INVESTIGATION OF LINEAR AND AREA CHANGES OF THE DELTA COASTS IN THE EASTERN OF LAKE VAN (TÜRKİYE)

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Abstract: *Coasts undergo constant change in the temporal universe due to a wide variety of factors, both spatial and linear. Delta geomorphology, formed by coastal and fluvial factors, is one of the elements most affected by changes occurring on the coast. Although coastal changes in many deltas around the world and in Turkey have been studied, there has been little research on deltas in lakes. This study examines the linear and spatial coastal changes between 1984 and 2024 in six delta areas (Zilan, Deliçay, Bendimahi, Karasu, Van and Engil deltas) located east of Lake Van, which has the largest water surface area in Turkey. First, water-land separation was performed using the Normalised Difference Water Index (NDWI) and threshold method analysis from Landsat satellite images from 1984, 1994, 2004, 2014 and 2024, and coastlines were generated. The quantitative dimension of linear changes occurring on the coast was analysed using statistics from the Digital Shoreline Analysis System (DSAS). The analyses were conducted on five different coastlines for both the long term (1984-2024) and two different coastlines for 10-year consecutive periods. Shoreline changes during the specified periods were evaluated using the Net Shoreline Movement (NSM), End Point Rate (EPR), Linear Regression Rate (LRR) and Shoreline Change Envelope (SCE) methods included in the DSAS tool. The sensitivity of coastline changes was calculated using LRR analysis results from long-term data on deltas. Finally, the spatial changes occurring on delta coasts were analysed using Geographic Information Systems (GIS). The study found that in the long-term change (1984–2024) results, shoreline accretion was dominant in most deltas, but a general shoreline retreat occurred during the 1984–1994 period. While high rates of linear and areal changes were observed in the Zilan (D1), Bendimahi (D3) and Engil (D6) deltas in particular, it was determined that anthropogenic effects were dominant in the Van Delta (D5) and that coastal change was at a low level. The Zilan delta has the highest sensitivity to coastal change. The findings indicate that delta coasts are trending towards advancement, which is associated with the lake's hydrological dynamics, rainfall variability in the basin, and the siltation effect of dams constructed on the rivers feeding the lake.*

Keywords: DSAS, Coastal change, Delta, Lake Van (Turkiye)

1. INTRODUCTION

Coasts are among the most dynamic geomorphological areas, constantly changing and being shaped by a wide variety of processes, offering morphological differences (Bird, 2008). Coasts have a hinterland and an area of influence on both the water and land surfaces. The geomorphological elements that form the boundary between land and water in seas, lakes and rivers are the coastlines. The shoreline is not a fixed element, but undergoes changes at different levels, affected by eustatic and tectonic movements, climatological factors, climate fluctuations, and local geomorphological and hydrographic processes (Turoğlu, 2017). This change takes the form of shoreline advance and retreat, and the dynamic processes that occur create areas of erosion and accumulation on the coast. As a result of this dynamic cycle, geomorphological elements on the coast change, and ecosystem differentiation and ecological interactions emerge (Davidson-Arnott, 2010). Coasts, where dynamic processes develop very rapidly, are among the areas where anthropogenic activities are concentrated, thanks to the favorable conditions they offer. Coasts, which are the intersection of natural and human conditions, are of strategic importance in sustainable environment and socio-economic development policies. It is very important to study, analyse and model shoreline changes for management and planning studies on coasts, which are subject to frequent changes in terms of space and time (Jiang et al., 2025).

The shoreline and the general geomorphological structure of the coast are affected by eustatic and tectonic movements, wind and wave action, erosive activities, sedimentation of coastal currents, lithological unit characteristics of the coast, local changes in sea and lake levels, precipitation patterns, fluvial factors, and anthropogenic factors such as port, shipyard, and breakwater construction. The aforementioned factors can alter the structure and geometry of the coastline, with such changes manifesting as coastal erosion due to sediment transport or coastal accretion due to increased sediment deposition (Mattheus et al., 2025). The temporal processes of changing coastal dynamics can be quite long, or linear and areal changes can occur on the coast in a very short time (Burningham & French, 2017). The differentiation caused by these changes affects geomorphological processes, leading to changes in the morphological appearance of coasts and causing human activities to adapt to these changes (Ciritci & Türk; 2020; Yasir et al., 2021).

A lake is defined as a hydrographic unit formed by the filling of geomorphologically formed depressions with water, balanced by the evaporation and seepage of the specified water (Hoşgören, 1994). Lakes around the world exhibit diversity based on the origin of their basins and the chemical properties of their waters. Lakes are also highly dynamic systems in terms of their surface water area, which varies annually and seasonally due to their spatial size, climatic factors, and geomorphological influences (Khorshiddoust et al., 2022; Sikder et al., 2023; Akbaş, 2024; Acheampong et al., 2025). The aforementioned conditions result in lake shores containing various geomorphological units and exhibiting variability due to different factors (Busker et al., 2019). The shoreline of lakes can change due to both natural processes and anthropogenic factors (Woolway et al., 2020; Roland & Zoet, 2025). Lakes also contain various systems with natural and human elements in their interaction area with andoreic basin characteristics (Liang et al., 2023). Changes resulting from interactions between the lake shoreline and the drainage basin can occur directly or indirectly through other factors in the lake's drainage basin (O'Reilly et al., 2015; Zhou et al., 2020).

Geomorphological accumulation forms that occur on coasts due to the effects of both coastal and fluvial processes are called deltas. Deltas form in various geometric shapes depending on the coast's current, wave direction, wind effect, geomorphology, lithological units, bathymetric characteristics, the amount and size of material carried by fluvial elements, the flow velocity and discharge of the river, and its bed (Nienhuis et al., 2020). In this regard, deltas are primarily formed by river-based, wave-current-based, and tidal-based processes. Dynamic delta coasts with intense deposition and erosion also harbour wetlands and exhibit high biodiversity in terms of flora and fauna (Kuleli et al., 2011). Deltas are influenced by coastal factors and natural and anthropogenic processes in the drainage basin, creating different temporal and spatial change dynamics (Foutrakis et al., 2007; Bombino et al., 2022). Deltas located on lake shores in andoric basins, with their wetland characteristics and exposure to direct or indirect anthropogenic factors, are among the most important areas to be studied in terms of the variability of natural dynamic processes (Gumus et al., 2022; Uzun, 2024b). Delta coasts located along ocean and sea shorelines worldwide undergo diverse changes over short periods (Siyal et al., 2022). In recent years, it has been noted that coastal erosion is occurring at a very rapid rate in many deltas as a result of siltation caused by dams built on the main rivers in the drainage basin that feed the deltas (Kale et al., 2019; Uzun 2024c). In many lakes with different morphological characteristics, delta coastline changes, coastal processes, hydrogeological variability of lakes, global climate change, and anthropogenic activities in lake basins are undergoing changes (Rahman et al., 2022). The spatial and temporal analysis of changes occurring in coastlines, deltas, or lake surface areas can be conducted in detail using Geographic Information Systems (GIS), Remote Sensing techniques, and other technological advancements developed in recent years (Mullick et al., 2019; Hu & Wang, 2020; Özpolat et al., 2021; Murray et al., 2023). In particular, water surface extraction is performed using various algorithms based on multispectral satellite images such as Landsat or Sentinel, which are freely accessible, and coastal changes are analysed temporally and spatially (Esmail et al., 2019; Hovsepyan et al., 2019). In recent years, the Digital Shoreline Analysis System (DSAS), a product of the United States Geological Survey (USGS) that enables statistical and spatial queries and the creation of models for the future, has been widely preferred in many different coastal change studies (Ataol vd., 2019; Nassar vd., 2019; Samra & Ali, 2021; Song vd., 2021; Akdeniz & İnam, 2023; Dinç, 2023; Kılar, 2023; Uzun 2024c; Yayla vd., 2025).

The aim of this study is to examine the linear and areal changes in six different delta coasts on the eastern side of Lake Van using statistics and other GIS analyses obtained from Landsat satellite images from 1984, 1994, 2004, 2014, and 2024, using statistics from the DSAS tool and other GIS analyses.

1.1. Study Area

The research area consists of six different delta coasts east of Lake Van, located in eastern Turkiye, which has the largest water surface area (3602 km2) in the country (Figure 1). Lake Van was formed by tectonic depressions that were reshaped morphologically by Quaternary volcanic activity. The lithological influence of the Nemrut and Süphan volcanic masses to the west and north of Lake Van has made the lake's waters salty (Degens et al., 1984). The high masses surrounding the lake to the south, west and north have resulted in a very narrow drainage basin in this area. In the eastern part of the lake, however, there is a wider drainage basin. Therefore, the relatively longer rivers flowing from this area have formed deltas due to the lower coastal relief. The deltas examined in this study are listed from north to south as the Zilan River Delta (D1), Deliçay River Delta (D2), Bendimahi River Delta (D3), Karasu River Delta (D4), Van Delta (D5), and Engil River (D6) (Figure 1).

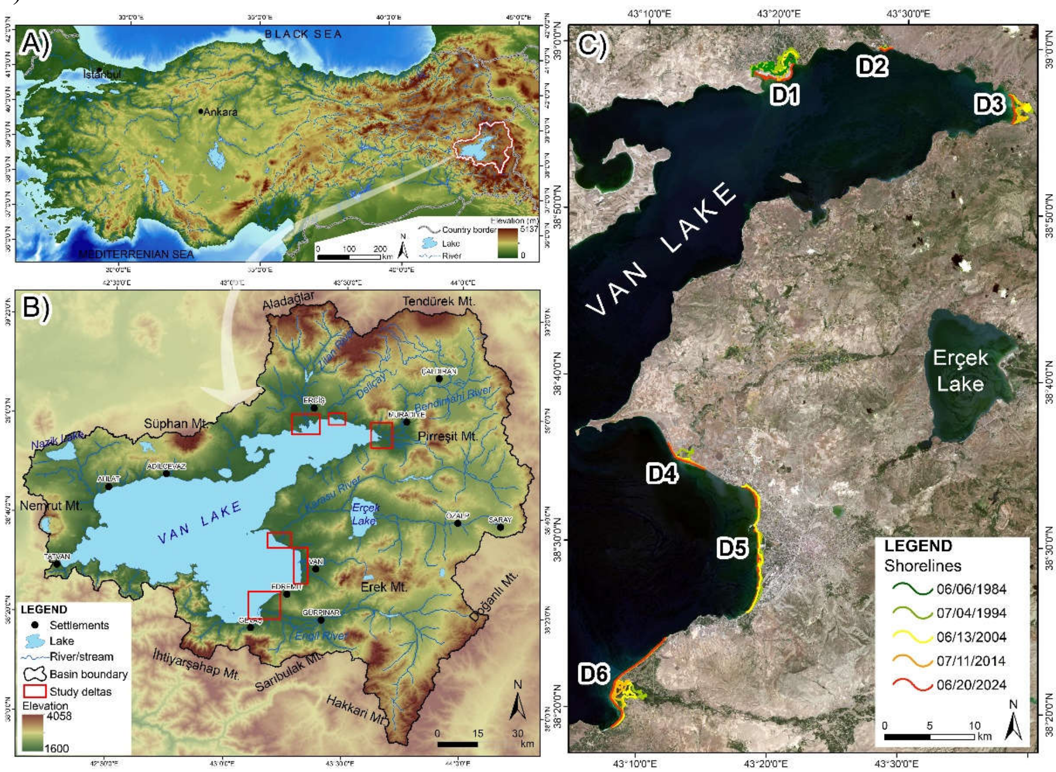

Figure 1: A) Location of Lake Van basin in Turkiye, B) Location of Lake Van basin and studied deltas, C) Deltas studied east of Lake Van and shorelines by year

Lake Van exhibits a complex structure, formed first by tectonics and karstification in the tectonic depression area stretching from the eastern plateau to the Muş plain, and later by the formation of lava barriers by the Süphan and especially Nemrut volcanoes (Hoşgören, 1994; Selçuk Biricik, 2009). The volcanic materials in the lake basin and its immediate surroundings have caused the lake to become one of the endorheic lakes with high salt and soda concentrations. The total annual average discharge of Van Lake is 2.2 km^3, approximately 80% of which occurs during the spring months due to snowmelt (Kuzucuoğlu et al., 2010). The lake's soda-rich chemical properties, alkalinity, and high evaporation rate have limited the lake's biodiversity. The total area of Lake Van's closed basin is 15,495 km². Although the lake's level and surface area vary, its water area has been calculated to be 3,602 km² (Akköprü et al., 2019). The lake's average elevation above sea level is 1,646 m, its average depth is 170 m, and its deepest point is 450 m. The total shoreline length of the lake is 430 km (Kuzucuoğlu et al., 2010). The wide drainage basin to the east of the lake and the fact that the relief is less rugged than to the west have resulted in low-lying shores on the eastern side of the lake. The formation of the deltas covered by the study has occurred in relation to the geological and geomorphological characteristics of the lake shore, its bathymetric conditions and fluvial processes. Dams have been constructed on the rivers discharging into the lake from the deltas, resulting in siltation. Findings from drilling and other methods conducted in the lake have revealed changes in the lake's water level and surface area. These changes were observed at +108 m and -340 m levels 105,000 years ago and 8,400 years ago, respectively (Kaden et al., 2010; Kuzucuoğlu et al., 2010; Akköprü et al., 2019). In the last 3,000 years, the change in lake level has been within the range of 1-2 m. Changes in lake level, surface area, and consequently along the shoreline are observed along the Van Lake shoreline through various geomorphological features such as cliffs, lacustrine terraces, deltaic sedimentary deposits, bed changes, and shoreline indentations.

