1997). The Menderes Massif is located at the center of this tectonic deformation where pervasive crustal extension in the Quaternary led to the development of extensional grabens delimited by faults trending E–W, NW–SE, and NE–SW (Özpolat et al. 2020; Ocakoğlu et al. 2014). E–W extension Büyük Menderes, Küçük Menderes, Gediz and Simav grabens divide the Massif into four sub-massif (Dora 1975). The Küçük Menderes Graben evolved as a result of rifting during the Plio-Quaternary which followed Late Miocene unroofing of the Menderes Massif and the evolution of the Büyük Menderes and Gediz grabens (Rojay et al. 2005). The Büyük Menderes Graben System bounded by active normal faults is one of the most active depositional settings of western Anatolia (Özpolat et al. 2020). The climatic and eustatic sea-level changes that have occurred since the Holocene are responsible for the current geomorphological characteristics of this Küçük Menderes Delta region. In the Early Holocene

period, the sea level rose rapidly, filled the Selçuk-Efes graben, and then advanced to the Belevi strait by covering the current delta surface. Altınbaş et al. (1997) stated that the shoreline of that period was 8 km inland compared to the current shoreline in this region and that the delta area at present formed a gulf in that period. It was on the southern shores of this gulf that the port city of Ephesus was established. In the Middle Holocene age, the sea level had reached its current level and did not rise any further. Alluviums carried by the Küçük Menderes River filled in the gulf. This change caused the delta area to rapidly advance toward the open sea. In the Late Holocene age, the delta area continued to advance rapidly toward the sea along with alluvial accretion, which resulted in the formation of landforms with characteristics different from those formed due to the other geomorphological effects (Öner 1997).

Hydrography

The Küçük Menderes Delta ecosystem is rich in hydrographic elements. The most important water sources of this delta are the Küçük Menderes River, after which the delta is named, and the distributaries of this river. The Küçük Menderes River is 129 km long with a drainage area of 3.225 km². It is one of the most important rivers of the Aegean Region (Ministry of Agriculture and Forestry, 2019). The river has an average annual flow of 11.45 m³/h, with the

highest flow recorded in the months of January, February, and March, and the lowest flow recorded in September and October (Muslu 2005). The river enters the delta plain from the Belevi strait and then flows, generally, along the east–west direction and flows into the Aegean Sea in Pamucak. The region where the river flows into the sea has the Gebekirse and Çakal Lakes in its vicinity. These lakes are alluvial-dam lakes covering a total area of approximately 150 ha. In the same vicinity is the Eleman Wetland, which has a surface area of 1.50 ha. In 1934, the bed of the Küçük Menderes River mouth was rearranged, as a consequence of which, the river mouth was transferred to its new 11-km long flatbed with adequate capacity further north from its old bed. Today, a large portion of this river’s water flows into the sea from this current river mouth, while only a small portion continues to flow into the sea from the old river mouth. No dam had been constructed on the Küçük Menderes River until the 2000s. Currently, there are several dams and ponds in the riverbed, either in operation or at the stage of construction, planning, or preliminary investigation. The Beydağ Dam (2007), Burgaz Dam (2015), Aktaş Dam (2017), and Bademli Pond (2015) are in operation, while the Ergenli (from 2014 to present) and Rahmanlar (from 2013 to present) Dams are under construction. The Uladı Dam is in the stage of project investigation, and the Birgi and Şirince Dams are in the planning stage (Ministry of Agriculture and Forestry, 2019).

Climatic characteristics

The climatic characteristics are based on the 1970–2020 data available in the records of the Selçuk Meteorology Station affiliated with the General Directorate of Meteorology. According to these data, the average annual temperature of the study area is 16.78 °C. The months with the lowest and highest average temperatures were January (8.0 °C) and July (26.6 °C), respectively. The average annual precipitation in the study area is 691.3 mm. The precipitation is unevenly distributed among the months. While the study area receives high precipitation in the winter season, the amount of precipitation in the summer months is quite low. The change in water level with tide is low, it is between 15 and 60 cm,

on average 20 cm. The annual average wave height is 0.6 m and its length is 150 m. In stormy periods, it can reach a height of 3 m and a wavelength of 50 m. The annual average wave power is 2 kW/m (Jadidoleslam 2014). Since the size and the direction of the sea waves are affected by the speed and direction of the winds, the latter become crucial in shoreline change research. In the 1970–2020 period, the average annual wind speed was 1.7 m/s, and no significant difference was observed in the average wind speed among different months. When the direction and percentage of the winds prevailing in the study area were analyzed, the effect of the sea and the relief could be observed in the wind direction. The West–NorthWest (WNW) winds created the prevailing average annual wind direction in the Küçük Menderes Delta, which extended to the Aegean Sea in the east–west direction. The wind blowing rate was calculated to be 12.81%. When all the climatic characteristics are considered together, it is understood that the study area has a Mediterranean climate type, with hot and dry summers and warm and rainy winters.

Materials and methods

Data sources

The potential data sources used in the research on shoreline changes include topographic maps, historical aerial photographs, orthophoto maps, satellite images, and field measurements data. The selection of the data source to be used in these studies is usually based on data availability and the scope of the study. In this study, orthophoto maps obtained from the General Directorate of Mapping (GDM) were used as the data source. The reason why orthophoto maps were used as the data source in the study was that they have high pixel resolution, have been widely used in many studies as a fast and economical data source for small and medium-scaled areas (Romine et al. 2009; BaMasoud and Byrne 2011; Ford 2013), are available free of charge, and provide data from older periods compared to satellite images. The datasets were selected to “the same seasons and certain periods”, to the extent possible, to minimize the effect of seasonal differences on the coastal area. In this study, black and white orthophoto maps for the years 1957, 1964, 1972, and 1993, and color orthophoto maps for the years 2009, 2018, and 2020 were used. Table 1 provides further details on the orthophoto maps used in this study.

