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THE EFFECT OF CHANGING THE SHORELINE ON THE EAST RECREATION AREA OF ALAKOL LAKE (KAZAKHSTAN)

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Abstract: The study aims to evaluate the dynamic coastal trends of Lake Alakol, Kazakhstan, using remote sensing and GIS technologies, focusing on shoreline erosion rates and their impact on the eastern recreational zone, a critical area for tourism development near the Kazakhstan-China border. Historical Landsat satellite imagery (1999–2023) was analyzed using the Digital Shoreline Analysis System (DSAS) in ArcGIS to calculate key shoreline change indicators, including Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR), and Linear Regression Rate (LRR). This approach enabled the quantification of long-term shoreline dynamics, identifying high-risk zones prone to erosion. The analysis revealed a significant average landward shoreline retreat of 89.1 meters over the study period. The eastern shore, particularly Zone A near the village of Kabanbay, exhibited the highest erosion rates (-14.18 m/year), posing a "very high" risk to recreational infrastructure and tourism activities. Other zones also showed moderate to high erosion risks, emphasizing the vulnerability of the eastern shoreline to environmental factors, such as wave activity and wind dynamics. These findings underscore the urgent need for proactive shoreline protection and sustainable coastal management practices to safeguard the region's ecological and economic assets. The research highlights the critical importance of protecting Lake Alakol's shoreline to ensure the long-term viability of tourism and recreational activities, which are central to regional development. Proactive measures, including the integration of advanced remote sensing technologies and eco-friendly shoreline reinforcement strategies, are essential for mitigating erosion risks. The findings also open opportunities for collaboration with neighboring regions, including China, in addressing shared environmental challenges. Continuous monitoring, stakeholder engagement, and alignment with sustainable tourism goals are imperative for balancing environmental conservation with socio-economic progress in the Alakol region.

Keywords: shoreline dynamics, Alakol Lake, remote sensing, GIS, coastal erosion, DSAS, sustainable tourism, recreational areas, environmental management

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INTRODUCTION

The shoreline is the line of contact between land and water. Monitoring shoreline conditions and the rate of shoreline change should be realized as an important indicator of effective basin management with the help of rapid and economic

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remote sensing techniques. Shoreline change is a dynamic natural phenomenon controlled by coastal sediments, beach formation, climate change and human impact. Changes in the shoreline are mainly due to natural conditions (Bird, 1985; Li & Gong, 2016). Rapid shoreline change causes socio-economic and ecological problems in the aquatic ecosystem and leads to degrading coastal conditions. Determining how the shoreline is changing represents an important component in the spatial and temporal analysis of water resources. The main methods of cartographic research and map use employed in this study were: visual analysis of the phenomena depicted on the maps; graphical methods of map analysis (Astakhova, 2016). Traditionally, the shorelines of water bodies are determined once in the interim period when updating cartographic products. In addition to one-time marking of the shoreline, satellite images make it possible to systematically determine the state of the shoreline.

Using satellite images from a multispectral camera, a set of images was compiled in which shorelines are clearly visible, and data on shorelines were obtained using remote sensing (Abrosimov & Dvorkin, 2009). In their 2009 study, Abrosimov and Dvorkin employed statistical analysis of numerical data obtained from remote sensing methods to examine indicators of shoreline change. They also mentioned that using the results of total detected shoreline change from 1999 to 2019, the average distance of the shoreline from the baseline and the annual rate of change for each decade were determined and stratified by risk. According to the latest data (Valeyev et al., 2019; Abitbayeva et al., 2016), the length of various types of erosion ridges on the land shore of Lake Alakol is 40% of the total shoreline length. The shoreline change in the area of the village of Kabanbay, according to research data for the period 1990-2014, was 70-100m. While a continuous increase in the surface of Lake Alakol was observed between 1990-2018, the landward movement of the shoreline was approximately 200-900 m (Abitbayeva et al., 2016). This change is explained by the peculiarity of the geological structure, and the geological structure of the lake has been studied by several scientists (Korovin, 1965; Sala et al., 2020; Bai et al., 2011).