2. DATA AND METHODOLOGY

The main data sources for this study are Landsat TM, ETM, and OLI multispectral satellite images from 1984, 1994, 2004, 2014, and 2024, obtained from the United States Geological Survey (USGS) Research Institute (Table 1). The moderate spatial resolution of the data (30x30), the availability of temporal resolution, and free access (Baig et al., 2020) made them the preferred choice for this study.

Table 1: Landsat satellite images and characteristics used in the study

	Date (m/d/y)	Sensor	Resolution	Cloudiness	Path/Row	Type
1	06/06/1984	Landsat 5 TM	30 m	3.21%	170/033	Geotff
2	07/04/1994	Landsat 5 TM	30 m	0.03%	170/033	Geotff
3	06/13/2004	Landsat 7 EM	30 m	1.0%	170/033	Geotff
4	07/11/2014	Landsat 8 OLI	30 m	1.76%	170/033	Geotff
5	06/20/2024	Landsat 9 OLI	30 m	1.00%	170/033	Geotff

The study's procedural methodology consists of different stages (Figure 2). First, radiometric preliminary examinations of the acquired satellite images were conducted, and the images were prepared for use in ArcGIS 10.5 software and analyses. Subsequently, water-land surface separation was performed, and the coastline extraction process was carried out. In this context, previous studies were reviewed and experiments were conducted using satellite images (Yılmaz, 2023; Karakus, 2025). In this study, it was concluded that the Normalised Difference Water Index (NDWI) provided the most appropriate and usable results. The NDWI analysis is calculated using the following formula (Equation 1).

$$NDWI = \frac{(P_{green} - P_{NIR})}{(P_{green} + P_{NIR})} \quad \text{Equation 1}$$

In the NDWI formula, P_{green} band 3 and P_{NIR} band 5 represent Landsat satellite images (McFeeters, 1996). NDWI results always take values between 1 and -1. Subsequently, water-land separation was performed using the threshold method algorithm (Reis et al., 2021) (Figure 3). In the results, a value of 0.01 was accepted as the threshold, and areas above this value were classified as water surface (Acharya et al., 2017; Hossain et al., 2021). After the obtained threshold value binary classification (land and water surface), 70 control points were marked on each delta coast for the accuracy analysis of the data. Based on the specified control data, the satellite image (band combination as water surface) of each year was used as a basis and accuracy analyses were performed. Accuracy analyses were conducted by examining whether the specified point was water (correct) or land mass (incorrect) based on the NDWI result of the controlled satellite image, and accuracy rates were calculated. In another stage of the study, the raster data obtained by NDWI analysis and the threshold method were converted to polygons in ArcGIS 10.5 software, and these data were converted to line data and applied to the shoreline extraction process for 5 different years within 6 different deltas.

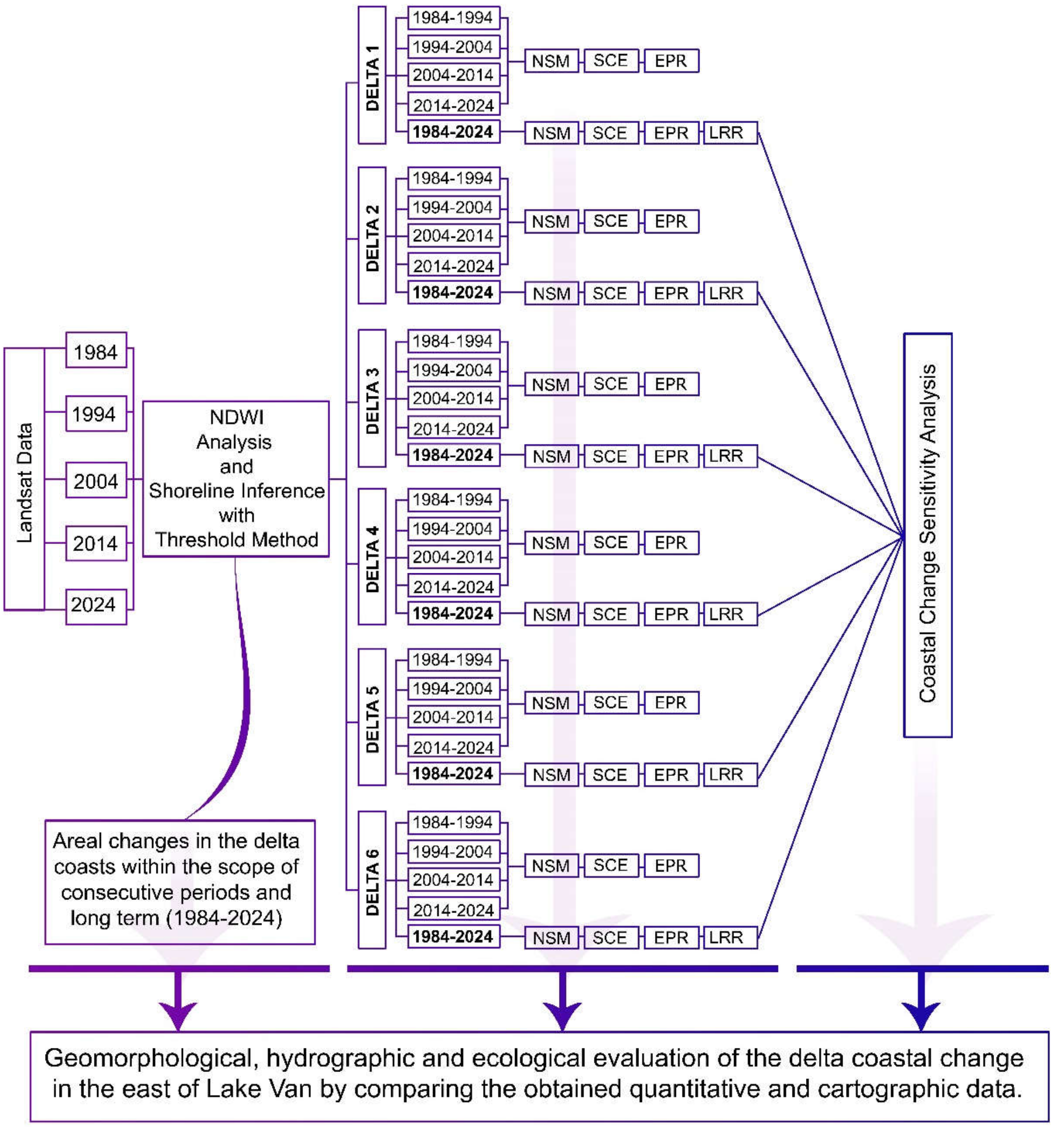

Figure 2: Workflow diagram of the study

The obtained coastlines were first subjected to length calculations and analyses in terms of period. In this process, the coastline length of each delta for each year studied was calculated, and the temporal change trend was examined using the linear trend method. Then, the change in shoreline length (in metres) and the proportional value of the change compared to the previous year were examined for consecutive periods. As a result of this examination, the indented structure of the delta coasts, the geomorphological change status and the coastal change mobility were evaluated.

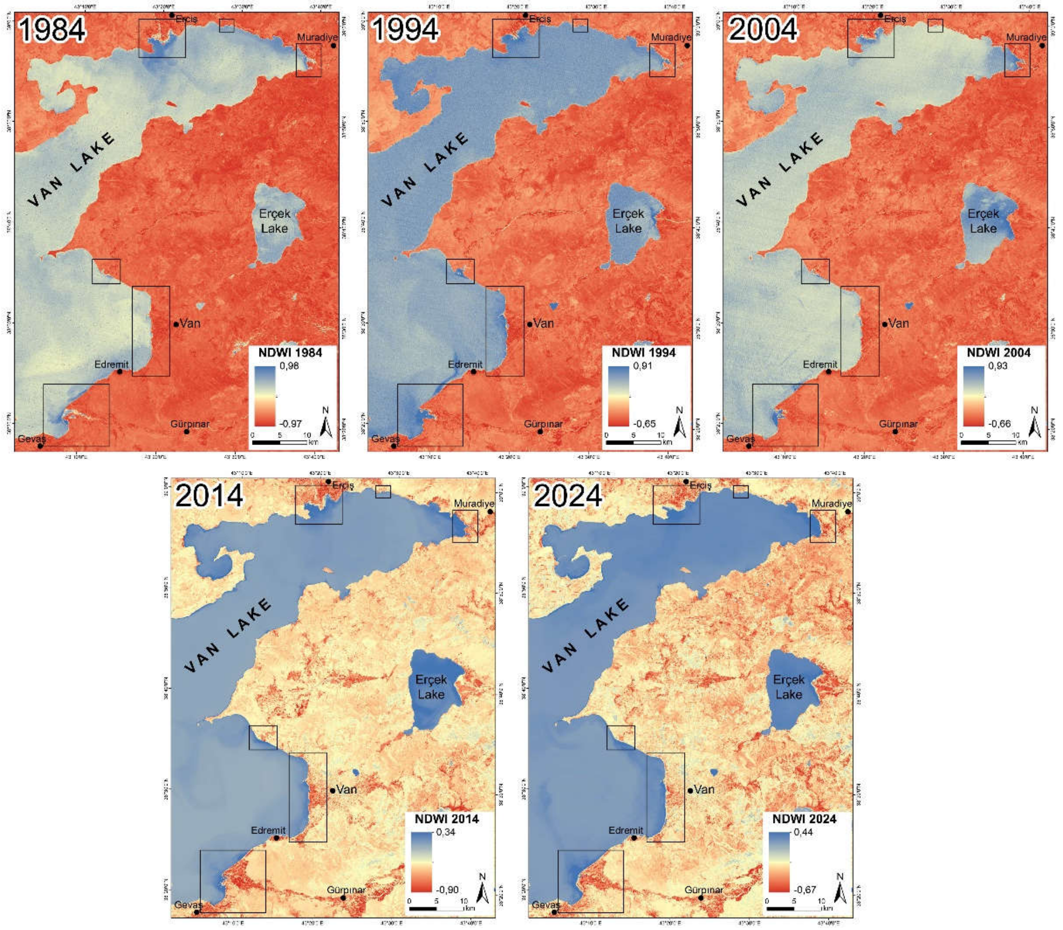

Figure 3: NDWI analyses of the study area

In this study, the Digital Shoreline Analysis System (DSAS), a product of the United States Geological Survey (USGS), was used for the quantitative analysis of linear changes along the coastline. The DSAS tool provides quantitative findings through various analyses within the tool based on coastlines (Kazı & Karabulut, 2023). DSAS V5.1 was used as an add-on to ArcGIS 10.5 software in this study. The Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR) and Linear Regression Rate (LRR) analyses included in the DSAS tool were used in this study. In the analysis of shoreline changes in 6 different deltas in Lake Van for 5 different years, the baseline lake (water surface) was taken in the DSAS tool, the orientation from west to east and north to south was determined, and the transect interval was set at 10 m for the analyses. A total of 562 transects were used for D1, 74 for D2, 163 for D3, 244 for D4, 707 for D5, and 496 for D6.

Among the statistical analyses used in the study, NSM determines the net change distance based on the oldest and newest coastlines. The NSM analysis also calculates the difference between the start and end points of the shorelines (Himmelstoss et al., 2018). NSM results take positive and negative values and reveal the direction of change (erosion or accumulation) on the coast.

The SCE analysis in the DSAS tool reveals the total change distance (the largest limit of change) along the transect line between all coastlines (Himmelstoss et al., 2018). In the SCE analysis, the sign of the total change distance between two coastlines is uncertain over time, so the resulting value is always positive (Thieler et al., 2009). Therefore, the SCE analysis reveals the largest extent of coastal change.

EPR analysis is calculated by dividing the distance between the oldest and most recent shoreline movement in the studies by the time between the two shorelines

(Himmelstoss et al., 2018). EPR analysis results describe the annual change in the distance of shorelines in m (m/y). EPR is calculated using the following formula.

$$EPR = \frac{(L_2 - L_1)}{(t_2 - t_1)} \quad \text{Equation 2}$$

In the above formula (Equation 1), L_1 and L_2 are the distances of the old and new coastlines from the reference line, and t_1 and t_2 are the dates of the old and new coastlines. The advantage of EPR is that it is easy to calculate and can be calculated using at least two coastlines. Therefore, EPR was used in this study to calculate periodic coastline changes. The disadvantage of the analysis is that it ignores a lot of additional information when there are more shorelines and other geomorphological elements.

The LRR analysis in the DSAS tool is calculated by applying least squares regression to all coastline points on the transect line (Himmelstoss et al., 2018). In the LRR analysis, a linear trend is established by considering the uncertainty value, and assessments are made by minimising the error rate in the results of annual data on coastline change. In this study, LRR analysis was used only for long-term analyses (all coastlines between 1984 and 2024) because it calculates based on at least three coastline data points.

The sensitivity levels of annual linear changes occurring on delta coasts have been classified in terms of the geomorphological direction and magnitude of the change. The classification of shoreline change sensitivity has been revised specifically for the research area based on the classifications made by Selvan et al. (2016), Baral et al. (2018), Himmelstoss et al. (2018) and Uzun (2024c) (Selvan et al., 2016; Baral et al., 2018; Himmelstoss et al., 2018; Uzun, 2024c) (Table 2). Since the value of annual change data in metres was used in the sensitivity classification, the LRR data determined on five different coastlines between 1984 and 2024 were used in the study.