Extraction of shorelines

In the study of shoreline changes, the first step is to determine the position of the shoreline as accurately as possible

Table 1 Characteristics of the orthophoto maps used in this study

Data Products	Source	Year	Scale	Resolution (m)
Orthophoto Map	GDM	15/09/1957	1:35.000	1.00
Orthophoto Map	GDM	22/07/1964	1:20.000	0.60
Orthophoto Map	GDM	03/06/1972	1:16.000	0.40
Orthophoto Map	GDM	05/08/1993	1:35.000	0.70
Orthophoto Map	GDM	07/08/2009	1:25.000	0.45
Orthophoto Map	GDM	15/09/2018	1:25.000	0.30
Orthophoto Map	GDM	10/07/2020	1:25.000	0.30

*GDM: General Directorate of Mapping

(Romine et al. 2009). The researchers have adopted shoreline indicators to determine the shoreline position. A shoreline indicator is a characteristic used for representing the ‘true’ position of a shoreline. In this study, the ‘High Water Line’ (HWL) indicator was used for extracting the shoreline position from all datasets. The HWL is visible from aerial photographs, owing to the contrast difference between the dry beach and the wet beach, which appears darker than the dry beach. The shoreline position was determined on each orthophoto map by using the HWL indicator. In this study, shoreline data were extracted using the “digitizing” method in ArcGIS software. In the study, shoreline belonging to 7 different periods were obtained. The digitizing method was preferred in this study because orthophoto maps present high-resolution values (ranging between 0.30 and 1.00 m),

due to which the land–water border is distinguishable. The flow chart of the study is shown in Fig. 2.

Calculation of shoreline uncertainties and errors

In shoreline determinations, uncertainties and sources of error have to be considered as these could affect the accuracy of the extracted shoreline positions and the final results of the study of shoreline changes. In the literature, has described five sources of uncertainty (seasonal, tidal, digitizing, pixel/resolution and orthorectification) encountered when extracting shorelines from orthophoto maps (Fletcher et al. 2003; Genz et al. 2007; Romine et al. 2009).

Similar to studies conducted by Ford (2013), Qiao et al. (2018), and Niang (2020), three sources of uncertainty, namely digitizing, pixel, and orthorectification, were used in this study. Seasonal and tidal uncertainties were not included in this study as the orthophoto maps were obtained for the same season of the year and the tidal range in the study area was low (Gökçen et al. 1990; Özpolat and Demir 2019). Pixel uncertainty (U_p) refers to the uncertainty arising due to the resolution (pixel size) of the orthophoto maps. In the study, pixel uncertainty was determined by resolution of each orthophoto maps. Orthorectification uncertainty (U_g) refers to the uncertainty of root mean square error. Orthorectification uncertainty values were obtained from GDM (<https://geoportall.harita.gov.tr/>). Digitizing uncertainty (U_d) is calculated by measuring the variability when digitizing the same coastal region several times. In this study, digitization uncertainty of each period was calculated as the standard deviation of repeated digitization of the shoreline by a single operator at five different times. The uncertainty values are listed in Table 2.

These sources of uncertainty are random and unrelated. The total shoreline position uncertainty (U) is calculated as the square root of the sum of the squares of the uncertainty source values. The total shoreline position uncertainty for each period was calculated using Eq. 1. The highest shoreline position uncertainty was estimated to be in the data from 1964 (10.32 m), while the lowest was estimated to be in the data from 2018 to 2020 (2.03 m). Total shoreline position uncertainty values are listed in Table 2.

$$U = \sqrt{U_d^2 + U_p^2 + U_g^2} \quad (1)$$

In such studies, shoreline change rate uncertainty (annualized error) needs to be calculated. The uncertainty of each transect in the shoreline change rate is calculated dividing the square root of the sum of the squares of the total shoreline position uncertainty values for both years by the time difference between the two shoreline dates (Hapke et

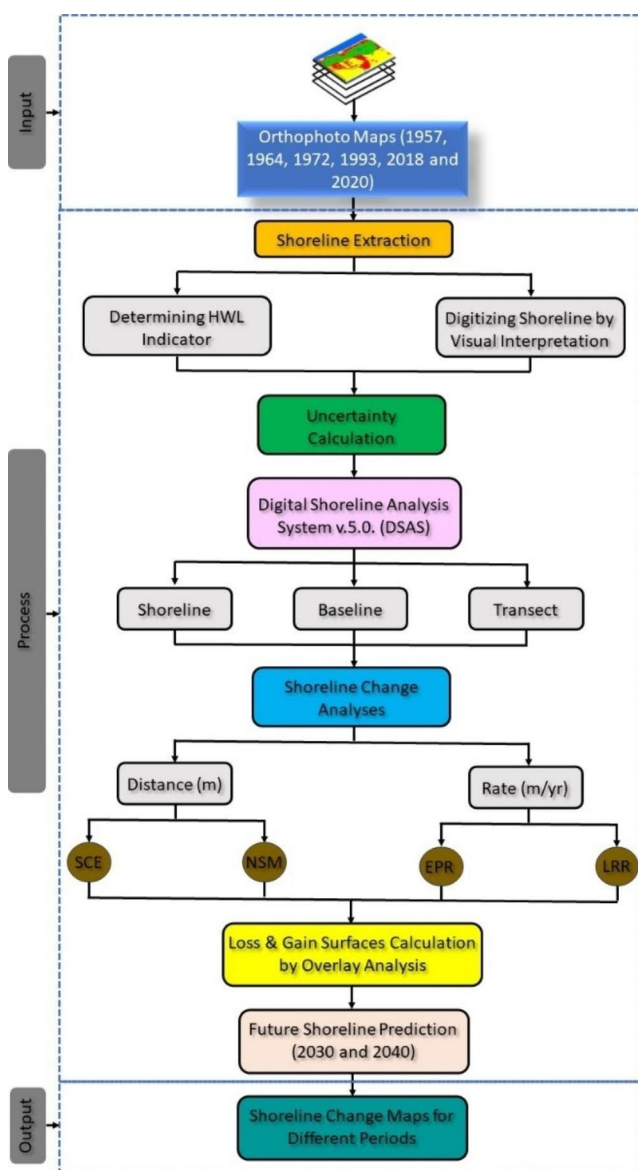


Fig. 2 Study flow chart

Table 2 The estimated shoreline position uncertainty values for each data source

Measurement Uncertainty	1957	1964	1972	1993	2009	2018	2020
Georeferencing Error (U_g)	±10 m	±10 m	±10 m	±10 m	±2 m	±2 m	±2 m
Digitizing Error (U_d)	±0.82 m	±2.48 m	±0.64 m	±0.47 m	±0.18 m	±0.17 m	±0.14 m
Pixel Error (U_p)	±1.00 m	±0.60 m	±0.40 m	±0.70 m	±0.45 m	±0.30 m	±0.30 m
Total Shoreline Position Uncertainty (U)	±10.08 m	±10.32 m	±10.03 m	±10.04 m	±2.06 m	±2.03 m	±2.03 m
Annualized Error (63 Years)	±0.163 m/yr						

al. 2010; Niang 2020). In this study, shoreline change rate uncertainty was calculated for change between 1957 and 2020. Rate of change uncertainty was calculated to dividing the square root of the sum of the squares 1957 and 2020 total shoreline position uncertainty values by 63-year time difference. The shoreline change rate uncertainty is presented in Eq. (2).