Alakol coast has special natural properties for the development of beach and health tourism and is among the objects included in the TOP-10 tourism project of the Republic of Kazakhstan. In the future, the state will spend 60 million for the development of the infrastructure of the resort region. Plans to invest and develop actively. Currently, the tourist flow is about 190 thousand. By 2030, this figure is expected to increase to 600,000. The main zone for the implementation of this plan is the area near the village of Kabanbay. Therefore, monitoring the dynamics of shoreline changes, risk prevention and planning measures for coastal protection is considered one of the important indicators (Kazakhstan Tourism, 2019).

There are many methods used to measure the long-term change of the shoreline (Haines-Young et al., 2003). One of them is that the use of traditional field research methods requires significant labor and time, and changes in the shoreline can be determined quickly and with high accuracy using Earth remote sensing methods and geographic information systems, which are more effective and cheaper than field methods using satellite images (Cracknell, 1999; Nayak, 2000). In recent years, it has become possible to quickly monitor and detect shoreline changes using historical remote sensing data.

Remote sensing monitoring allows not only to detect changes over time, but also to conduct research on a large area. There are several methods of remote sensing and geoinformation system used to determine the shoreline change: light vision and range detection (LIDAR) method, video technology-based and airborne laser scanner method with synthesized system. These methods provide more accurate data than satellite images, but such data are limited due to the high cost of the database and the data is expensive (Richardson et al., 2014; Genc et al., 2005). Thus, aerial photographs and multispectral satellite imagery are effective tools for cost-effectively monitoring shoreline changes and by comparing images over time. At the same time, studies using such reliable data make it possible to identify and monitor changes in the shoreline at the local level.

In recent years, several studies have been carried out in this area using satellite imagery, including Landsat satellite imagery. For example, Tao et al. (2015), using satellite images of the Earth from the 1980s to the 2000s, identified the rapid loss of lakes in the Mongolian Plateau due to changes in precipitation and agricultural practices. Yiğit et al. (2022) analyzed long-term and short-term shoreline changes in Antalya, Turkey, revealing a strong correlation between shoreline movement indicators but noting limitations in Landsat's spatial resolution. Alwi et al. (2023) found accretion to be dominant in Indonesia's Karimunjawa islands, contrasting with erosion trends elsewhere, yet highlighted the inefficacy of existing coastal defenses. Similarly, Daswin Ebenezer & Kumar (2023) forecasted shoreline changes in Tamil Nadu, India, identifying significant erosion but acknowledging uncertainties in predicting future trends. Pham et al. (2024) examined coastal fluctuations in Vietnam's Sam Son City, attributing changes to both natural forces and tourism-driven development.

Remote sensing techniques have been used to analyze the change in the water surface in this region (Abitbayeva et al., 2016), but the amount of coastal change in certain areas has not been specifically determined. The main objective of the study is to determine the dynamics of changes in the shoreline of the East Coast over the period from 1999 to 2023. Coastal change is especially important in investment regions. For this reason, this study will provide important predictions in the regional distribution of investments to be made in the area, and studies on the amount of shoreline should be carried out for a special area (Bahrami & Siadatmousavi, 2025). The Alakol coast has special natural features for the development of beach and health tourism and is among the objects included in the TOP-10 tourism project of the Republic of Kazakhstan. In the near future, the state plans to actively invest and develop the infrastructure of the resort area, spending 60 million on its development. The number of tourists, which is currently 190 thousand, is expected to increase to 600 thousand in 2030. Analyzing the village of Kabanbay and the surrounding areas, which are expected to attract a large number of tourists with investments, will facilitate taking measures for future natural disasters.

Therefore, the aim of this study is to analyze and quantify the shoreline dynamics of the East Coast of Alakol Lake (Kazakhstan) from 1999 to 2023 using remote sensing and GIS techniques. Given the increasing tourism development in the region, particularly around the village of Kabanbay, monitoring shoreline changes is critical for sustainable shoreline management and infrastructure planning. This study seeks to identify erosion and accretion trends, assess their potential impact on tourism and environmental stability, and provide data-driven insights for future investment and risk mitigation strategies. By integrating cartographic analysis, statistical methods, and satellite imagery, this research will contribute to effective shoreline management and the sustainable development of Alakol Lake's coastal areas.