Table 2: Coastal change sensitivity classification used in the study

Shoreline change rate LRR (m/yıl)	Coastal and shoreline change classification	Coastal Change Sensitivity	Coastal Change direction
< -5	High levels of erosion	High	Coastal Erosion
-5,01 - -3,01	Moderate levels of erosion	Moderate	
-3,09 - -0,51	Low levels of erosion	Low	
-0,50 - 0,50	Stabil	Stabil	Nötr
0,51 – 3,09	Low levels of accretion	Low	Coastal Accretion
3,1 – 5,09	Moderate levels of accretion	Moderate	
> 5,1	High levels of accretion	High	

Source: Selvan vd., 2016; Baral vd., 2018; Himmelstoss vd., 2018; Uzun, 2024c

Spatial calculations for the delta coasts were analysed using the Union method in ArcGIS Geoprocessing. Within this scope, coastal erosion, coastal accumulation, and total changing coastal area calculations were performed for each delta between successive periods (1984-1994, 1994-2004, 2004-2014, and 2014-2024) and for the long period between 1984 and 2024. Additionally, the total changing delta coastal areas corresponding to the satellite images used in this study were calculated by overlaying the coastal areas for all years.

3. FINDINGS

First, the shoreline length of each delta was calculated based on the satellite images examined in the study (Table 3 and Figure 4). Changes in shoreline length provide preliminary information about the geomorphological structure, process and dynamics of coastal movement. The findings show that the shoreline length has decreased over all periods only on the Zilan Delta (D1) coast, while variations have been observed on the other deltas. When the length values of the delta coastlines were examined linearly by year, the R2 values were calculated as 0.965 for D1, 0.5063 for D2, 0.6675 for D3, 0.2319 for D4, 0.02 for D5, and 0.0251 for D6 (Figure 4). The data obtained show that the lengths of all delta shorelines tend to decrease. The largest decrease was observed in the D1, D3 and D2 deltas, while the smallest decrease was observed in the D5 delta. The largest values between years were found to be between 1984-1994 and 2014-2024 (Table 3). The findings reveal that the deltas are undergoing geomorphological change processes, particularly in terms of linear and areal changes.

Table 3: Shoreline lengths and rates of change of deltas over the years

	Delta 1			***Delta 2***			***Delta 3***		
	Length (m)	Change (%)	Change Direction	Length (m)	Change (%)	Change Direction	Length (m)	Change (%)	Change Direction
1984	20,7672			1,8599			14,1064		
1994	17,0299	18	Decrease	2,0960	23,6	Increase	13,9567	1,1	Decrease
2004	16,2828	4,3	Decrease	1,9535	6,8	Decrease	15,9546	14,3	Increase
2014	12,1463	25,4	Decrease	1,6887	13,5	Decrease	8,9261	44	Decrease
2024	8,1664	32,78	Decrease	1,6414	2,9	Decrease	3,9476	55,8	Decrease

	Delta 4			***Delta 5***			***Delta 6***		
	Length (m)	Change (%)	Change Direction	Length (m)	Change (%)	Change Direction	Length (m)	Change (%)	Change Direction
1984	6,1254			15,9482			18,3469		
1994	8,4300	37,6	Increase	19,8615	24,5	Increase	23,9840	30,7	Increase
2004	5,9965	28,8	Decrease	19,0514	4,2	Decrease	23,2227	3,1	Decrease
2014	5,8733	2,1	Decrease	18,3320	3,77	Decrease	26,4965	14,1	Increase
2024	5,6739	3,4	Decrease	16,9393	7,6	Decrease	14,7132	44,4	Decrease

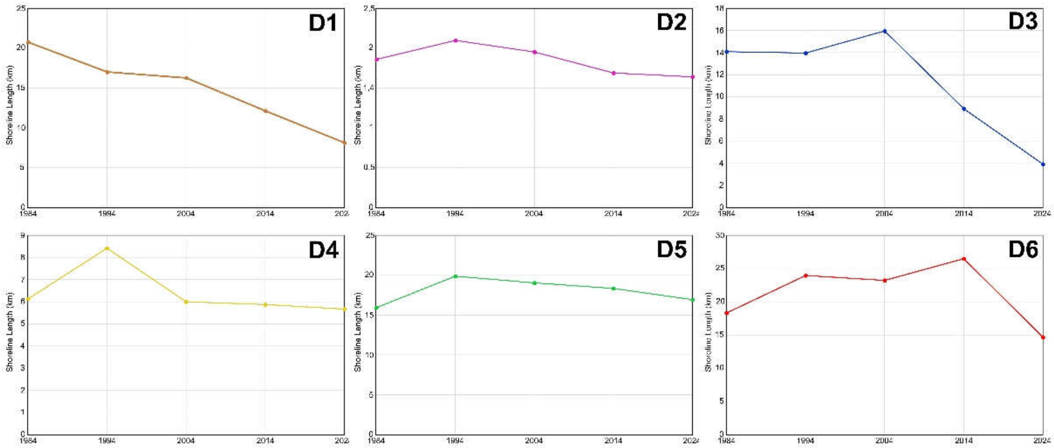

Figure 4: Shoreline lengths and changes over the years for the deltas studied

3.1. Shoreline Change Analyses Using Statistics from the DSAS Tool

In the study, each delta was analysed separately using statistics from the DSAS tool for long-term (1984-2024) and sequential periods, each containing five different coastlines (Tables 4 and 5). Since there were more than two shorelines in the long-term analyses, LRR analysis was used in addition to NSM, SCE, and EPR analyses, but only NSM, SCE, and EPR analyses were used in the sequential period analyses.

Table 4: Results of DSAS analysis of the studied delta shorelines in successive periods

	NSM			SCE			EPR		
DELTA 1	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
1984-1994	-737,72	-26,75	-1545,3	737,72	1543,3	26,75	-73,23	-2,66	-153,4
1994-2004	307,13	1542,15	-1235,47	337,52	1542,15	1,41	30,88	155,06	-124,23
2004-2014	343,12	1322,18	-212,55	361,01	1322,18	0,78	34,06	131,25	-21,1
2014-2024	745,28	1645	79,97	745,28	1645	79,97	74,93	165,41	8,04
DELTA 2	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
1984-1994	-38,89	-2,14	-168,16	38,89	168,16	2,14	-3,86	-0,21	-16,69
1994-2004	19,31	98,6	-29,99	25,54	98,6	0,02	1,94	9,91	-3,02
2004-2014	40,11	219,9	-25,47	45,04	219,9	1,84	3,98	21,83	-2,53
2014-2024	89,29	219,21	15,79	89,29	219,21	15,79	8,97	22,04	1,59
DELTA 3	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
1984-1994	-405,24	32,53	-1579,63	407,17	1579,63	4,58	-40,22	3,23	-156,8
1994-2004	130,34	1382,57	-214,8	158,4	1382,57	2,05	13,1	139,02	-21,6
2004-2014	92,99	717,77	-427,84	105,01	717,77	0,05	9,23	71,25	-42,47
2014-2024	431,09	1281,88	80,03	431,09	1281,88	80,03	43,34	128,89	8,05
DELTA 4	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
1984-1994	-300,78	26,65	-1148,16	301,71	1148,16	0,2	-29,85	2,65	-13,97
1994-2004	231,65	1007,82	-46,93	255,86	1007,82	0,14	23,29	101,34	-4,72
2004-2014	43,39	226,6	-17,77	44,37	226,6	0,3	4,3	22,49	-1,76
2014-2024	81,42	186,02	0,55	81,42	186,02	0,55	8,18	18,7	0,06
DELTA 5	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
1984-1994	-277,52	52,37	-638,49	278,03	638,49	5,38	-27,54	5,2	-63,38
1994-2004	93,73	492,13	-101,99	108,06	492,13	0,08	9,42	49,48	-10,26
2004-2014	40,55	396,99	-200,79	57,36	396,99	0,29	4,02	39,41	-19,93
2014-2024	118,66	447,49	-21,11	118,79	447,49	0,3	11,93	45	-2,12
DELTA 6	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
1984-1994	-599,45	24,25	-4000,34	600,46	4000,34	0,07	-59,5	2,41	-397,1
1994-2004	139,77	2530,91	-494,89	156,7	2530,91	0,08	14,05	254,48	-49,76
2004-2014	338,12	2519,63	-22,11	339,03	2519,63	0,23	33,56	250,11	-2,19
2014-2024	124,69	904,84	-18,5	124,87	904,84	0,77	12,53	90,98	-1,86

Table 5: Long-term (1984-2024) DSAS analysis results for the deltas studied

	NSM			*SCE*			*EPR*			*LRR*		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
D1	629,5	1687,1	-1297,4	1337,7	2394,8	17,44	15,44	42,14	-52,79	18,77	38,88	-52,65
D2	107,73	334,13	-23,46	150,5	449,02	16,87	2,68	8,35	-0,78	2,73	9,46	-0,43
D3	242,35	1186,3	-107,11	658,83	1758,65	41,64	6,03	29,63	-3,56	7,05	28,87	-2,9
D4	53,39	198,47	-32,37	366,72	1162,93	45,87	1,33	4,96	-0,81	3,78	12,38	-0,64
D5	-23,69	297,11	-300,9	293,11	638,49	7,63	-0,63	7,42	-11,11	0,86	7,04	-11,12
D6	4,86	257,2	-145,78	625,07	4000,34	10,13	0,12	6,42	-3,64	4,85	37,93	-3,12

When analyzing the Zilan Delta, i.e. D1 analyses, the average of the long-term (1984-2024) NSM data was calculated as 629.5 m, the maximum value as 1687.13 m, and the minimum value as -1297.46 m. According to the SCE analysis, the average is 1337.78 m and the maximum total shoreline change is calculated as 2384.81 m (Table 5 and Figure 5). The shoreline was calculated as 15.44 m/year on average in the EPR analysis based on 5 different values over a 40-year period, while the LRR analysis calculated it as 18.77 m/year on average. It was determined that, in the long term, there was a shoreline change of more than 500 m across the entire delta, except for the narrow areas on the eastern and western coasts. When examining the DSAS analyses of the Zilan Delta in successive periods, the NSM average was negative only in the 1984-1994 period, while it showed positive values in all other periods. In the NSM analysis, the average values were calculated as –737.72 m for the 1984–1994 period, 307.13 m for the 1994–2004 period, 343.12 m for the 2004–2014 period, and 745.28 m for the 2014–2024 period (Table 4). This shows that the delta shoreline receded significantly in 1994 and advanced with coastal accumulation in other periods. According to the SCE analysis, the maximum shoreline change in the Zilan River Delta (D1) was calculated to be over 1300 m in all consecutive periods. According to EPR analysis, the average annual coastline change was –73.23 m/y in 1984–1994, 30.88 m/y in 1994–2004, 34.06 m/y in the period 2004-2014, and 74.93 m/y in the period 2014-2024. The analysis data shows that the fastest shoreline change in D1 occurs annually, followed by a 10-year period.

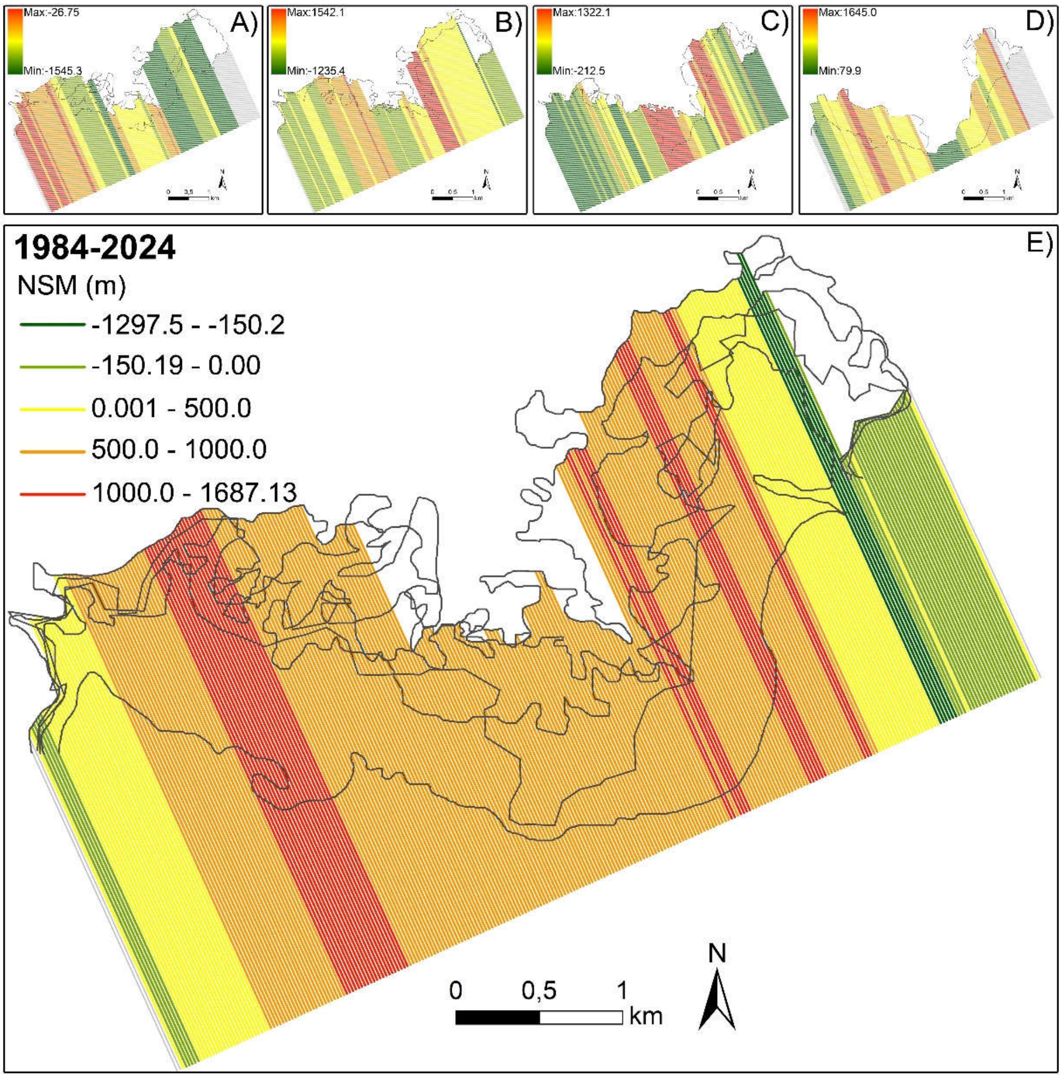

Figure 5: NSM analysis of the Zilan Stream Delta (D1) A) 1984-1994, B) 1994-2004, C) 2004-2014, D) 2014-2024 and E) 1984-2024