$$U_r = \frac{\sqrt{U_1^2 + U_2^2}}{Year_2 - Year_1} \quad (2)$$

Shoreline change analyses

The temporal shoreline changes in the Küçük Menderes Delta were analyzed using the Digital Shoreline Analysis System (DSAS) version 5.0 developed by the USGS and operating within the ESRI ArcGIS software package. The identification of shoreline changes using the DSAS requires determining a baseline first. The practitioner decides whether the baseline should be produced on the side of the sea or the side of the land. In this study, a baseline that was “in the direction of the sea and approximately 150 m away from the shorelines” was produced by conducting a buffer analysis. In the long-term shoreline change analysis (1957–2020) conducted in this study, a total of 509 transects separated by an interval of 25 and 750 m in length were produced. In the short-term change analyses (1957–1964, 1964–1972, 1972–1993, 1993–2009, 2009–2018, and 2018–2020), the number of transects produced ranged from 509 to 520, separated by an interval of 25 and 750 m in length. A section of the baseline and the transect lines produced in the long-term change analysis of the study area is depicted in Fig. 3. The long-term shoreline change analysis was conducted using the Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR), and Linear Regression Rate (LRR) statistical methods. The NSM and EPR statistical methods were used for the short-term shoreline change analyses. In the NSM statistical method, the distance between the oldest and the most recent shorelines in the study area was calculated for each transect, while the distance between the farthest and the closest shorelines relative to the baseline was calculated for each transect in the SCE statistical method. In the EPR statistical method, the

calculation involved dividing the distance between the most recent and the oldest shorelines by the time difference. This calculation only used the shoreline data from two different dates and, therefore, the result was a rate and not a distance value. The LRR statistical method, on the contrary, used all the shoreline data in the study to generate the most appropriate regression line. The slope of this regression line for each transects indicated the shoreline change rate.

The long-term shoreline change analysis involved calculations at a 95% confidence interval for the transects crossing a minimum of 7 shorelines. In the analysis results, positive values indicated the advance of the shoreline toward the sea (accretion), while the negative values indicated the retreat of the shoreline toward the land (erosion). In this study, the statistical results of EPR and LRR were categorized into the following five classes – high erosion (<−1 m/year), low erosion (−1 to −0.25 m/year), stable (−0.25 to 0.25 m/year), low accretion (0.25 to 1 m/year), and high accretion (> 1 m/year) (Oyedotun, 2014; Kermani et al. 2016; Nassar et al. 2018).

In the study of temporal shoreline changes, besides calculating the shoreline change distances and rates, the amounts of soil lost (due to erosion) and gained (due to accretion) are also estimated. In this study, the area change was calculated using the polygon area difference method, and the erosion/accretion area ratio (ha/year) was calculated by dividing the total area change by the time difference.

Future shoreline forecasting

The estimation of the future position of shoreline is crucial in long-term coastal planning studies conducted within the scope of ICZM as it allows undertaking effective decisions in coastal management and minimizing the damages that could otherwise be caused due to the impact of coastal erosion/accretion processes in the region. Nonetheless, while estimating the future shoreline position is important in coastal planning and management studies, determining the sustainability of the delta coasts, which have a susceptible and fragile ecosystem with low elevation and slope, is of greater importance.

In this study, the future shoreline positions and the uncertainty values of the Küçük Menderes Delta region were estimated for the years 2030 and 2040 using the extended

Fig. 3 Multiyear of shorelines, baseline and transect lines on the Küçük Menderes Delta coast



Kalman Filter method integrated into the DSAS software. The Extended Kalman Filter method was originally developed by Long and Plant (2012) to be used for estimating future shoreline positions. This analysis method is integrated into the DSAS software and allows estimating the future (for the next 10 or 20 years) shoreline position based on the past shoreline position data without considering the complex

morphological effects (Davidson et al. 2010). The Extended Kalman Filter method starts by using the estimated LRR rate and the oldest dataset and estimates the shoreline position for each successive time step until it encounters another shoreline observation. When another shoreline observation is encountered, the model performs an analysis to minimize the error between the modeled shoreline position and the

Table 3 The shoreline change values and rates according to the analysis based on the NSM, SCE, EPR, and LRR statistics for the 1957–1964, 1964–1972, 1972–1993, 1993–2009, 2009–2018, 2018–2020, and 1957–2020 study periods

Statistics	1957–1964	1964–1972	1972–1993	1993–2009	2009–2018	2018–2020	1957–2020
Total Number of Transect	517	520	509	511	512	511	509
Shoreline Length (km)	13.27	13.25	13.26	13.01	13.04	13.05	13.10
NSM (m)							
Average	6.68	6.07	21.05	-3.52	-2.17	-1.74	26.66
Minimum	-31.65	-51.28	-65.33	-71.20	-48.67	-23.07	-142.37
Maximum	117.72	62.97	158.82	34.12	44.52	13.78	248.99
Standard Deviation	21.85	14.82	31.94	17.53	12.28	6.26	65.55
EPR (m/yr)							
Average	0.97	0.77	0.99	-0.22	-0.24	-0.96	0.42
Minimum	-4.62	-6.52	-3.09	-4.45	-5.34	-12.68	-2.27
Maximum	17.18	8.01	7.50	2.13	4.89	7.57	3.96
Standard Deviation	3.19	1.88	1.51	1.10	1.35	3.44	1.04
SCE (m)							
Average	-	-	-	-	-	-	54.45
Minimum	-	-	-	-	-	-	2.98
Maximum	-	-	-	-	-	-	302.16
Standard Deviation	-	-	-	-	-	-	61.23
LRR (m/yr)							
Average	-	-	-	-	-	-	0.43
Minimum	-	-	-	-	-	-	-2.19
Maximum	-	-	-	-	-	-	3.65
Standard Deviation	-	-	-	-	-	-	1.00
Erosion Transects, Number	109 (21%)	136 (26%)	21 (4%)	188 (37%)	213 (42%)	267 (52%)	54 (11%)
Stable Transects, Number	156 (30%)	122 (24%)	219 (43%)	223 (43%)	192 (37%)	49 (10%)	211 (41%)
Accretion Transects, Number	252 (49%)	262 (50%)	269 (53%)	100 (20%)	107 (21%)	195 (38%)	244 (48%)
Overall Trend of Period Change	Accretion	Accretion	Accretion	Erosion	Erosion	Erosion	Accretion

shoreline position in the observation data, based on which it improves its modeled estimate for this time point (Long and Plant 2012). This process is repeated until the intended forecast date is reached.