MATERIALS AND METHODS

The Alakol Lake lies in the Balkhash-Alakol lowland, spanning the border of Almaty and East Kazakhstan regions, forming the eastern part of the Balkhash-Alakol Basin near the boundary with China. It receives water from over 15 tributaries including the Urzhar, Katynsu, Emelkysa, Ygrajty, Zhamanty, Zhamanotkel, and Tasty rivers, which typically dry up in summer due to the semi-arid climate. Kazakhstan affirmed its dedication to preserving the region's unique biodiversity by ratifying the Convention on Biological Diversity in 1994. As a part of this commitment, the Alakol Lake State Reserve was established in 1998, marking a significant step toward protecting the area's natural richness and fulfilling the goals set in international agreements (Jiyenbekov et al., 2018). Alakol has no current and extends from northwest to southeast. It is located at an absolute altitude of 247.3 m above sea level. The area of the lake, including islands, is 2696 km², with a length of 104 km, a maximum width of 52 km, a shore length of 384 km, an average depth of 22.1 m, and a deepest part of 54 m. The lake's water volume is 58-60 km³. The catchment area is 47,859 km². More than 15 rivers flow into Alakol (Zhetysu Encyclopedia, 2004). The climate of the region is continental and dry (Mannig et al., 2013).

The eastern shore of the Alakol lake basin was considered as the research object (Figure 1). In recent years, the eastern shoreline of the study area, located close to the Chinese border, has undergone natural changes due to the influence of strong waves (Mikhailova & Loginovskaya, 2012; Mikhailova, 2019). The eastern coast of Lake Alakol is considered an important recreational area of the country, mainly for tourism, where recreation and recreation centers are located. It is therefore important to consider the rate of change and shoreline dynamics in this region.