The long-term (1984-2024) NSM data average for the D2 delta formed by Deliçay is calculated as 107.13 m, with a maximum value of 334.13 m and a minimum value of -23.46 m (Table 5). During this period, the shoreline shifted an average of 150.5 m, 449.02 m, and a minimum of 16.87 m according to SCE. According to the EPR analysis, the average annual shoreline change was 2.68 m/y, while this value was calculated as 2.73 m/y according to the LRR analysis. The distribution of long-term DSAS analysis results reveals that linear changes have occurred, especially at the mouth of the Deliçay delta (Figure 6). When successive period DSAS analyses are examined, it is determined that intense shoreline retreat in the NSM data of the Deliçay delta occurred only in the 1984-1994 period. The average values of the NSM analysis were calculated as –38.89 m for the 1984–1994 period, 19.31 m for the 1994–2004 period, 40.11 m for the 2004–2014 period, and 89.29 m for the 2014–2024 period. According to the SCE analysis, the maximum shoreline change in the 1984-1994 period was 168.16 m, the maximum value in 1994-2004 was 98.6 m, in 2004-2014 it was 219.9 m, and in the 2014-2024 period it was 219.21 m (Table 4). According to EPR analysis average data, the annual coastline change was -3.86 m/y between 1984 and 1994, 1.94 m/y between 1994 and 2004 was 1.94 m/y, between 2004 and 2014 it was 3.98 m/y, and between 2014 and 2024 it was 8.97 m/y (Table 4). This shows that the shoreline first receded during the periods studied, then advanced at a relatively slower rate, and has been advancing more rapidly over the last 10 years.

The long-term (1984-2024) NSM analysis average of the D3 delta formed by the Bendimahi River was determined to be 242.45 m, with a maximum value of 1186.3 m and a minimum value of -107.11 m (Table 5). During the period 1984-2024, the SCE analysis of the D3 delta shoreline showed an average displacement of 658.83 m, a maximum displacement of 1758.65 m, and a minimum displacement of 41.64 m. During this period, the annual shoreline change was calculated as 6.03 m/y according to the EPR analysis and 7.05 m according to the LRR analysis. It was determined that the shoreline locations with the highest values in terms of distance in the delta were particularly at the mouths of rivers discharging from several branches in the north and south (Figure 7). When successive periods were examined, the average values calculated using NSM analysis were –405.24 m for the 1984–1994 period, 130.34 m for the 1994–2004 period, 92.99 m for the 2004–2014 period, and 431.01 m for the 2014–2024 period. According to the SCE analysis, the maximum shoreline change in the 1984-1994 period was 1579.63 m, the maximum value in 1994-2004 was 1382.57 m, 717.77 m between 2004 and 2014, and 1,281.88 m between 2014 and 2024 (Table 4). According to the average data of the EPR analysis, the annual shoreline change was -40.22 m/y between 1984-1994, 13.1 m/y between 1994-2004 was 13.1 m/y, between 2004 and 2014 it was 9.23 m/y, and between 2014 and 2024 it was calculated to be 43.34 m/y. Statistical analysis data from the DSAS tool shows that the Bendimahi River Delta (D3) experienced intense coastline retreat between 1984 and 1994, followed by coastline advance at a certain annual rate in subsequent periods, and rapid coastline advance in the most recent period between 2014 and 2024.

According to the NSM analysis, the long-term coastline of the D4 delta formed by the Karasu River between 1984 and 2024 showed an average change of 53.39 m, a maximum change of 198.47 m, and a minimum change of -32.37 m (Table 5). According to the SCE analysis, the shoreline has shifted an average of 366.72 m, a maximum of 1162.93 m, and a minimum of 45.87 m. During this period, the shoreline has changed an average of 1.33 m per year according to the EPR analysis and 3.78 m per year according to the LRR analysis. In the long term, it was determined that there was coastal retreat in the western part of the Karasu Delta and coastal advance with maximum changes in the eastern part (Figure 8). When the sequential period analysis of the D4 delta shoreline was examined, it was determined that the shoreline changed by an average of –300.78 m in the 1984-1994 period, 231.65 m during the 1994-2004 period, 43.39 m during the 2004-2014 period, and 81.42 m during the 2014-2024 period. According to the SCE analysis, the maximum shoreline change in the 1984-1994 period was 1148.16 m, the maximum value in 1994-2004 was

1007.82 m, 226.6 m in 2004-2014, and 186.02 m in the 2014-2024 period. According to the average data of the EPR analysis, the annual shoreline change was -29.85 m/y between 1984-1994, 23.29 m/y between 1994-2004 was 23.29 m/y, between 2004 and 2014 it was 4.3 m/y, and between 2014 and 2024 it was calculated to be 8.18 m/y (Table 4). DSAS analysis data revealed that the D4 delta experienced significant coastal retreat in terms of distance between 1984 and 1994, particularly at the mouth of the river, followed by coastal advance and a decrease in the rate of coastal change in recent years.

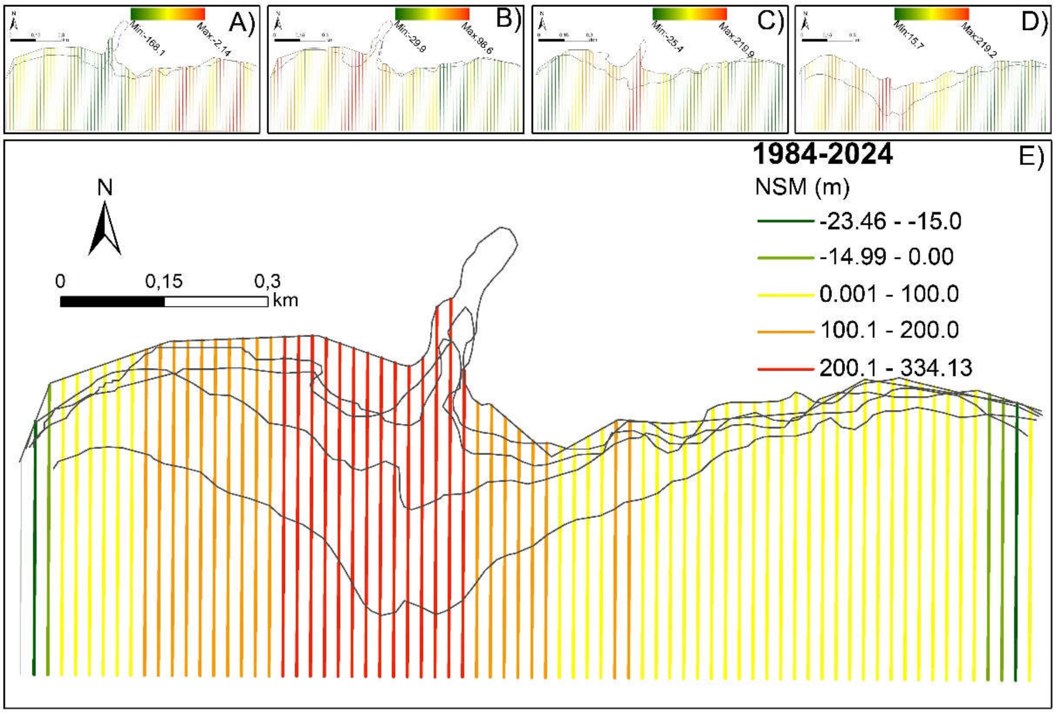

Figure 6: NSM analysis of the Deliçay Stream Delta (D2) A) 1984-1994, B) 1994-2004, C) 2004-2014, D) 2014-2024 and E) 1984-2024

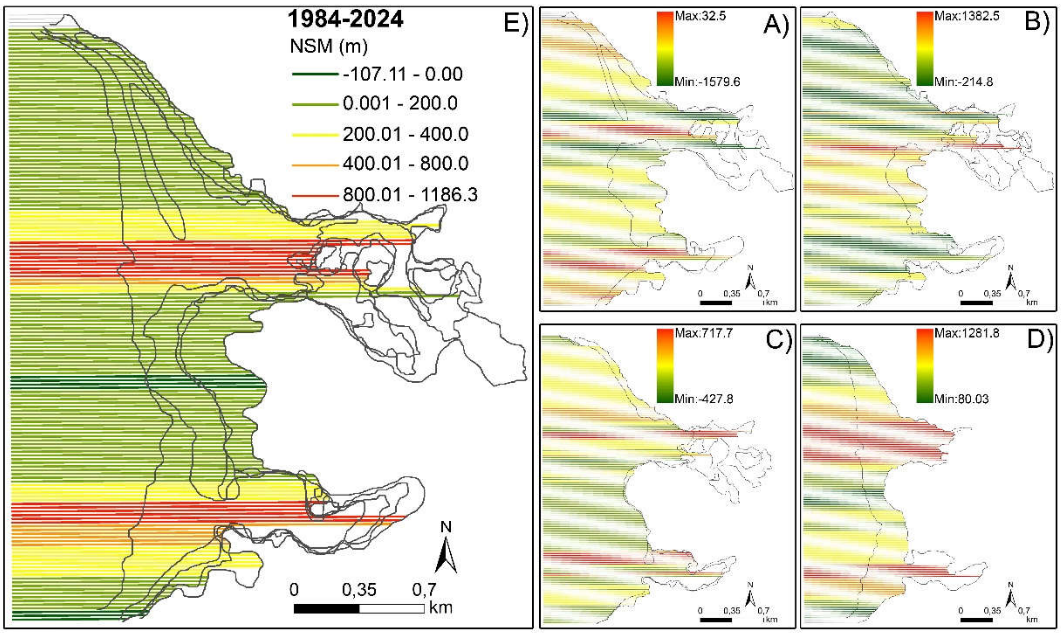

Figure 7: NSM analysis of the Bendimahi Stream Delta (D3) A) 1984-1994, B) 1994-2004, C) 2004-2014, D) 2014-2024 and E) 1984-2024

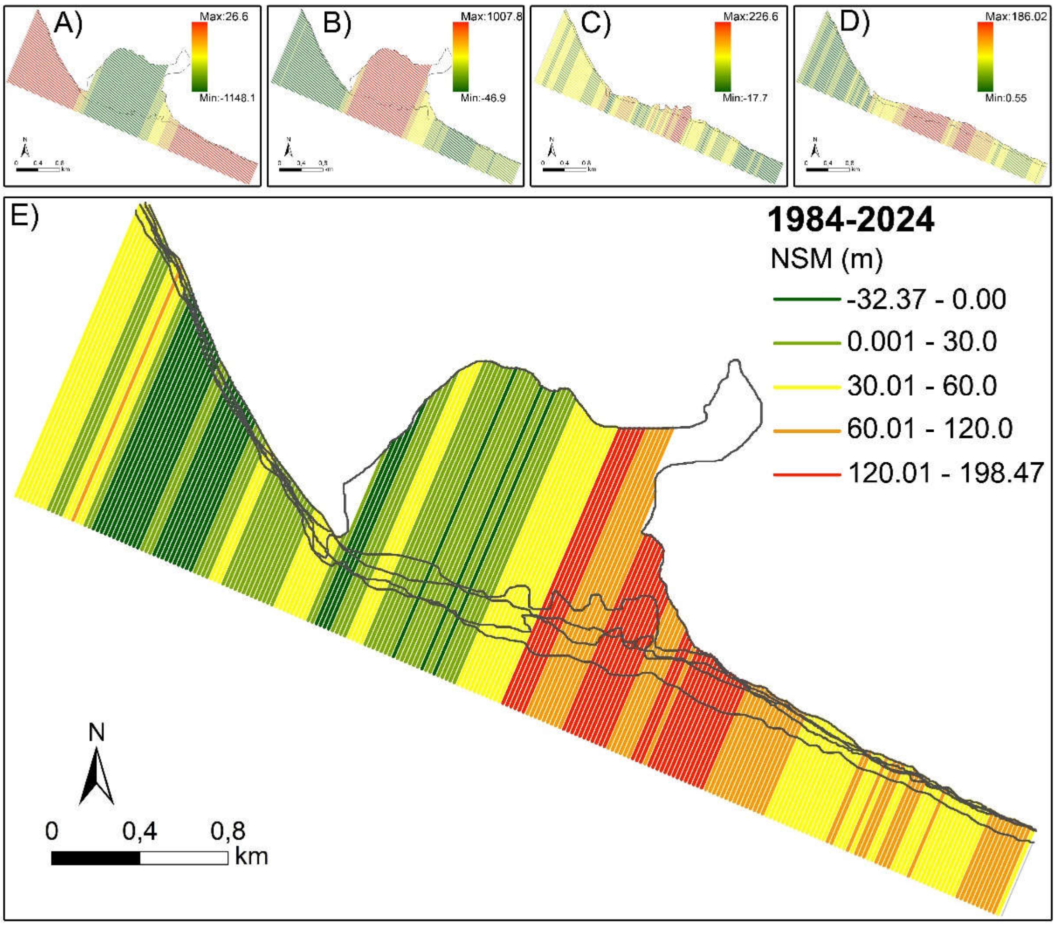

Figure 8: NSM analysis of the Karasu Stream Delta (D4) A) 1984-1994, B) 1994-2004, C) 2004-2014, D) 2014-2024 and E) 1984-2024

According to the NSM analysis, the long-term (1984-2024) coastline change of the D5 delta, located immediately east of the provincial centre of Van and formed by multiple short rivers compared to other deltas in the study area, was found to be an average of -23.69 m, with a maximum of 297.11 m and a minimum of -300.9 m (Table 5). In the long-term SCE analysis, the shoreline shifted a maximum of 638.49 m. It was determined that the shoreline changed by an annual average of -0.63 m/year according to the EPR analysis and 0.86 m/year according to the LRR analysis during the 1984-2024 period. During this period, complex processes were observed, with general shoreline retreat north of the pier on the coast and both coastal advance and retreat south of the pier (Figure 9). When successive periods are examined in terms of the D5 delta, the shoreline changed on average by -277.52 m in the 1984-1994 period, 93.73 m in the 1994-2004 period, 40.55 m during the 2004-2014 period, and 118.66 m during the 2014-2024 period. According to the SCE analysis, the maximum shoreline change in the 1984-1994 period was 638.49 m, the maximum value in 1994-2004 was 492.13 m, 396.99 m in 2004-2014, and 447.49 m in the 2014-2024 period (Table 4). According to the average data of the EPR analysis, the annual shoreline change was -27.24 m/y between 1984-1994, 9.42 m/y between 1994-2004 , 4.02 m/y between 2004 and 2014, and 11.93 m/y between 2014 and 2024. It was determined that the maximum and minimum locations of shoreline change differed for each period in successive periods.