Results

Long-term shoreline changes

The long-term analysis (1957–2020) of the shoreline changes in the Küçük Menderes Delta based on the NSM statistics revealed a shoreline change distance ranging from –142.37 to 248.99 m, with an average variation of 26.66 m (Table 3). In this period (1957–2020), the maximum shoreline advance occurred between the current Küçük Menderes River mouth and the old river mouth, while the maximum shoreline retreat occurred at the mouth of the current Küçük Menderes River (Figs. 4 and 5). The long-term analysis (1957–2020) of the shoreline changes based on the SCE statistics revealed that the maximum distance between the farthest and the closest shorelines relative to the baseline was 302.16 m and that the minimum distance was 2.98 m, with an average change of 54.45 m (Table 3). In addition, the

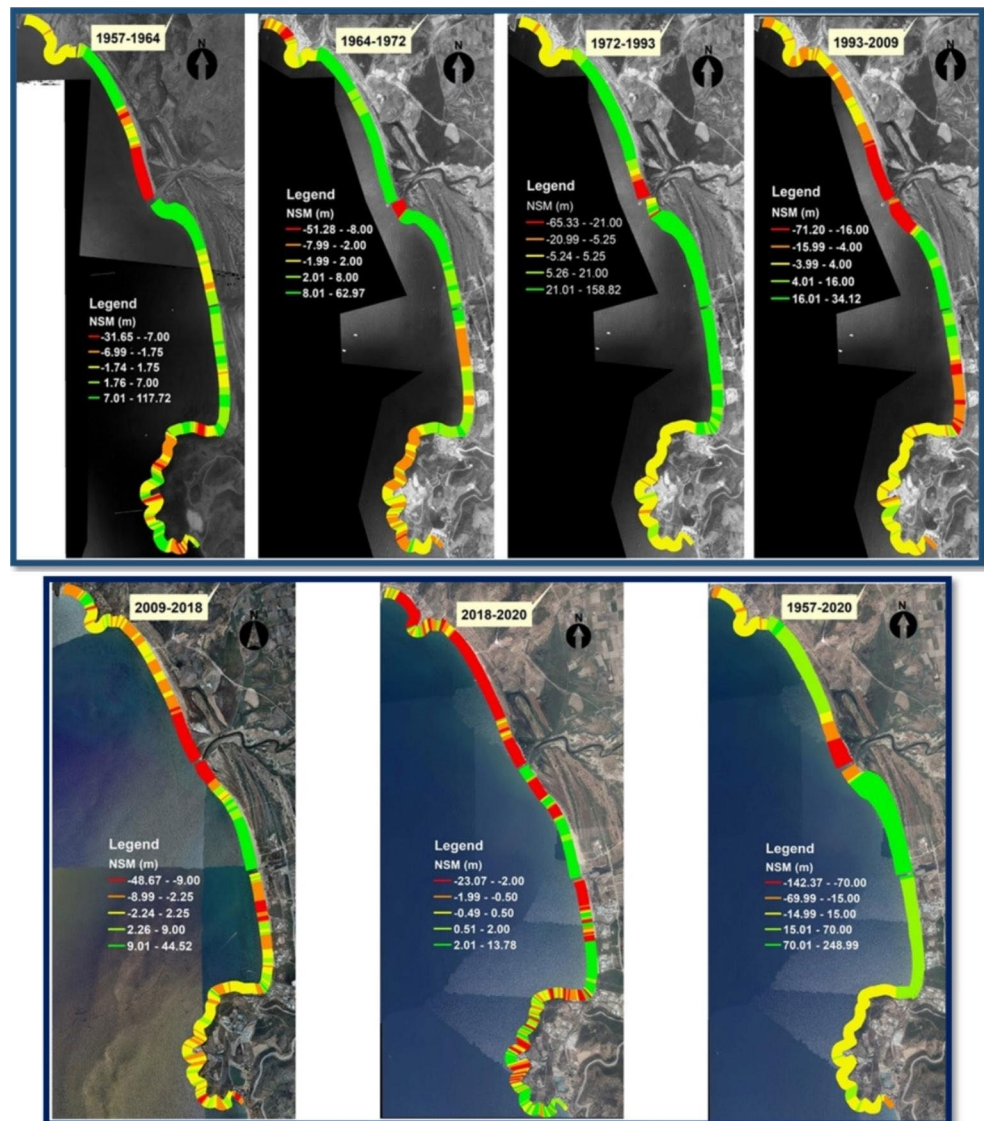
Table 4 Changes in the coastal area and the shoreline length in the Küçük Menderes Delta region

Time Interval	Net Coastal Area Change Amounts (ha)	Net Coastal Area Change Rate (ha/yr)	Net Shoreline Length Change Amount (m)
1957–1964	8.90	1.27	-15.10
1964–1972	8.70	1.09	4.25
1972–1993	28.36	1.35	-243.13
1993–2009	-3.76	-0.23	16.03
2009–2018	-2.44	-0.27	6.05
2018–2020	-2.38	-1.19	59.73
1957–2020	37.01	0.58	-172.17

minimum distance change was observed to have occurred on the hard rocky and steep-sloped coasts of the study area.

The analysis based on the EPR statistics revealed a shoreline change rate ranging between –2.27 m/year and 3.96 m/year, with an average of 0.42 m/year, while it was observed to vary between –2.19 m/year and 3.65 m/year, with an average of 0.43 m/year in the analysis based on the LRR statistics (Table 3). In the long-term study period, 47.23 ha of the coastal area of the Küçük Menderes Delta had migrated from the land to the sea (accretion), while 10.22 ha of the area had migrated from the sea to the land (retreat). The total coastal area change in the delta was 57.45 ha (Table 4).