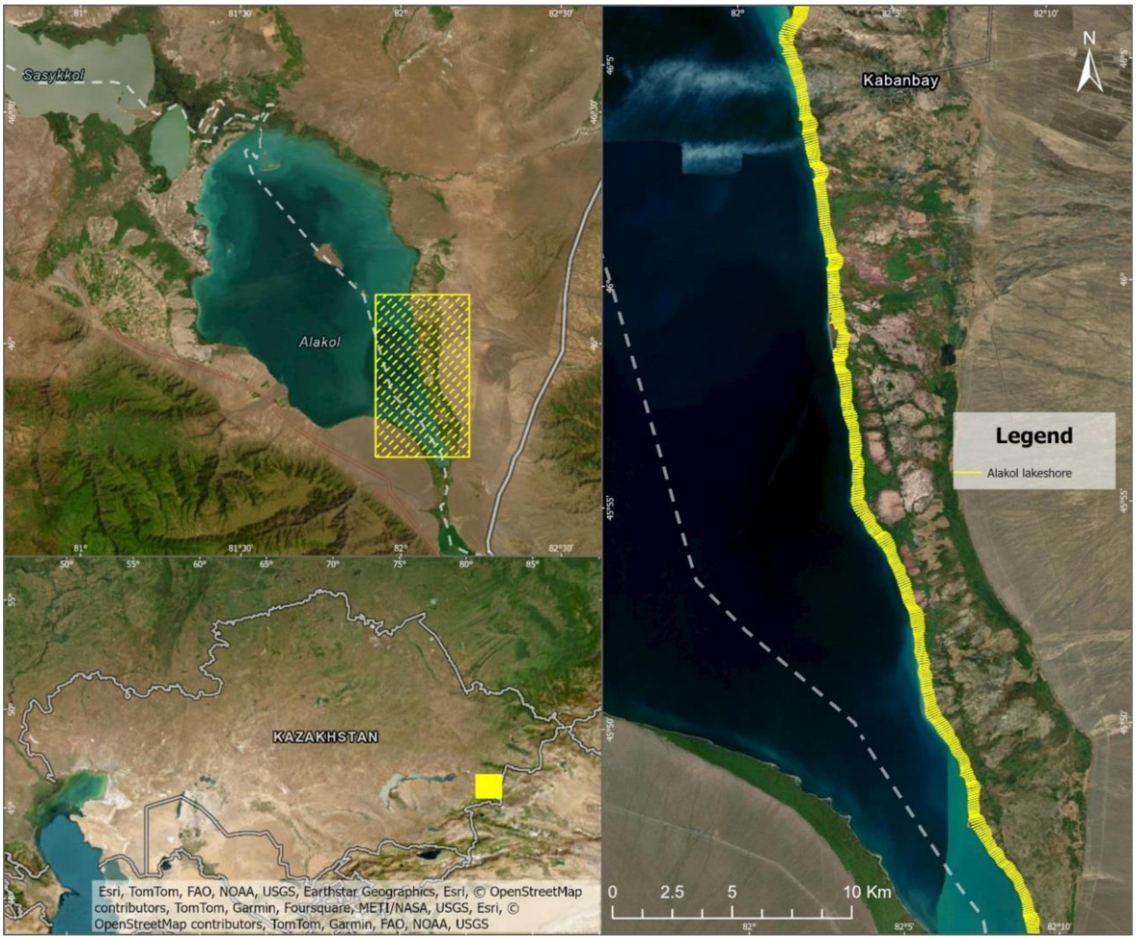

Figure 1. Study area – the Shoreline on the East Area of Alakol Lake (Kazakhstan)

A feature of the rocks that make up the abrasive areas is the predominance of sandstones and mudstones, overlain by sandy-clayey sediments of the Quaternary period. Along the coast in the area of the village of Kabanbay, predominantly modern deposits are widespread: sands, clays, gravel, as well as Upper Quaternary - modern deposits: sands, sands, clays, gravel. Shoreline erosion is the most active modern geomorphological process. First of all, their geological structure is suitable for this. The lithological section of loose coastal sediments begins with strong peats on the surface. Below is a layer of sand and clay. In winter, peat bogs, saturated with moisture, freeze, and they melt almost throughout the summer. As a result of seasonal melting of permafrost, sandy clay rocks are gradually saturated with moisture, which causes the development of surface processes. In general, the climatic and geological factors in the study area are very favorable for the rapid development of abrasion processes. Coastal areas in river valleys can be considered thermos abrasive (Are, 1980).

The coastal zone is a marshy gentle slope with a height of 10-20 m in the south and 60-80 m in the north. In this regard, based on the height of the coast and the composition of the rocks composing it, the eastern coast is conventionally divided into 3 regions: northern, middle and southern. In the first northern area, the average height of the rocks is 60 m and Paleozoic metamorphic schists are developed, forming the base of the Quaternary marine terraces. The second middle platform is quite low, 40 m high. The accumulative coast is marked by a strip of dunes. The third is composed of Quaternary sediments of clayey composition, actively eroded from the south. The processes of landslides and landslides are intense in this area. When peat is mined, rocks with lenses