The long-term (1984-2024) coastline change of the D6 delta formed by Engil Dere was determined to be an average of -4.86 m, a maximum of 257.2 m, and a minimum of -145.78 m according to the NSM analysis (Table 5). According to the SCE analysis, the shoreline changed by an average of 625.07 m, a maximum of 4000.34 m, and a minimum of 10.13 m during this period. The annual average change in the shoreline was determined to be 0.12 m/y according to the EPR analysis results and 4.85 m/y according to the LRR analysis. It was determined that large changes occurred at the mouth of the delta, while very few changes occurred on the coast bordered by the fault line to the north, which is not within the actual scope of the delta (Figure 10). In particular, the wetland structure of the delta shows that large changes in the shoreline occurred from the mouth towards the south. When DSAS analyses of the D6 delta are examined in terms of successive periods, the average shoreline change according to NSM was -599.45 m in the period 1984-1994, 139.77 m in the period 1994-2004, 338.12 m during the 2004-2014 period, and 124.69 m during the 2014-2024 period. According to the SCE analysis, the maximum shoreline change in the 1984-1994 period was 400.34 m, the maximum value in 1994-2004 was 2530.91 m, 2519.63 m in 2004-2014, and 904.84 m in the 2014-2024 period. According to the average data of the EPR analysis, the annual shoreline change was -59.5 m/y between 1984 and 1994, 14.05 m/y between 1994 and 2004 was 14.05 m/y, between 2004 and 2014 it was 33.56 m/y, and between 2014 and 2024 it was 12.53 m/y (Table 4). It was determined that the shoreline receded by 4000 m between 1984 and 1994 at the mouth of the delta, and then advanced with the coastal accumulation of the delta.

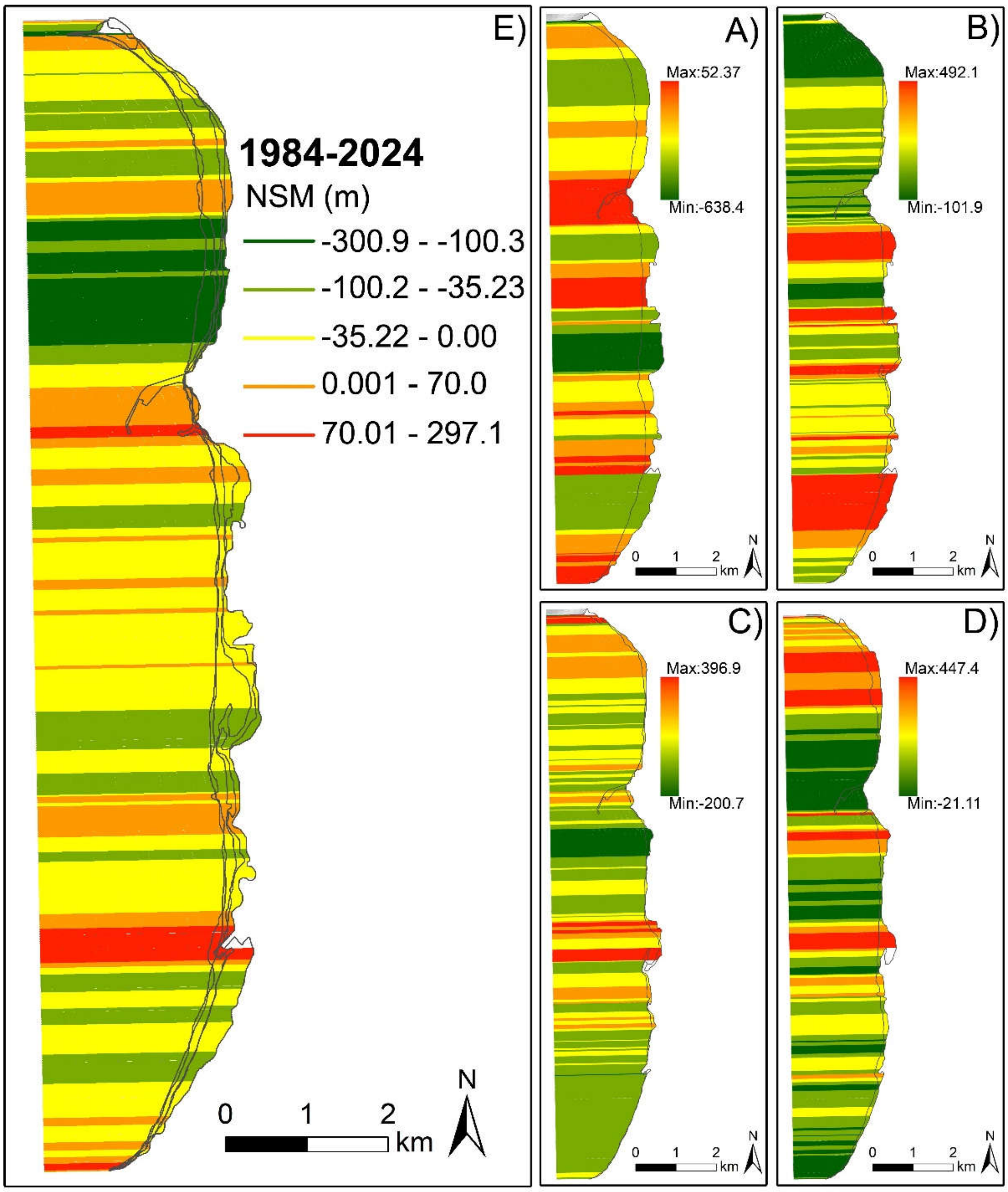

Figure 9: NSM analysis of the Van Delta (D5) A) 1984-1994, B) 1994-2004, C) 2004-2014, D) 2014-2024 and E) 1984-2024

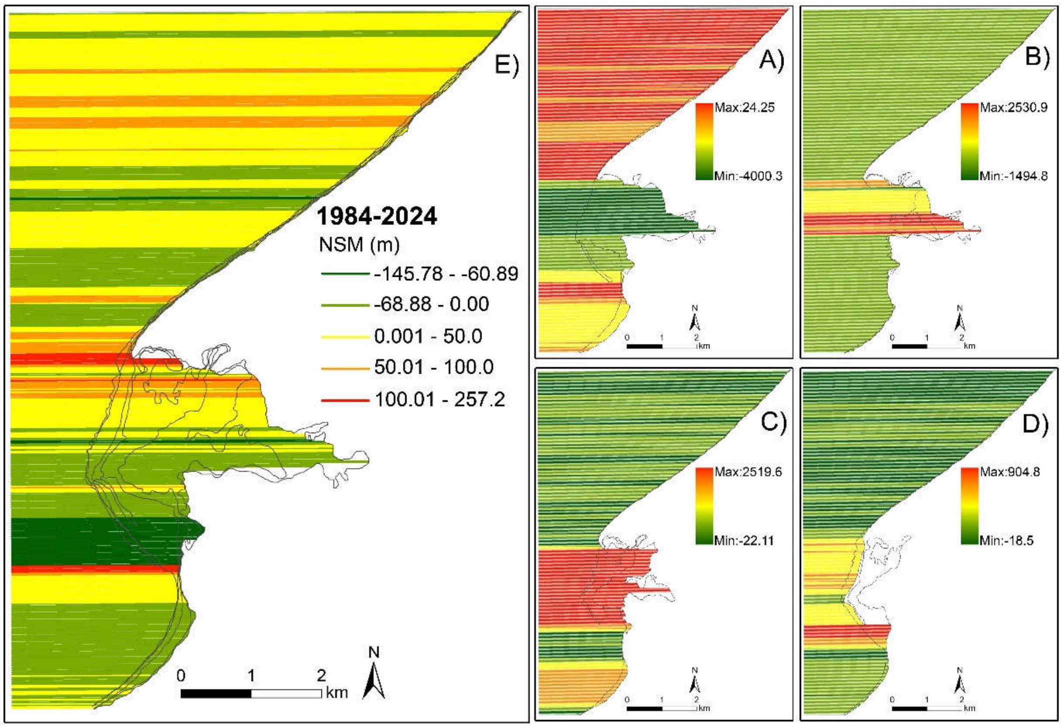

Figure 10: NSM analysis of the Engil River Delta (D6) A) 1984-1994, B) 1994-2004, C) 2004-2014, D) 2014-2024 and E) 1984-2024

3.2. Coastal Change Sensitivity

Long-term (1984-20204) change data from the delta coasts east of Lake Van also reveal morphological processes involving changes of varying magnitude in certain areas of the coast. This highlights the need to identify the areas of the delta coast where change is most sensitive. By adapting the classifications from previous studies to the research area, the extent of change in the delta coastlines was examined in terms of LRR analysis and categorised into seven different classes (Figure 11).

According to the findings, the general trend and intensity of coastal change sensitivity is in the form of coastal accumulation. When the number of high accumulations transects containing the highest values of coastal change sensitivity was analysed for each delta, the total number of transects was 81.8% for D1 delta, 20.2% for D2, 41.2% in D3, 29.5% in D4, 1.5% in D5, and 24.2% in D6 (Figure 11). It was found that the sensitivity to coastal change in D1, D3, D4, and D6 deltas, which constitute the main drainage sources of Lake Van, is high. In areas with high sensitivity to coastal change, it was found that this sensitivity is present in almost all deltas, particularly at the river mouth and on both sides of the delta lobes.

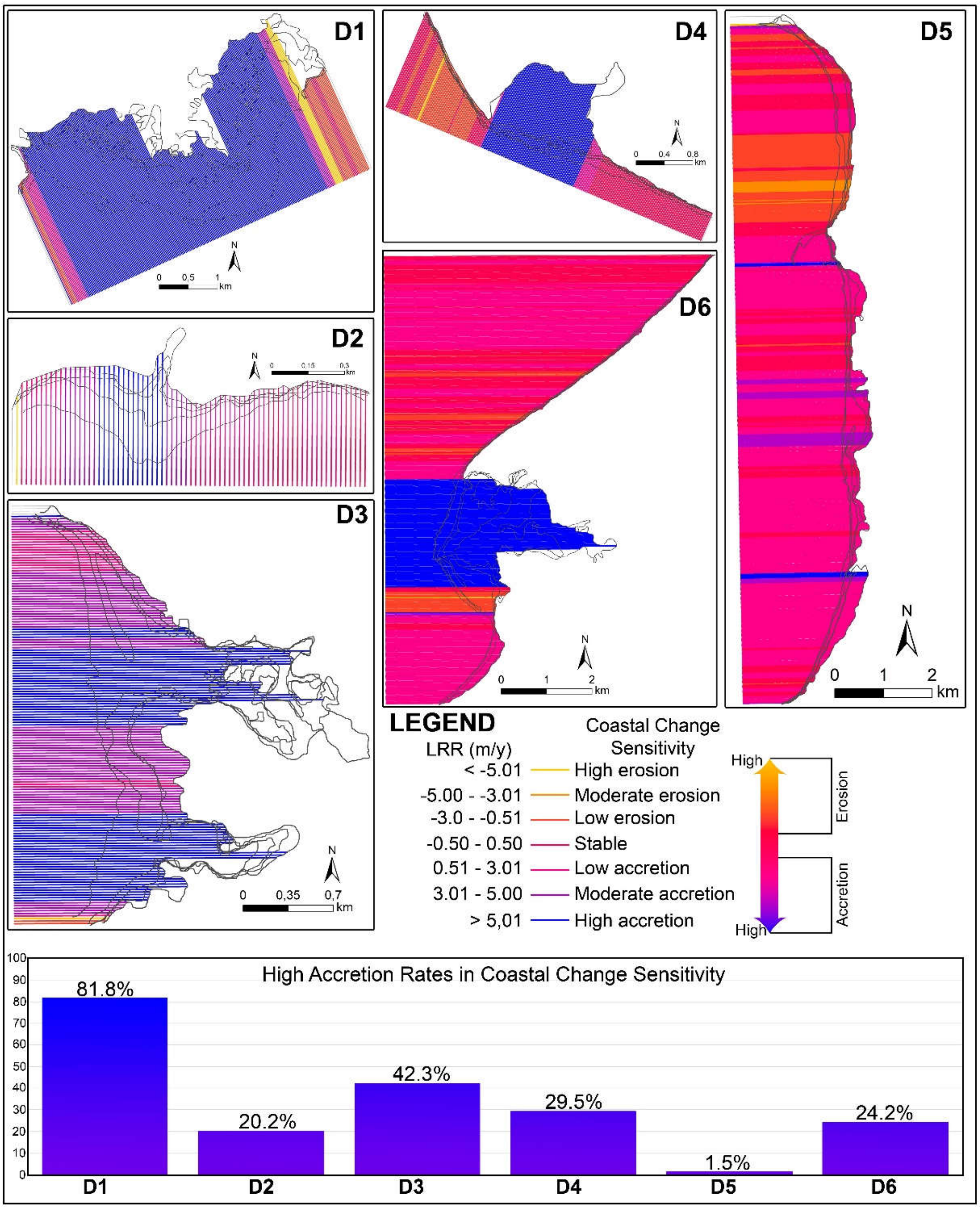

Figure 11: Coastal change sensitivity and proportional graphs of deltas studied east of Lake Van