Fig. 4 Maps for all periods of the study area according to NSM statistical results



Overall, the coastal area of the Küçük Menderes Delta had migrated from the land toward the sea in the 63-year study period, indicating a net accretion of 37.01 ha and a shoreline change rate of 0.58 ha/year (Table 4; Fig. 6).

Short-term shoreline changes

As a result of evaluation of the shoreline changes of Küçük Menderes Delta according to the NSM statistics, the shoreline change distance revealed (Table 3);

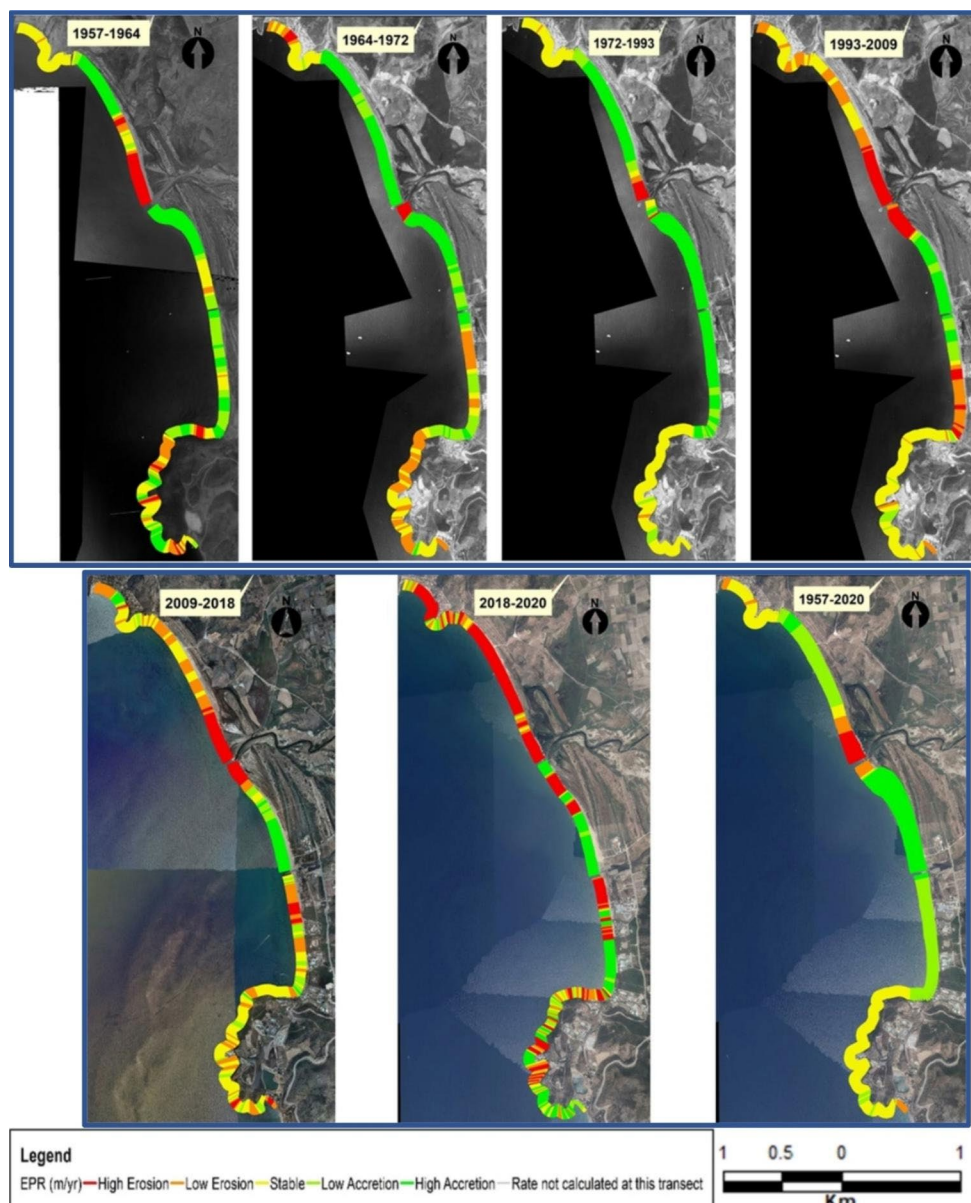
- 1957–1964 year, it ranged between -31.65 and 117.72 m, with an average value of 6.68 m,
- 1964–1972 year, it ranged between -51.28 and 62.97 m, with an average value of 6.07 m,
- 1972–1993 year, it ranged between -65.33 and 158.82 m with an average value of 21.05 m,

- 1993–2009 year, it ranged between -71.20 and 34.12 m with an average value of -3.52 m,
- 2009–2018 year, it ranged between -48.67 and 44.52 m with an average value of -2.17 m,
- 2018–2020 year, it ranged between -23.07 m and 13.78 m with average value of -1.74 m,

As a result of evaluation of the shoreline changes of Küçük Menderes Delta according to the EPR statistics, the shoreline change rate revealed (Table 3);

- 1957–1964 year, it ranged between -4.62 m/year and 17.18 m/year, with an average value of 0.97 m/year,
- 1964–1972 year, it ranged between -6.52 m/year and 8.01 m/year, with an average value of 0.77 m/year,
- 1972–1993 year, it ranged between -3.09 m/year and 7.50 m/year, with an average value of 0.99 m/year,

Fig. 5 Maps for all periods of the study area according to EPR statistical results



- 1993–2009 year, it ranged between -4.45 m/year and 2.13 m/year, with an average value of -0.22 m/year,
- 2009–2018 year, it ranged between -5.34 m/year and 4.89 m/year, with an average value of -0.24 m/year,
- 2018–2020 year, it ranged between -12.68 m/year and 7.57 m/year, with an average value of -0.96 m/year,

As a result of statistical evaluations, these changes in spatial interaction;

- a. It was determined that in these seven years (1957–1964), the maximum shoreline advance occurred between the current Küçük Menderes River mouth and the old river mouth, and the maximum shoreline retreat occurred at the north of the current Küçük Menderes River mouth

(Figs. 4 and 5). Overall, in this period, a net accretion of 8.90 ha occurred in the study area, with the coastal area of the delta exhibiting a seaward migration.