are formed in the lower bedrock. Processes similar to thermal abrasion occur here. The average height of the rock in this area is 15 m. Along with differences in the resistance of rocks to abrasion, the intensity of abrasion processes is influenced by differences in the hydrodynamic activity of coastal waters. A peculiarity of the mechanism of erosion of the shores of the northern part of the lake is that almost all the material coming from the coastal zone as a result of the destruction of the shores is carried away. The rate of shore erosion is different for different parts of the lake and is determined by the running features of hydrodynamic and lithological processes.

Thus, the eastern coast of Lake Alakol, in its geological structure and hydrodynamic conditions, is very suitable for the development of abrasion processes, both currently and geologically, and high abrasion processes can be expected here.

In addition, another feature of Lake Alakol is the strong groundwater supply of underground and artesian waters formed in mountainous regions and alluvial networks of rivers. The total flow to the underground lake (mainly to Lake Alakol) is 0.8 km^3 per year (Bexeitova, 2010). These geological and hydrodynamic conditions, combined with the strong groundwater supply feeding into Lake Alakol, set the stage for significant geomorphic activity. Adding to these dynamics, the wind regime of the Alakol basin is distinguished by its complexity and originality due to the basin's location in the orographic zone. The average annual wind speed in this region is 3-7 m/s, with 10-15% of days experiencing strong winds (over 15 m/s). In some years, this can reach up to 140 days, with recorded maximum wind speeds reaching 60 m/s, as noted at the Zhalanashkol weather station. The observed storm winds, particularly in the Dzungarian Gate area, contribute to seasonal variations in shoreline processes, with the strongest winds occurring in winter and the weakest in summer.