3.3. Spatial-Area Changes in Delta Coasts

Linear changes occurring in the deltas east of Lake Van cause both landward and seaward spatial changes (Figures 12 and 13). This causes coastal erosion and coastal accumulation on the delta coasts to vary in spatial values both in the long term (1984-2024) and in successive periods. All these spatial changes alter both the delta morphology and coastal geomorphology, as well as causing changes in the lake's surface water area. When the total value of spatial coastal changes occurring in all periods is examined, the greatest change belongs to the D1 delta, with an area of 8.7 km². Following this delta in terms of spatial size are, in order, the D6 (6.72 km²), D5 (4.22 km²), D3 (2.73 km²), D4 (1.91 km²), and D2 (0.23 km²) deltas (Figure 12A).

The total areas of change caused by coastal erosion and coastal accumulation in each successive period in the deltas east of Lake Van also show differences. According to the findings obtained from the analyses, the greatest spatial change in the D1 delta occurred between 2014 and 2024 and between 1984 and 1994, in the D2 delta between 2014 and 2024, in the D3 delta between 2014 and 2024, in D4 between 1984 and 1994, in the D5 delta during the 1984-1994 period, and in the D6 delta during the 1984-1994 period (Figure 12B). Based on the 40-year change data between 1984 and 2024, the D1 delta experienced a change of 4.78 km², the D2 delta experienced a change of 0.16 km², 1.43 km² in D3, 0.27 km² in D4, 0.62 km² in D5, and 1.05 km² in D6. The data reveal that the morphological appearance of the delta coasts exhibits significant variability both over the long term and across consecutive periods.

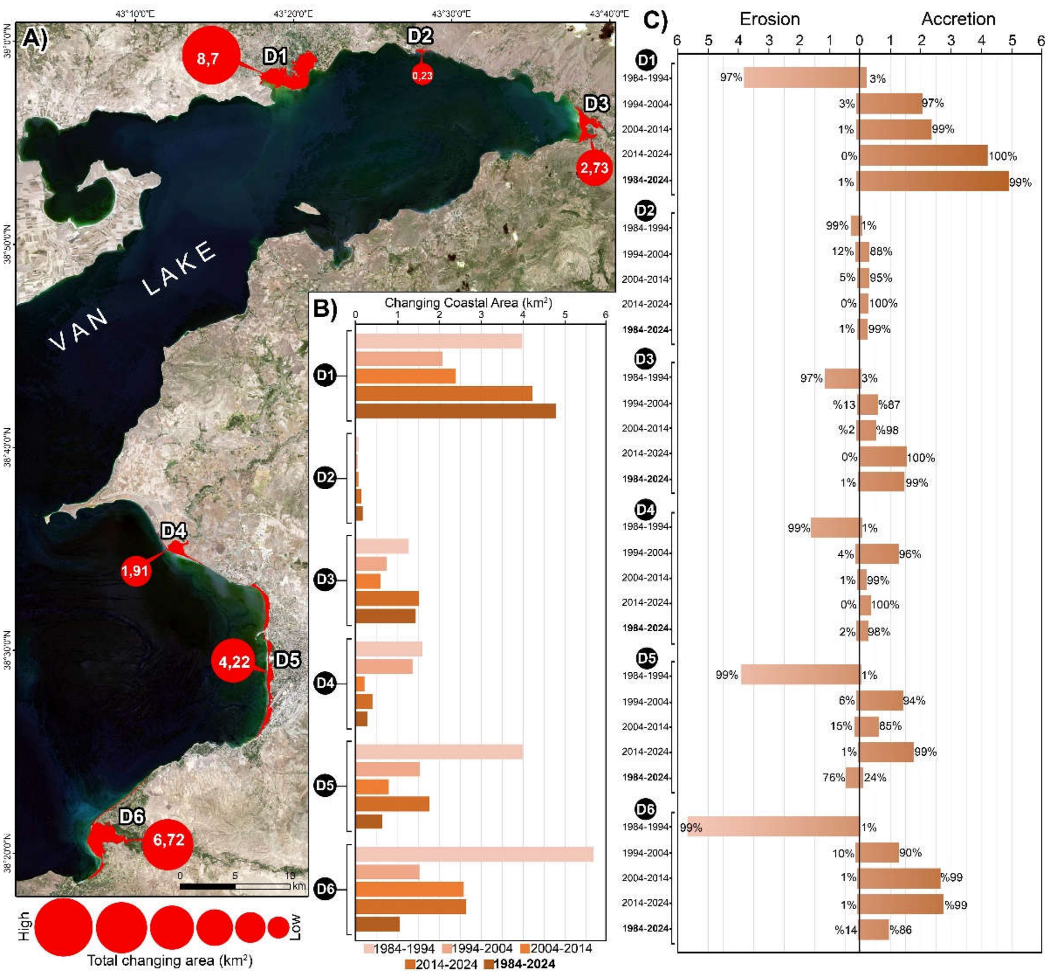

Figure 12: A) Total change in coastal areas of the studied deltas throughout all periods, B) Coastal areas that changed within the periods, C) Seasonal coastal erosion and coastal accumulation amounts of delta coasts

The long-term and sequential changes in coastal erosion and coastal accumulation for each delta were also evaluated quantitatively. Long-term analysis findings revealed that coastal deposition occurred at a rate of 84%–99% in deltas D1, D2, D3, D4, and D6, while coastal erosion occurred at a rate of 76% in delta D5 (Figure 12C). However, different quantitative values were also observed in successive periods in the deltas. Between 1984 and 1994, coastal erosion was observed in all deltas at a rate of 97% to 99%, while between 1994 and 2004, coastal accumulation was observed at a rate of 87% to 97%. In the 2004-2014 and 2014-2024 periods, it was also determined that the change pattern in all deltas was coastal deposition in terms of area.

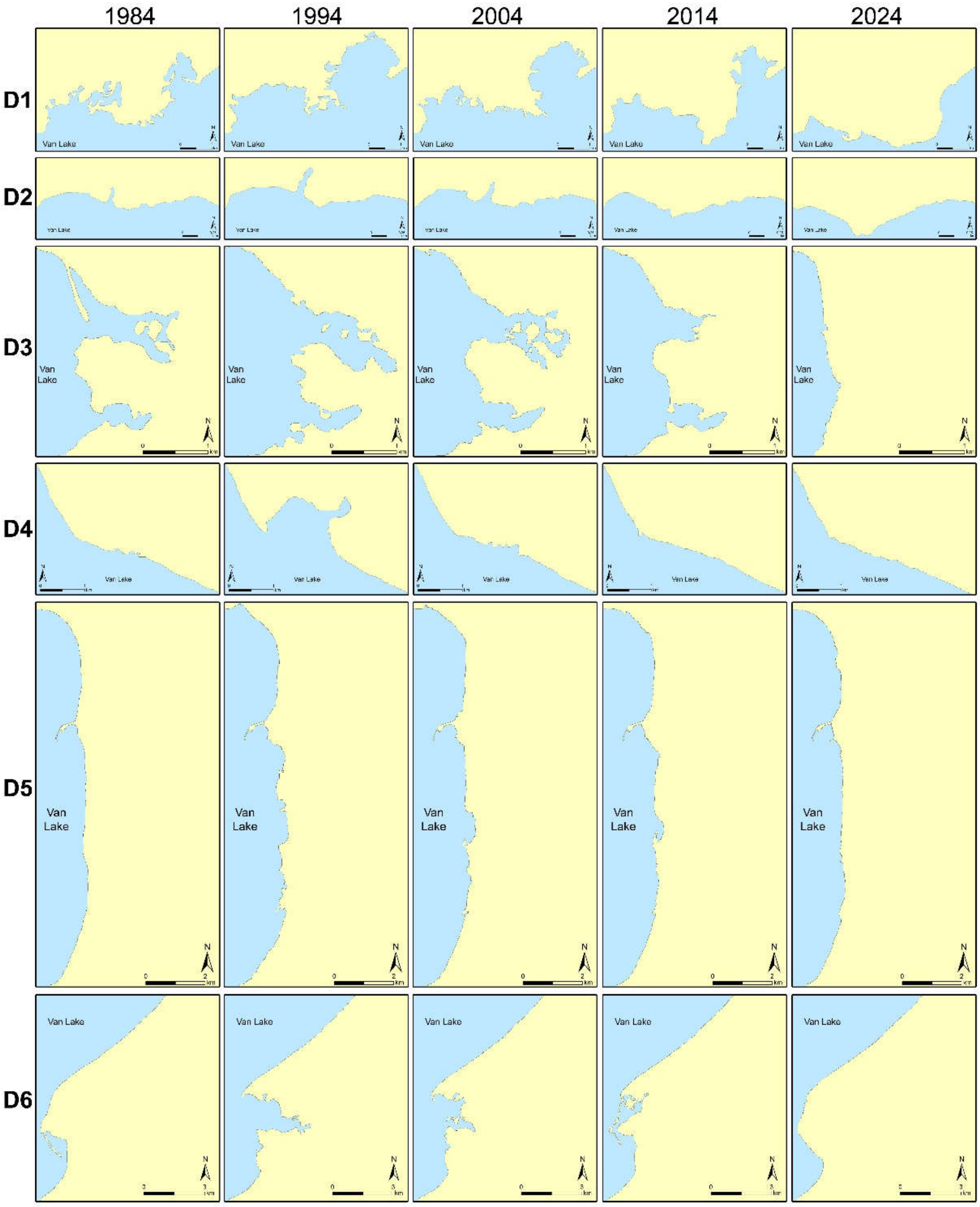

Figure 13: Temporal change of delta coasts east of Lake Van

4. DISCUSSION

It has been determined that the general coastal change trend in deltas around the world and along the Turkish coastline is in the form of coastal erosion (Kuleli et al., 2011; Nienhuis et al., 2020; Akdeniz & İnam, 2023; Tağıl et al., 2023). In particular, the siltation process caused by dams constructed in the lower reaches of rivers that transport material to delta coasts with a geomorphological formation dominated by rivers leads to rapid changes in delta coasts (Öztürk & Sesli, 2015; Kale, 2019; Özpolat & Demir, 2019; Bombino et al., 2022; Wu et al., 2022; Kılar, 2023). Different types of changes are also occurring on lake shores that have an andoreic basin feature and a narrower drainage area compared to Turkish coasts (Hoşgören, 1994; Altan Aydın & Doğu, 2018; Dereli & Tercan, 2020; Ataol & Onmuş, 2021; Gümüş et al., 2022; Alevkayalı et al., 2023; Uzun, 2024a). The main reason for these changes is the decrease in water levels in lakes, especially in regions with continental climatic conditions (Aydın et al., 2020). In addition, agricultural and other irrigation-related uses of lakes and their surroundings have caused a decrease in water levels, a reduction in surface area, and changes in lake shores in many lakes in Turkey (Duru, 2017; Dinç, 2023; Uzun, 2024b; Yayla et al., 2025). However, previous studies have not focused much on the changes in deltas along lake shores (Uzun 2024b). In this study, the long-term changes over 40 years and sequential changes over 10 years in six different deltas on the eastern shore of Lake Van were identified using CBS and UA techniques and evaluated using different statistics. While there are various studies on Lake Van, the research indicates that the lake level has decreased, particularly over the past 20 years (Kuzucuoğlu et al., 2010; Aydın & Karakuş, 2016; Altan Aydın & Doğu, 2018; Akköprü et al., 2019; Üner, 2022). This situation affects the Zilan, Bendimahi, Karasu, and Engil deltas, which are among the most ecologically sensitive areas with wetland characteristics.

In this study, five different coastlines were taken as a basis for the long term, and linear changes were analysed using the DSAS tool. In the long-term (1984-2024) investigations, according to the average result of the NSM analysis, a change of 629.5 m was found in D1, 107.73 m in D2, 242.35 m in D3, 53.39 m in D4, -23.69 m in D5, and 4.86 m in D6. The average magnitude of change in the Zilan (D1) and Bendimahi (D3) deltas is particularly high. The anthropogenic limitation of the D5 delta's feeding conditions has caused the change to occur in a different direction and magnitude compared to other deltas. Some studies have linked the formation origin and extent of change in deltas to various factors (Üner, 2022). In this study, the long-term results of the DSAS indicate that, except for the D5 delta, the other deltas continue to undergo morphological shaping and change dominated by rivers. Additionally, it reveals that changes in delta coasts are influenced not only by wave effects but also by changes in lake levels and hydrology, annual climate conditions, and anthropogenic impacts (Kuzucuoğlu et al., 2010; Aydın & Karakuş, 2016; Altan Aydın & Doğu, 2018; Akköprü et al., 2019; Üner, 2022). In this regard, the study examined changes in delta coasts over successive periods.