- b. In this 8-year study period (1964–1972), the maximum shoreline advance occurred between the shores of the Eleman Wetland and the current Küçük Menderes River mouth and the old river mouth, while the maximum shoreline retreat occurred on the Yoncaköy coast and at the current Küçük Menderes River mouth (Figs. 4 and 5). Overall, in this period, a net accretion of 8.70 ha occurred in the study area, with the coastal area of the delta exhibiting a seaward migration.
- c. In this 21-year study period (1972–1993), the maximum shoreline advance occurred between the current Küçük Menderes River mouth and the old river mouth

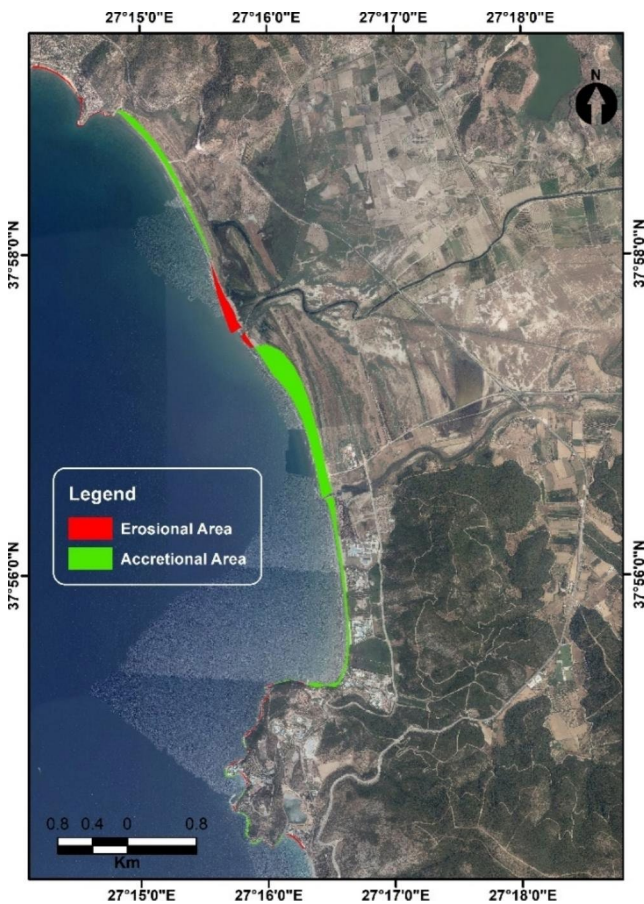


Fig. 6 Changes on coastal area of Küçük Menderes Delta between 1957 and 2020

and on the Pamucak coast, while the maximum shoreline retreat occurred at the current river mouth (Figs. 4 and 5). Overall, in this period, high levels of accretion occurred on the coasts of Küçük Menderes Delta, with the coastal area exhibiting a seaward migration and a net accretion of 28.36 ha.

- d. In this 16-year study period (1993–2009), the maximum shoreline advance occurred between the current Küçük Menderes River mouth and the old river mouth and on a portion of the Pamucak coast, while the maximum shoreline retreat occurred on the coast of Eleman Wetland and at the current river mouth (Figs. 4 and 5). Overall, in this period, low levels of erosion occurred on the coasts of the Küçük Menderes Delta, with the coastal area exhibiting a landward migration and a net eroded area of -3.76 ha.
- e. In this 9-year study period (2009–2018), the maximum shoreline advance occurred between the current Küçük Menderes River mouth and the old river mouth, while the maximum shoreline retreat occurred at the mouth of the current Küçük Menderes River (Figs. 4 and 5). Overall, in this period, the delta coasts experienced low

levels of erosion, with the coastal area exhibiting a landward migration and a net eroded area of -2.44 ha.

- f. The changes occurring in the Küçük Menderes Delta and the Küçük Menderes River in the last two years (2018–2020) due to increased anthropogenic activities (dam construction, riverbed improvement works, increased irrigated agriculture, coastal projects, etc.) were analyzed. In this period between 2018 and 2020, the maximum shoreline advance occurred in a portion of the region between the current river mouth and the old river mouth, while the maximum shoreline retreat occurred on the shores of Yoncaköy, Eleman Wetland, and at the south of the old river mouth (Figs. 4 and 5). Overall, in this period, the delta coasts experienced high levels of erosion, with the coastal area exhibiting a landward migration and a net eroded area of -2.38 ha.

Forecasting the future shoreline changes

If the current conditions that occurred in the last 63 years continue with similar effects, according to the future shoreline estimates for the Küçük Menderes Delta region based on the extended Kalman Filter method; it was predicted that this shoreline would advance along the coasts of Eleman Wetland, in the area between the current river mouth and the old river mouth, and along the Pamucak coasts, while it would retreat along the Yoncaköy, Adagöl Lagoon and the coasts of the current Küçük Menderes River mouth between the years 2030 and 2040. Moreover, the shoreline was estimated to remain stable on the hard rocky and high cliff edges in the study area.

The coastal area of the Küçük Menderes Delta is estimated to change by 11.70 ha seaward (accretion) and 1.07 ha landward (retreat) between 2020 and 2030. The estimated net accretion is 10.63 ha, and the estimated coastal area change rate is 1.06 ha/year for this period (Table 5; Fig. 7).