The prevailing wind directions, from west to east at the Alakol weather station and north-southeast at the Zhalanashkol station, further influence the erosion and sediment transport patterns essential to the lake's dynamic landscape (Environmental Impact Assessment, 2019). These complex geological, hydrodynamic, and wind regime factors have contributed to significant shoreline changes in the Alakol basin. As a result, accidents have occurred due to these shifts, leading to the evacuation of some settlements in the region (Bedareva, 2000). The Digital Shoreline Analysis System (DSAS) is a key component of the USGS Shoreline Change Risk Study. DSAS is a tool for processing large volumes of data. DSAS software is designed to simplify the process of calculating shoreline changes and provide the rate of change and statistics needed to determine the accuracy of the calculated results. The latest version currently available is DSAS version 6 and tool offers advanced baseline placement types, attribute automation, data visualization, shoreline change prediction, and the ability to produce a final summary report of identified data (US Geological Survey, 2019). Long-term rates of shoreline change are calculated using linear regression for each perpendicular survey line (transect) from the earliest to the latest shoreline. Linear regression is used in research because it is the most statistically reliable quantitative method (Crowell et al., 1997). It is also the most commonly used statistical method for representing shoreline movement and estimating rates of change (Crowell & Leatherman, 1999; Morton et al., 2004). The methodology followed in this study is summarized in a flowchart (Figure 2), which outlines the sequential steps from satellite image acquisition to shoreline analysis, including image processing, classification, and the determination of shoreline change indicators using the DSAS tool.

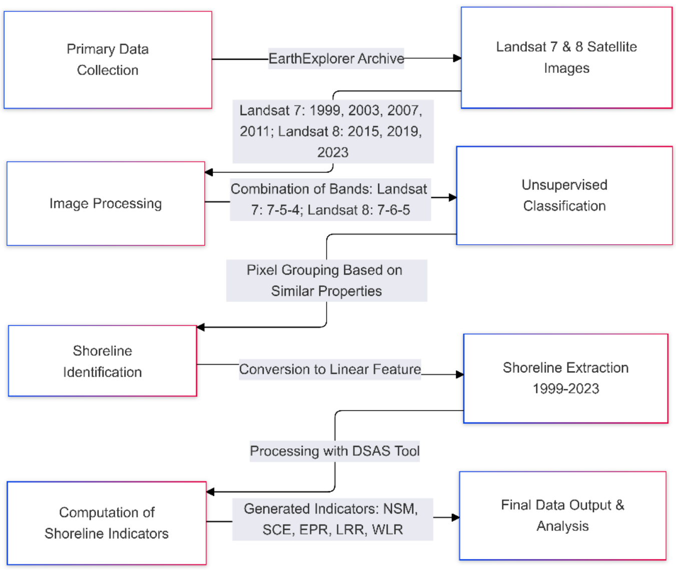

Figure 2. Flowchart of the shoreline analysis methodology, including image processing and DSAS-based indicator calculation

The primary data used was data obtained through the EarthExplorer website (https://earthexplorer.usgs.gov/), which is an open archive. Landsat 7 satellite images from 1999, 2003, 2007, 2011 and Landsat 8 from 2015, 2019, 2023 (spatial accuracy

30 m/pixel) were used as remote sensing data when studying the dynamics of changes in the shoreline. It has been shown that conducting research using Landsat 7 TM satellite images is more effective than using high-precision satellite images when monitoring changes in the shoreline (Kevin & El Asmar, 1999). The Additionally, in Annibale Guariglia's (2006) study on a multi-resource approach to mapping shorelines and detecting coastal change, the land-water boundary determined using Landsat satellite imagery was consistent with GPS-based field studies (Guariglia et al., 2009). The data was used for this study obtained (less than 10% cloud) in a georeferenced form with a UTM projection (zone 44N, WGS-84) shown in Table 1.