The average NSM value for all delta coasts examined between 1984 and 1994 was negative (-37 m to -737 m), indicating coastal retreat. In the following period, between 1994 and 2004, coastal advance was observed in all deltas (values ranging from 19 m to 307 m). The changes in the deltas between 1984 and 1994 are explained in Üner's (2022) study, particularly in relation to the siltation caused by the dams built on the Zilan, Bendimahi, Karasu and Engil deltas, which provide the main river supply to the lake (Üner, 2022). The study by Kuzuoğlu et al. (2010) and especially the study by Akköprü et al. (2019) on the Engil delta indicate that the Van Lake basin received its maximum rainfall in the last 50 years in 1993, and that the lake level rose to its maximum in 1993, 1994, 1995, and 1996, and that some anthropogenic activities and structures along the shores were damaged (Kuzucuoğlu et al., 2010; Akköprü et al., 2019). The findings of this study reveal that the changes between 1984-1994 and 1994-2004 were not caused by a single factor. The primary cause of shoreline retreat in the deltas was the rise in lake level as a result of the Van Lake basin receiving its maximum rainfall in 1993 and this potential being added to the hydrological budget over several years (the duration of water seeping underground in the hydrological cycle). The situation described in this study is explained by the fact that the D5 delta, which is less variable, is also subject to coastal erosion. On the other hand, anthropogenic structures such as the Koçköprü Dam (1992) on the Zilan River, the Sarıahmet Dam (1991) on the Karasu Creek, and the Zernek Dam (1988) on the Engil River reduce material transport to the coast and increase siltation, which is another reason for the change in the deltas (Üner, 2022). For this reason, the linear dimensions of the changes in the specified deltas are greater in terms of distance. NSM and EPR analysis data in the deltas have revealed a permanent shoreline advance (from land to sea) over the last 30 years. Notably, the Morgedik Dam, constructed on the Deliçay River and operational since 2015, has not caused sedimentation along the delta coastline. This suggests that changes in lake surface area and water level play a more significant role in delta changes.

According to SCE analysis, the coastline along the delta has undergone significant changes both over the 40-year period and in successive 10-year periods. Between 1984 and 2024, the coastline in the deltas, according to the SCE maximum data, was 2394.8 m in D1, 449.02 m in D2, 1,758.65 m in D3, 1,162.93 m in D4, 638.49 m in D5, and 4,000.34 m in D6. The obtained values indicate that the morphological structure of the deltas has changed significantly. Therefore, a coastal change sensitivity analysis was conducted using long-term LRR data in this study. The narrow drainage basin of the D5 delta compared to other deltas and the direct anthropogenic impact on the coastline resulted in a high sensitivity level of only 1.5% in this delta. In the Zilan delta, the coastal change sensitivity ratio is 81.8%. In the D2, D3, D4, and D6 deltas, the sensitivity ratio for coastal accumulation is also very high, exceeding 20%. This situation reveals that the deltas east of Lake Van, which harbour wetland structures and ecological environments, are highly sensitive to change, and that this sensitivity has manifested itself as very high levels of coastal accumulation based on 40 years of data.

Spatial changes occurring in delta coasts with dynamic characteristics affect both the structure of the delta and the surface area of Lake Van. According to the findings, the Zilan Delta has the largest total change (8.7 km2). In terms of successive periods, coastal erosion occurred in all delta coasts between 1984 and 1994 (between 97% and 99%). However, in all successive periods covering the last 30 years, it was determined that there was a significant amount of coastal accumulation. The findings reveal that the surface area of Lake Van has shrunk and that the delta coasts have advanced and accumulated. In terms of morphological appearance, it has been determined that the D1, D2, D4 and D6 deltas protrude towards the water body with a river-dominated appearance. In the Bendimahi delta (D3), it has been determined that coastal accumulation has filled the shallow areas in particular and that the delta does not protrude as of 2024 due to its location in a bay. In the D5 delta, geomorphological factors, particularly anthropogenic coastal engineering, have resulted in a more linear morphological appearance.

5. CONCLUSION

This study examines linear and areal coastal changes that occurred in six different delta areas (Zilan, Deliçay, Bendimahi, Karasu, Van, and Engil deltas) in the eastern part of Lake Van using Geographic Information Systems (GIS), Remote Sensing (RS) techniques and DSAS analysis tools. The findings of the study reveal that significant linear and areal changes have occurred in the morphological structures of the delta coasts east of Lake Van. These changes have also brought about geomorphological, hydrographic and ecological changes in the delta areas and their immediate surroundings.

According to the results of the DSAS analysis in the study, shoreline change in the majority of the deltas is accretive, with the Zilan (D1), Bendimahi (D3), and Engil (D6) deltas exhibiting particularly high rates of change. This is related to the large drainage basins of these deltas and the significant impact of river-based sediment transport. The siltation effect of dams constructed on the streams feeding these deltas is another reason for this change. In contrast, shoreline regression and morphological instability were observed to be more pronounced in the Van Delta (D5), which has a more limited drainage area and is subject to anthropogenic interventions (coastal regulations, landfills). LRR analyses conducted within the scope of the study indicate that the sensitivity to coastal change is particularly high in the D1, D3, and D6 deltas. It was concluded that sensitivity is particularly high in these deltas at the river mouth, that the delta structure has changed geomorphologically, and that its ecological sensitivity has increased to a high level. In this context, it should be emphasized that coastal changes may lead to not only geomorphological but also ecological consequences. Another conclusion drawn from this study's findings is that the linear changes observed along the delta coasts are shaped by fluctuations in lake level, variations in annual precipitation and evaporation rates, siltation processes resulting from dam construction, and anthropogenic activities. Areal change analyses revealed that the Zilan Delta, with a total change area of 8.7 km², is the delta with the most dynamic morphological structure, followed by the Engil, Van, and Bendimahi deltas. While all deltas were generally subject to coastal erosion, particularly between 1984 and 1994, an increase in the tendency toward coastal deposition was observed in subsequent periods. These findings indicate that delta formation processes are actively continuing alongside the gradual shrinkage of Lake Van's surface area.

In conclusion, this study reveals the dynamic nature of the delta systems along the eastern shores of Lake Van and demonstrates that changes in shoreline and delta morphology are important factors to consider for future environmental planning and wetland management strategies. It is suggested that the high sensitivity of delta areas, in particular, is critical to the sustainability of ecosystems in the region and that these areas require both scientific and management monitoring.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Ethics and Consent to Participate declarations

The authors state that ethical and participation permission statements are not required for this study.

References

1. Acharya, T. D., Subedi, A., Yang, I. T., & Lee, D. H. (2017). Combining water indices for water and background threshold in Landsat image. Multidisciplinary Digital Publishing Institute Proceedings, 2(3), 143. https://doi.org/10.3390/ecsa-4-04902.
2. Acheampong, E., Lafreniere, D., Williams, R., & Meadows, G. (2025). Improving geospatial coastal vulnerability indices for the Great Lakes. Journal of Great Lakes Research, 51(4), 102544. https://doi.org/10.1016/j.jglr.2025.102544
3. Akbaş, A. (2024). Human or climate? Differentiating the anthropogenic and climatic drivers of lake storage changes on spatial perspective via remote sensing data, Science of the Total Environment. 912. Makale 168982. https://doi.org/10.1016/j.scitotenv.2023.168982
4. Akdeniz, H.B., & İnam, Ş. (2023). Spatio-temporal analysis of shoreline changes and future forecasting: the case of Küçük Menderes Delta, Türkiye. J Coast Conserv 27, 34. https://doi.org/10.1007/s11852-023-00966-8
5. Akköprü, E., Aydin, F. A., Doğu A. F. (2019). The effect of Van Lake level changes on the geomorphology of the Delta Stream and its relationshipwith the Dilkaya Mound. Turkish Geographical Review, (72), 45-51. https://doi.org/10.17211/tcd.536643
6. Alevkayalı, Ç., Atayeter, Y., Yayla, O, Bilgin, T. & Akpınar, H. (2023). Long-term coastline changes and climate relationship in Burdur Lake: Spatio-temporal trends and forecasts. Turkish Geographical Review, 82, 37-50. https://doi.org/10.17211/tcd.1287976
7. Aydin, FA, & Dogu, AF (2018). Level changes in lakes and their causes: Van Lake example. Journal of Yuzuncu Yil University Social Sciences Institute, (41),183-208.
8. Ataol, M., Kale, M.M., Tekkanat, İ.S. (2019). Assessment of the changes in shoreline using digital shoreline analysis system: a case study of Kızılırmak Delta in northern Turkey from 1951 to 2017. Environ Earth Sci 78, 579. https://doi.org/10.1007/s12665-019-8591-7,
9. Ataol, M. & Onmuş, O. (2021). Wetland loss in Turkey over a hundred years: implications for conservation and management. Ecosystem Health and Sustainability, 7(1), 1-13. https://dx.doi.org/10.1080/20964129.2021.1930587
10. Aydin, H., Karakuş, H. (2016). Estimation of evaporation for Lake Van. Environ Earth Sci 75, 1275. https://doi.org/10.1007/s12665-016-6077-4

11. Aydın, F., Erlat, E. & Türkeş, M. (2020). Impact of climate variability on the surface of Lake Tuz (Turkey), 1985–2016. Reg Environ Change, 20, 68. https://doi.org/10.1007/s10113-020-01656-z
12. Baig, M. H. A. Zhang, L. Shuai, T. Tong, Q. (2020). Derivation of a tasselled cap transformation based on Landsat 8 at satellite reflectance. Remote Sensing Letters, 11(1), 66–75. https://doi.org/10.1080/2150704X.2020.1714329
13. Baral, R., Pradhan, S., Samal, R. N., Mishra, S. K. (2018). Shoreline change analysis at Chilika Lagoon Coast, India using digital shoreline analysis system. Journal of the Indian Society of Remote Sensing, 46 (10), 1637–1644. https://doi.org/10.1007/s12524-018-0818-7
14. Bird, E. (2008). Coastal geomorphology: An introduction Second edition. John Wiley ve Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England.
15. Bombino, G., Barbaro, G., D'Agostino, D., Denisi, P., Foti, G., Labate, A., Zimbone, S. M. (2022). Shoreline change and coastal erosion: the role of check dams. first ındications from a case study in Calabria, Southern Italy, CATENA, 217. https://doi.org/10.1016/j.catena.2022.106494
16. Burningham H, & French J (2017). Understanding coastal change using shoreline trend analysis supported by cluster-based segmentation. Geomorphology 282:131–149 https://doi.org/10.1016/j.geomorph.2016.12.029
17. Busker, T., de Roo, A., Gelati, E., Schwatke, C., Adamovic, M., Bisselink, B., Pekel, J. F., & Cottam, A. (2019). A global lake and reservoir volume analysis using a surface water dataset and satellite altimetry. Hydrology and Earth System Sciences, 23(2), 669–690. https://doi.org/10.5194/hess-23-669-2019
18. Ciritci, D., & Türk, T. (2020). Analysis of coastal changes using remote sensing and geographical information systems in the Gulf of Izmit, Turkey. Environ Monit Assess 192, 341-360. https://doi.org/10.1007/s10661-020-08255-9
19. Davidson-Arnott, R., (2010). Introduction to Coastal Processes and Geomorphology, University Press Cambridge. United Kingdom.
20. Dereli, M.A. & Tercan, E. (2020). Assessment of Shoreline Changes using Historical Satellite Images and Geospatial Analysis along the Lake Salda in Turkey. Earth Sci Inform 13, 709–718. https://doi.org/10.1007/s12145-020-00460-x
21. Degens, E.T., Wong, H.K., Kempe, S. and Kurtman, F., (1984). A geological study of Lake Van, Eastern Turkey. Geologische Rundschau, 73, 701–734.
22. Dinç, G. (2023). Unveiling shoreline dynamics and remarkable accretion rates in Lake Eğirdir (Turkey) using DSAS. The implications of climate change on lakes. Tema. Journal of Land Use, Mobility and Environment, 95-108. http://dx.doi.org/10.6092/1970-9870/10111
23. Duru, U. (2017). Shoreline change assessment using multi-temporal satellite images: a case study of Lake Sapanca, NW Turkey. Environ Monit Assess, 189, 385. https://doi.org/10.1007/s10661-017-6112-2
24. Esmail M, Mahmod WE, Fath H (2019) Assessment and prediction of shoreline change using multi-temporal satellite images and statistics: case study of Damietta coast, Egypt. Appl Ocean Res 82:274–282
25. Foutrakis, P., Poulos, S., Maroukian, H., & Livaditis, G. (2007). A study of the deltaic coast morphometry of river Pinios in relation to its hydro- & sediment dynamics. Bulletin of the Geological Society of Greece, 40(4), 1522–1529. https://doi.org/10.12681/bgsg.17055
26. Gumus, M. G., Durduran S. S., Gumus, K., (2022). Investigation of shoreline change rates using the digital shoreline analysis system in Lake Beyşehir, Turkey. Bulletin of Geophysics and Oceanography 63(1), 119-142. https://doi.org/10.4430/bgo00369
27. Himmelstoss, E. A., Henderson, R. E., Kratzmann, M. G., Farris, A. S. (2018). Digital Shoreline Analysis System (DSAS) Version 5.0 User Guide (No. 2018-1179). US Geological Survey.
28. Hossain, S. Yasir, M. Wang, P. Ullah, S. Jahan, M., Hui, S., Zhao, Z., (2021). Automatic shoreline extraction and change detection: A study on the southeast coast of Bangladesh. Marine Geology 441, 1-15. https://doi.org/10.1016/j.margeo.2021.106628
29. Hoşgören, M. Y. (1994). Lakes of Turkey. Turkish Geographical Review, 29, 19-51.
30. Hovsepyan A., Tepanosyan G., Muradyan V., Asmaryan Sh., Medvedev A., Koshkarev A. (2019). Lake Sevan Shoreline Change Assessment Using Multi-Temporal Landsat Images. Geography, Environment, Sustainability. 12(4):212-229. https://doi.org/10.24057/2071-9388-2019-46