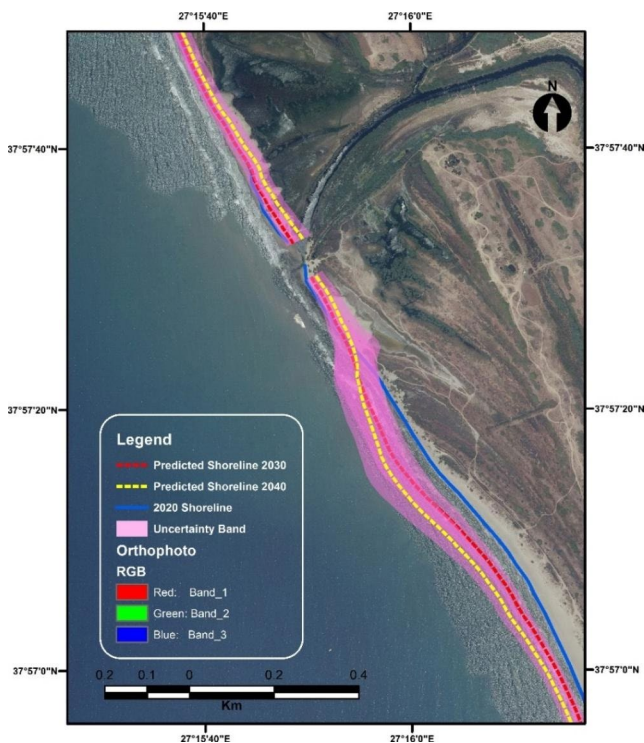
The coastal area of the delta is estimated to advance by 19.13 ha seaward (accretion) and retreat 2.97 ha landward (retreat) between the years 2020 and 2040. The estimated net accretion is 16.16 ha, and the estimated coastal area change rate is 0.81 ha/year for this period (Table 5; Fig. 7).

Discussion

The analysis of the shoreline changes in the Küçük Menderes Delta between the years 1957 and 2020 indicated that the shoreline progradation during this period was slow (average change of only 0.42 m/year). It was determined that this slowness in shoreline progradation in the last half-century was because the bed arrangements that were completed in

Table 5 Estimated coastal area changes for the years 2030 and 2040

Time Interval	Accretion Area (ha)	Erosion Area (ha)	Total Coastal Area Change (ha)	Net Coastal Area Change (ha)	Net Coastal Area Change Rate (ha/yr)
2020–2030	11.70	1.07	12.77	10.63	1.06
2020–2040	19.13	2.97	22.10	16.16	0.81

**Fig. 7** Map showing a transect of the Küçük Menderes Delta shoreline in 2030 and 2040

1934 divided the Küçük Menderes River into two portions – its northern and southern bayous. In addition to this division caused the extent of erosion and alluvium deposition to be limited as only little and small-sized sediments reached the Küçük Menderes Delta while the relatively larger sediments accumulated in the portion inside the Belevi Strait in the eastern part of the delta. Also, the water level in the basin to gradually decrease (decreased 30 m between 1968 and 1985, 60 m in 1995, 100 m in 2009, and 150 m in 2015) and the river flow regime to change drastically (average flow 13.9 m³/s during 1952–1986, 14.0 m³/s during 1972–1984, and 11.45 m³/s in 2005) caused slowness in shoreline progradation (Gökçen et al. 1990; Öner 1997; EIE, 1984; EIE, 1993; Muslu 2005). In this study as well, long-term changes occurring on the shoreline of the Küçük Menderes Delta were observed to have remained stable on the rocky and steep slopes of this region, while erosion/accretion occurred on the low sandy beaches due to rapid changes in this area (Eleman Wetland coast, current river mouth, the area between the current river mouth and the old river mouth, and the Pamucak coast).

When the long-term shoreline changes are examined in the short-term; from 1957 to 1964, the delta shoreline and the coastal area advanced entirely under the influence of natural processes as there was no exposure to any significant anthropogenic effects that might have caused these changes. In this period, the coasts of the Küçük Menderes Delta were shaped by natural processes, such as the quantity of sediment carried by the river, the wind strength and direction, and the wave effect. The reason for the maximum shoreline advance observed at the current river mouth and the south of the river mouth during this period was the accretion of the sediments carried by the Küçük Menderes River at the river mouth. Additionally, the accumulation of these sediments occurred due to the northwest wave regime formed under the influence of the prevailing West–North West (WNW) winds in the study area.

From 1964 to 1972, the delta coasts were mostly under the influence of natural processes, although the effects of anthropogenic activities, to a limited extent, were also observed. In this period, a portion of the Pamucak coast and the coasts of the Adagöl Lagoon experienced erosion (Figs. 4 and 5). This shoreline retreat could be attributed to the extraction/accretion of sand from the delta coasts during the construction of tourist facilities on both the Pamucak coast and the Adagöl Lagoon coasts. The maximum shoreline retreat during this period occurred in the south of the current river mouth (Figs. 4 and 5). The analysis of the orthophoto maps from the years 1964–1972 revealed that this change stemmed from the river mouth enlargement works. In this period as well, the maximum shoreline advance occurred in the region between the current river mouth and the old river mouth, with the effect of the waves in the northwest direction. Bolca et al. (2005) stated that the sediment movement was toward the south of the current river mouth.

From 1972 to 1993, natural processes as well as anthropogenic activities influenced the shoreline changes. Shoreline changes due to anthropogenic activities in the delta area during this period could be attributed to the construction of tourist facilities, secondary housing, and docks and breakwaters. The Pamucak coast was declared a tourism center during this period, with the decision of the Council of Ministers (dated: November 7, 1985; issue: 85/10,036), and two tourist facilities were constructed on the coast. It is understood that during the 1972–1993 period, high accretion occurred on almost the entire Pamucak coast, while low

accumulation was observed on the coast in front of the two tourist facilities constructed during this period; this change was due to the extraction of sand from the coast during the construction of the tourist facilities (Figs. 4 and 5).

In 1972–1993 period, a shoreline advance was also observed in the rocky area toward the south of the Pamucak coast, and this change was attributed to the construction of a dock. Uzun (2014) stated that docks constructed for tourism purposes led to shoreline changes. Another shoreline change that occurred due to anthropogenic activities during this period was on the coasts of the Pine Bay Holiday Resort hotel (Figs. 4 and 5). The breakwater constructed in this region prevented wave-induced erosion, thereby resulting in sand accumulation on the coast. Several previous studies have stated that the breakwaters constructed on a coast prevent coastal retreat and cause accumulation (Ricchetti et al., 2004; Esmail et al., 2019).

Moreover, it was determined that the length of the shoreline in 1993 was lower compared to that in the previous period (1972), and this change was attributed to the filling and accretion of the indented/protruding lines of the shoreline. In addition, the changes that occurred on the delta shoreline and the coastal area during this period were mostly along the axis of the influence of natural processes and exhibited similarities with the average shoreline change rate (0.97 m/year) occurring during the 1957–1964 period.

The effect of anthropogenic activities was dominant in the shoreline changes between 1993 and 2009. Within the periods studied, the delta area expanded along with the sediments carried by the Küçük Menderes River during 1957–1993, following which the expansion stopped and shrinking began and continued during the 1993–2009 period. However, the year when the shoreline advance stopped or the year when the retreat commenced could not be determined based on the available data.