Table 1. Data sets and their descriptions used in studying the dynamics of shoreline change

A set of data	Date	Resolution	Data source
Landsat 7	1999/07/09	30	U.S. Geological Survey
Landsat 7	2003/07/20	30	U.S. Geological Survey
Landsat 7	2007/07/31	30	U.S. Geological Survey
Landsat 7	2011/07/10	30	U.S. Geological Survey
Landsat 8	2015/07/13	30	U.S. Geological Survey
Landsat 8	2019/07/08	30	U.S. Geological Survey
Landsat 8	2023/07/27	30	U.S. Geological Survey

A combination of channels 7-5-4 of Landsat 7 space images and a combination of channels 7-6-5 of Landsat 8 space images were built (Figure 3). The shorelines, selected site, are clearly defined by built images. Open soil (yellow), open water (black) and plants (blue) area are also apears on images. Currently, ENVI and ArcGIS programs are used to process multispectral raster images, which have a special add-on for studying shorelines.

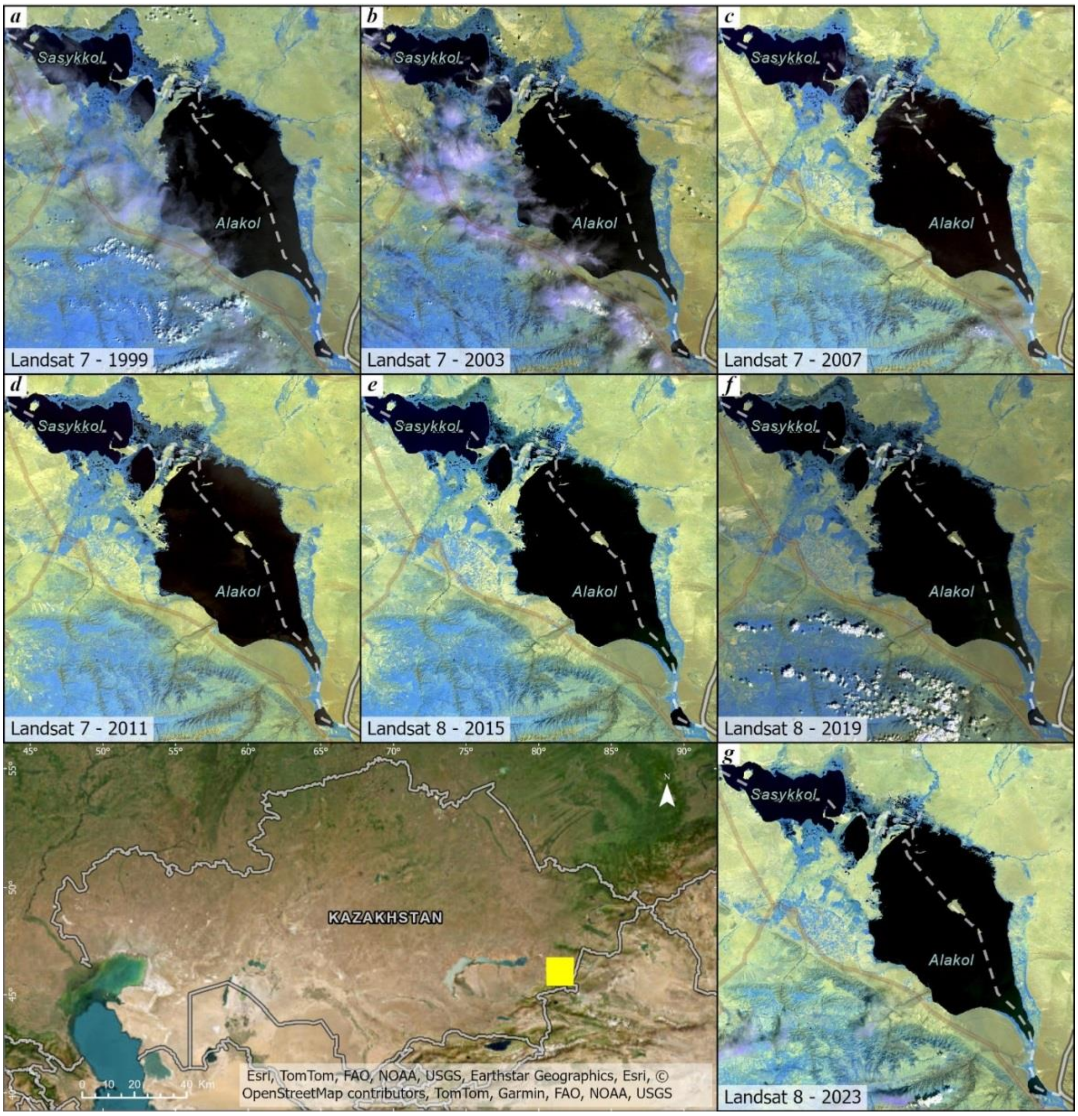

Figure 3. Combination of Landsat 7 7-5-4 satellite images and combination of Landsat 8 7-6-5 satellite images a) 1999; b) 2003; c) 2007; d) 2011; e) 2015; f) 2019; g) 2023

The satellite images were first processed using the visual decoding method. The water-land boundary in the study material is clearly defined due to the reflective properties of the water surface in the combination used in the Landsat bands.Shorelines from 1999, 2003, 2007, 2011, 2015, 2019 and 2023 were identified using an unsupervised classification method (Baban, 1997) (Figure 4). This type of classification is based on the characteristics of pixels in a space image by grouping pixels with similar static properties into clusters. Two clusters were identified from the imagery and converted to a linear feature to highlight the shoreline (Daniels, 2012). These shorelines were processed using the DSAS tool, and the indicators Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), End Point Rate (EPR), and Linear Regression Rate (LRR) were determined (US Geological Survey, 2018). The NSM measures the total shoreline movement between the earliest and latest shoreline positions, while the SCE captures the maximum shoreline displacement.

The EPR represents the rate of shoreline change based on the distance between two shorelines, and the LRR calculates a trend of shoreline movement over time. To compute these indicators, a perpendicular transect was drawn from each shoreline to a predefined baseline. The baseline was created in ArcGIS by merging shorelines from 1999 to 2023 and applying a buffer tool to smooth variations and establish a reference line (ArcGIS, 2019). This method ensures consistency when measuring shoreline displacement. The DSAS tool then generated the NSM, SCE, EPR, LRR, and Weighted Linear Regression (WLR) indicators at each transect. In this study, perpendicular transects were spaced every 200 m, and measurements were taken up to 1500 m from the baseline to capture regional shoreline trends (Fig. 3). These distances were chosen to balance spatial resolution and computational efficiency while ensuring comprehensive shoreline analysis.