31. Hu, X., & Wang, Y. (2020). Coastline Fractal Dimension of Mainland, Island, and Estuaries Using Multi-temporal Landsat Remote Sensing Data from 1978 to 2018: A Case Study of the Pearl River Estuary Area. Remote Sensing, 12, 2482. https://doi.org/10.3390/rs12152482
32. Jiang, D., Marino, A., Ionescu, M., Gvilava, M., Savaneli, Z., Loureiro, C., Spyrakos, E., Tyler, A., & Stanica, A. (2025). Combining optical and SAR satellite data to monitor coastline changes in the Black Sea. ISPRS Journal of Photogrammetry and Remote Sensing, 226, 102-115. https://doi.org/10.1016/j.isprsjprs.2025.05.003
33. Kaden, H., Peeters, F., Lorke, A., Kipfer, R., Tomonaga, Y. and Karabıyıkoğlu, M., (2010). Impact of lake level change on deep-water renewal and oxic conditions in deep saline Lake Van, Turkey. Water Resources Research, 46, W11508.
34. Kale, M.M., Ataol, M. Tekkanat, İ.S. (2019). Assessment of shoreline alterations using a Digital Shoreline Analysis System: a case study of changes in the Yeşilırmak Delta in north Turkey from 1953 to 2017. Environ Monit Assess 191, https://doi.org/10.1007/s10661-019-7535-8
35. Karakus, P. (2025). Detection of Water Surface Using Canny and Otsu Threshold Methods with Machine Learning Algorithms on Google Earth Engine: A Case Study of Lake Van. Appl. Sci. 2025, 15, 2903. https://doi.org/10.3390/app15062903
36. Kazı, H., & Karabulut, M. (2023). Monitoring the shoreline changes of the Göksu Delta (Türkiye) using geographical information technologıes and predictions for the near future. International Journal of Geography and Geography Education (50), 329-352.
37. Khorshiddoust, A. M., Patel, N., Khalilzadeh, E. Bostanaba, A. S. & Tajbar, S., (2022). A comparative study of the surface level changes of Urmia Lake and Aral Lake during the period of 1988 to 2018 using satellite images. Front. Earth Science. https://doi.org/10.1007/s11707-022-1010-5
38. Kılar, H., (2023). Shoreline change assessment using DSAS technique: A case study on the coast of Meriç Delta (NW Türkiye). Regional Studies in Marine Science, 57, 102737. https://doi.org/10.1016/j.rsma.2022.102737
39. Kuleli, T., Güneroğlu, A., Karslı, F., Dihkan, M., (2011). Automatic detection of shoreline change oncoastal Ramsar wetlands of Turkey, Ocean Engineering 38, 1141–1149. https://doi.org/10.1016/j.oceaneng.2011.05.006
40. Kuzucuoğlu, C., Christol, A., Mouralis, D., Doğu, A.F., Akköprü, E., et al. (2010). Formation of the Upper Pleistocene terraces of Lake Van. Journal of Quaternary Science, 25, 1124–1137. https://doi.org/10.1002/jqs.1431
41. Liang, M. Li, J. Luo, R. Li, Y. (2023). Analysis of Lake Shoreline Evolution Characteristics Based on Object Increments. Sustainability, 15, 14108. https://doi.org/10.3390/su151914108
42. Mattheus, C. R., Pearce, K., Rosario, L., & Spitzer, E. (2025). Water-Level Changes and Beach Morphodynamics: Insights from Topobathymetric Monitoring of a Receding Shoreline, Illinois Beach, Lake Michigan. Journal of Coastal Research. https://doi.org/10.2112/JCOASTRES-D-25-00014.1
43. McFeeters, S. K. (1996). The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features, International Journal of Remote Sensing, 17(7) 1425-1432,
44. Mullick, M.R.A., Tanim, A.H., Islam, S.M.S., (2019). Coastal vulnerability analysis of Bangladesh coast using fuzzy logic based geospatial techniques. Ocean Coast Manag. 174, 154–169. https://doi.org/10.1016/j.ocecoaman.2019.03.010.
45. Murray, J., Adam, E., Woodborne, S., Miller, D., Xulu, S., Evans, M. (2023). Monitoring shoreline changes along the southwestern coast of South Africa from 1937 to 2020 using varied remote sensing data and approaches. Remote Sensing, 15 (2), 317. https://doi.org/10.3390/rs15020317
46. Nassar, K., Mahmod, W. E., Fath, H., Masria, A., Nadaoka, K., Negm, A. (2019). Shoreline change detection using DSAS technique: Case of North Sinai coast, Egypt. Marine Georesources ve Geotechnology, 37(1), 81–95. https://doi.org/10.1080/1064119X.2018.1448912.
47. Nienhuis, J.H., Ashton, A.D., Edmonds, D.A., Hoitink, A. Kettner, A. Rowland, J.C. Tornqvist, T.E. (2020). Global-scale human impact on delta morphology has led to net land area gain. Nature 2020, 577, 514–518. https://doi.org/10.1038/s41586-019-1905-9
48. O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., Schneider, P., Lenters, J., D., McIntyre, P., B., Kraemer, B., M., Weyhenmeyer, G. A.,

Straile, D., Dong, B., Adrian, R., Allan, M., G., Anneville, O., Arvola, R., Austin, J., Bailey, J., B., Baron J., S., ... & Zhang, G. (2015). Rapid and highly variable warming of lake surface waters around the globe. Geophysical Research Letters, 42(24), 10773–10781. https://doi.org/10.1002/2015gl066235
49. Özpolat, E., & Demir, T. (2019). The spatiotemporal shoreline dynamics of a delta under natural and anthropogenic conditions from 1950 to 2018: A dramatic case from the Eastern Mediterranean. Ocean & Coastal Management, 180, 104910. https://doi.org/10.1016/j.ocecoaman.2019.104910
50. Özpolat, E., Şahiner, E., Özcan, O., Demir, T., & Owen, L. A. (2021). Late-Holocene landscape evolution of a delta from foredune ridges: Seyhan Delta, Eastern Mediterranean, Turkey. The Holocene, 31(5), 760-777. https://doi.org/10.1177/0959683620988047
51. Özturk, D., & Sesli, F. A. (2015). Shoreline change analysis of the Kizilirmak Lagoon Series. Ocean & Coastal Management, 118, 290-308. https://doi.org/10.1016/j.ocecoaman.2015.03.009
52. Rahman, M.K.; Crawford, T.W.; Islam, M.S. (2022). Shoreline Change Analysis Along Rivers and Deltas: A Systematic Review and Bibliometric Analysis of the Shoreline Study Literature from 2000 to 2021. Geosciences, 12, 410. https://doi.org/10.3390/geosciences12110410
53. Reis, L. G. de M., Souza, W. de O., Ribeiro Neto, A., Fragoso, C. R., Ruiz-Armenteros, A. M., Cabral, J. J. da S. P., & Montenegro, S. M. G. L. (2021). Uncertainties involved in the use of thresholds for the detection of water bodies in multitemporal analysis from landsat-8 and sentinel-2 images. Sensors, 21(22), 7494. doi: 10.3390/s21227494.
54. Roland, C, J. & Zoet, L, K. (2025). LiDAR-derived measurements of rapid coastal change along Wisconsin's Lake Superior coast (2009–2019), Journal of Great Lakes Research, 51 (1). 102366, https://doi.org/10.1016/j.jglr.2024.102366
55. Samra, R. M. & Ali, R. R. (2021). Applying DSAS tool to detect coastal changes along Nile Delta, Egypt. The Egyptian Journal of Remote Sensing and Space Science, 24(3-1), 463-470. https://doi.org/10.1016/j.ejrs.2020.11.002
56. Selçuk Biricik, A. (2009). Fiziki coğrafya – jeomorfoloji ile hidrolojinin temel prensipleri ve araştırma yöntemleri (Cilt 1). Gonca Yayınevi.
57. Selvan, C. S., Kankara, R., Markose, V. J., Rajan, B., Prabhu, K. (2016). Shoreline change and impacts of coastal protection structures on Puducherry, SE coast of India. Natural Hazards, 83, 293–308. https://doi.org/10.1007/s11069-016-2332-y
58. Sikder, M. S., Wang, J., Allen, G. H., Sheng, Y., Yamazaki, D., Song, C., Ding, M., Crétaux, J. F. & Pavelsky, T. M. (2023). Lake-TopoCat: a global lake drainage topology and catchment database, Earth Syst. Sci. Data, 15, 3483–3511, https://doi.org/10.5194/essd-15-3483-2023
59. Siyal, A. A., Solangi, G. S., Siyal, P., Babar, M. M. & Ansari, K. (2022). Shoreline change assessment of Indus delta using GIS-DSAS and satellite data. Regional Studies in Marine Science, 102405 http://dx.doi.org/10.1016/j.rsma.2022.10245
60. Song, Y., Shen, Y., Xie, R., Li, J. (2021). A DSAS-based study of central shoreline change in Jiangsu over 45 years. Anthropocene Coasts, 4(1), 115-128. https://doi.org/10.1139/anc-2020-0001
61. Tağıl, Ş., Alevkayalı, Ç., Aytan, B. (2023). Gediz Deltası Sulak Alanı Boyunca Kıyı Şeridi Evrimi ve Erozyon Hassasiyetinin Değerlendirilmesi. Ege Coğrafya Dergisi, 32(Cumhuriyet'in 100. Yılı Özel Sayısı), 127-142. https://doi.org/10.51800/ecd.1322803
62. Thieler, E. R., J. F. O'Connell, and C. A. (2009). The Digital Shoreline Analysis System (DSAS) version 4.0-An ArcGIS extension for calculating shoreline change (No.2008-1278). U.S. Geological Survey. https://doi.org/10.3133/ofr20081078
63. Turoğlu, (2017). Deniz ve Göllerde Kıyı, Yasal ve Bilimsel Boyutlarıyla Kıyı, (Editörler: H. Turoğlu, H. Yiğitbaşıoğlu) Jeomorfoloji Derneği Yayını No: 1.
64. Uzun, M., (2024a) Analysis of Manyas Lake Surface Area and Shoreline Change Over Various Periods with DSAS Tool, Turkish Journal of Remote Sensing -TJRS, 6(1), 35–56, 2024, https://doi.org/10.51489/tuzal.1443490.
65. Uzun, M. (2024b). Future predictions according to DSAS and artificial neural network models based on temporal change analysis of Uluabat Lake surface area, Turkish Geographical Review, (86), 25-43. https://doi.org/10.17211/tcd.1481187
66. Uzun, M. (2024c). Shoreline Change Sensitivity in The Kocasu Stream Delta and The Future (2033 and 2043) Shore Change Predictions, Journal of Geography (49), 135-154. https://doi.org/10.26650/JGEOG2024-1513029

67. Üner S. (2022). Natural and anthropogenic driving forces on Holocene coastline evolution of Lake Van (Eastern Anatolia): A geological approach. Yerbilimleri 43 2 96–120. https://doi.org/10.17824/yerbilimleri.1059064
68. Wu, Q., Miao, S., Huang, H., Guo, M., Zhang, L., Yang, L., Zhou, C. (2022). Quantitative Analysis on Coastline Changes of Yangtze River Delta based on High Spatial Resolution Remote Sensing Images. Remote Sensing. 14, 310. https://doi.org/10.3390/rs14020310
69. Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O'Reilly, C. M. & Sharma, S. (2020). Global lake responses to climate change. Nature Reviews Earth & Environment, 1, 388–403, https://doi.org/10.1038/s43017-020-0067-5
70. Yasir, M., Hui, S., Hongxia, Z., Hossain, M. S., Fan, H., Zhang, L., Jixiang, Z. (2021). A Spatiotemporal Change Detection Analysis of Coastline Data in Qingdao, East China. Scientific Programming, 2021, 6632450. https://doi.org/10.1155/2021/6632450
71. Yayla, O., Akpınar, H., Bilgin, T., Atayeter, Y. & Korkmaz, O. (2025). An evaluation of the long-term changes in the shoreline of Lake Eğirdir in relation to climate and anthropogenic factors. Coğrafya Dergisi–Journal of Geography, (50), 65-78. https://doi.org/10.26650/JGEOG2025-1620561
72. Yılmaz, O. S. (2023). Performance Analysis of Water Extraction Indices Used in Detection of Water Surfaces with Remote Sensing Techniques. Turkish Journal of Remote Sensing and GIS, 4(2), 242-261. https://doi.org/10.48123/rsgis.1256092
73. Zhou, Y.; Dong, J.; Xiao, X.; Liu, R.; Zou, Z.; Zhao, G.; Ge, Q (2019). Continuous monitoring of lake dynamics on the Mongolian Plateau using all available Landsat imagery and Google Earth Engine. Sci. Total Environ., 689, 366–380. https://doi.org/10.1016/j.scitotenv.2019.06.341