Dam construction on rivers is among the most important anthropogenic activities that affect the delta areas (Nilsson et al. 2005). With the amount of water and sediment held in these dams, a lesser amount of sediments reach the lower course of the river, causing the delta area growth to decelerate or stop or even leading to delta retreat (Kondolf 1997; Vörösmarty et al. 2003; Syvitski et al. Milliman, 2007). The analysis of the results obtained for this type of anthropogenic activity in the study area confirmed the accuracy of these findings once again. Beydağ Dam on the Küçük Menderes River, the construction of which began in 1993 and was completed in 2007, emerged as the main reason for the retreat of the shoreline during this period. Kılar and Çiçek (2018) stated that the changes on the shoreline that occurred at and around the mouth of a river are directly affected by the changes in the flow rate and the sediment quantity of the river.

In the 1993–2009 period, the maximum shoreline retreat occurred at the mouth of the current Küçük Menderes River (Figs. 4 and 5), which was attributed, in addition to the construction of dams, to the withdrawal of water from the riverbed as a consequence of increasing irrigation-based agricultural activities. Sütgibi (2009) explained that agricultural irrigation using river water affected the sediment quantity transported and caused erosion of the delta shores. Accordingly, it was determined that the shoreline and coastal area changes during the 1993–2009 period developed along the axis of agricultural activities and the Beydağ Dam that was constructed on the river. In addition, the two tourist facilities constructed on the Pamucak coast and the forming a connection of the Adagöl lagoon with the sea by opening a channel caused the shoreline retreat in this region (Figs. 4 and 5). In this period, a shoreline advance occurred between the current river mouth and the old river mouth. However, this change did not indicate a continued growth of the delta coast area. Instead, it showed that the materials separated due to erosion of the river mouth protrusion area in the 1993 orthophoto map had accumulated in this region under the influence of northwest waves and winds.

The reconstruction work of the ancient port, which was the first stage in the Ephesus Ancient Canal Project, was completed by 2008; a 60-m-long dock was constructed to the north of the old river mouth, and a fisherman's shelter was constructed on the riverbed. These human activities caused accumulation in the northern portion of the dock.

The average shoreline change rate between 2009 and 2018 (−0.24 m/year) was close to the average rate of change during 1993–2009 (−0.22 m/year). In this period, various arrangements (main bed arrangement project, main bed slope fortification project, and flood protection project) were introduced into the main bed and the side beds of the Küçük Menderes River. Owing to these arrangements, the maximum shoreline retreat during 2009–2018 occurred at the current Küçük Menderes River mouth (Figs. 4 and 5). It was determined that the river mouth observed in the orthophoto map of 1993 became smooth in 2018 as a consequence of erosion. The tourist facilities constructed on the Pamucak coast during this period also caused erosion on the coast. The effect of the connecting of Adagöl Lagoon to the sea via a canal continued during this period as well. A shoreline retreat on the Yoncaköy coast was also attributed to anthropogenic activities.

The average shoreline retreat rate between 2018 and 2020 was increased compared to that in the previous period. This change was attributed to the Burgaz dam, which was operational by 2018, in addition to the Beydağ dam. In this period, the sediments carried by the Küçük Menderes River had begun accumulating in both Beydağ dam and Burgaz dam, thereby reducing the amount of sediment reaching

the Küçük Menderes Delta and causing an extremely rapid retreat (average: -4.71 m/year) at the current river mouth. The highest retreat (-0.96 m/year) of all periods observed in the Küçük Menderes Delta in this study occurred during this period.

The shoreline position of the Küçük Menderes Delta in 2030 and 2040 was estimated, excluding the influence of planned anthropogenic activities like dams, ponds, canals, and other related facilities intended for the main and side riverbeds. This estimation also doesn't account for the Ephesus Ancient Canal Project in the old riverbed or natural processes, such as sea level rise and tidal events. If the conditions between 1957 and 2020 continue with similar effects, it is estimated that the future shoreline would advance in certain regions while retreating in others, with the retreat in certain regions expected to extend into the existing facilities/usage areas.

Conclusion

In this study, long-term and short-term shoreline changes in the Küçük Menderes Delta region were determined, and the future shoreline position of the delta coast was also estimated. Orthophoto maps from different time points were used as datasets in this study, and shoreline changes were analyzed based on the NSM, SCE, EPR, and LRR methods of the DSAS. The future shoreline position of the Küçük Menderes Delta for the years 2030 and 2040 was estimated using the extended Kalman Filter method. It was determined that the coastal area of the Küçük Menderes Delta had advanced from the land to the sea (net 37.01 ha, maximum 248.99 m, average 3.96 m/year) during the 63-year study period (1957–2020). The shoreline changes in this period had mostly occurred in the low and sandy beaches and at the current river mouth, while the shoreline at the hard rocky and steep slopes had remained stable. According to the results of the analysis of short-term shoreline changes, the average EPR rate was 0.97 m/year during 1957–1964, 0.77 m/year during 1964–1972, and 0.99 m/year during 1972–1993. The delta coasts were shaped under the influence of natural processes from 1957 to 1993, with a net accretion of 45.96 ha. It was determined that the accretion in the delta area stopped after 1993 as a consequence of anthropogenic activities, such as increased irrigation-based agricultural activities, riverbed arrangement works, dam constructions, tourist facility constructions, and coastal engineering structures and projects and that there was a landward migration. The shoreline changes occurred mostly at the mouth of the current Küçük Menderes River. If the estimated rates of change continue under the current conditions with similar effects, it is estimated, without considering

the complex morphological effects, that the delta shoreline would advance in certain regions and retreat in certain other and that the delta area would expand by 10.63 ha in 2030 and by 16.16 ha in 2040. These findings demonstrated that the coasts of the Küçük Menderes Delta underwent significant morphological, ecological, hydrographic, and spatial changes during the period studied and that this region has quite a dynamic structure.

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Data Availability Data available on request from the authors.

Declarations

This study was extracted from the master's thesis titled "Examination of Shoreline Temporal Changes and Development of Coastal Management System", accepted by Konya Technical University Graduate Education Institute on July 28, 2021.

Human participants and/or animals This article does not contain any studies with human participants or animals performed by any of the authors.

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