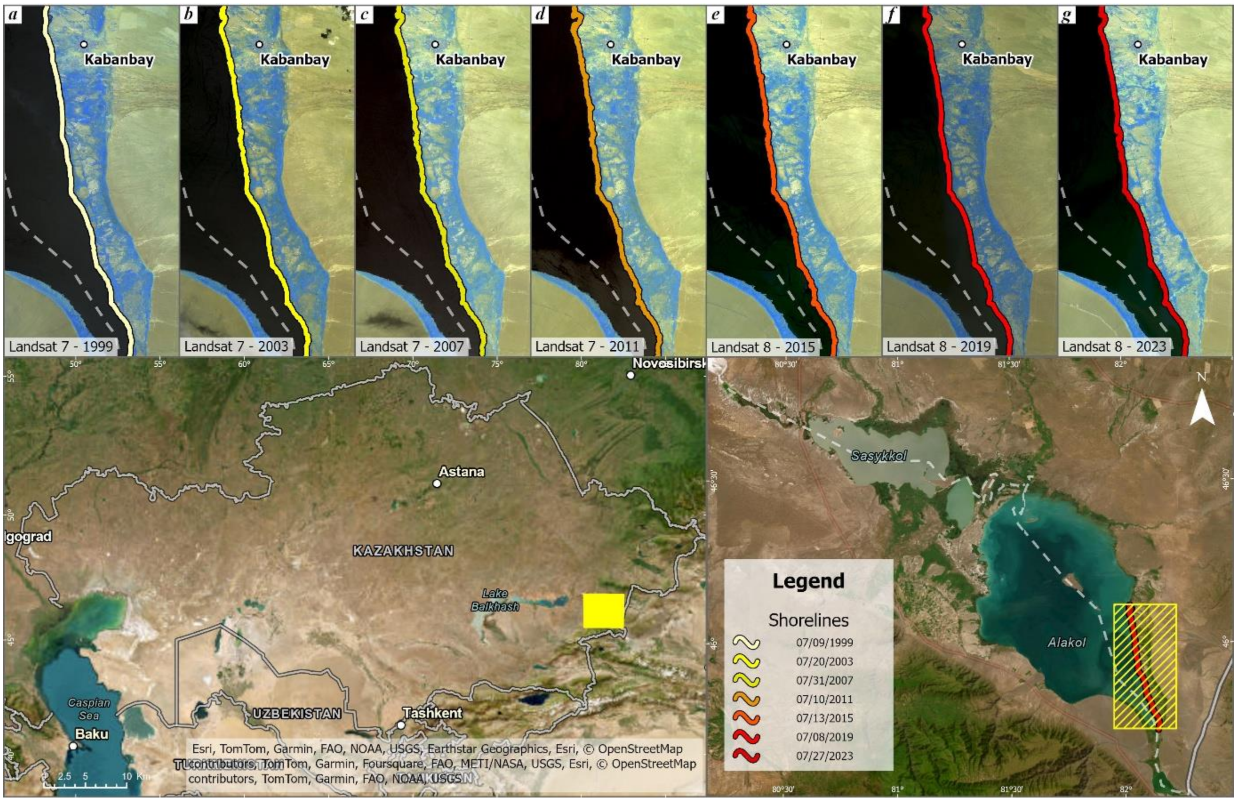

Figure 4. Shorelines identified from Landsat satellite imagery a) 1999; b) 2003; c) 2007; d) 2011; e) 2015; f) 2019; g) 2023

The identified shorelines were analyzed using the methods outlined in the table below.

Table 2. Description of indicators used in the study of shoreline change dynamics

DSAS statistics	Definition
NSM	Net Shoreline Movement is the distance between the oldest and most recent shoreline
SCE	Shoreline Change Envelope – indicates the distance between the closest to the farthest shoreline with reference to the baseline as observed within the temporal horizon
EPR	End Point Rate – is simply the Net Shoreline Movement divided by the time interval
LRR	Linear Regression Rate – is used to show the long-term rate of shoreline change.
WLR	Weighted Linear Regression – provides the best-fitted line for the linear rate of change by considering the uncertainty value

EPR (End Point Rate) – End Point Rate was calculated by dividing the distance of shoreline travel by the elapsed time between the oldest and most recent shoreline (Sam & Gurugnanam, 2022). By calculating the value of the movement of the point of intersection with the perpendicular drawn from the shoreline to the baseline, the LRR index was determined, and it indicates the annual change of the shoreline (m/year). The indicators of NSM, EPR, SCE used in determining the dynamics of the change of this shoreline are closely related to each other (Figure 5).

$$\mathrm{EPR} = \frac{\mathrm{NSM}}{\textit{the time between the oldest and the most recent shoreline}}$$

where, EPR: Represents the annual rate of shoreline movement, either erosion or accretion, measured in meters per year (m/year); NSM: Refers to the total distance between the position of the oldest shoreline and the most recent shoreline along a given transect. This is measured in meters (m).

Figure 5. Interrelationship of NSM, EPR, SCE indicators, NSM = distance between oldest and latest shoreline (m), SCE= distance between two extreme shorelines (m)

RESULTS AND DISCUSSION

1999, 2009, 2019, obtained by classifying satellite images using special tools built into ArcGIS, long-term data analysis was carried out (Fatih & Durduran, 2016; Emran et al., 2016): The area of selected areas of abrasion and consolidation was calculated, and the rate of shore retreat in selected areas was estimated.

According to the determined NSM, the maximum shoreline change towards land was a value of about 280 meters (Figure 6). On the contrary, the change of shoreline towards water showed a value of about 80 meters. According to the NSM, the distance between the oldest and the latest shoreline or the direction of net shoreline movement was toward land.

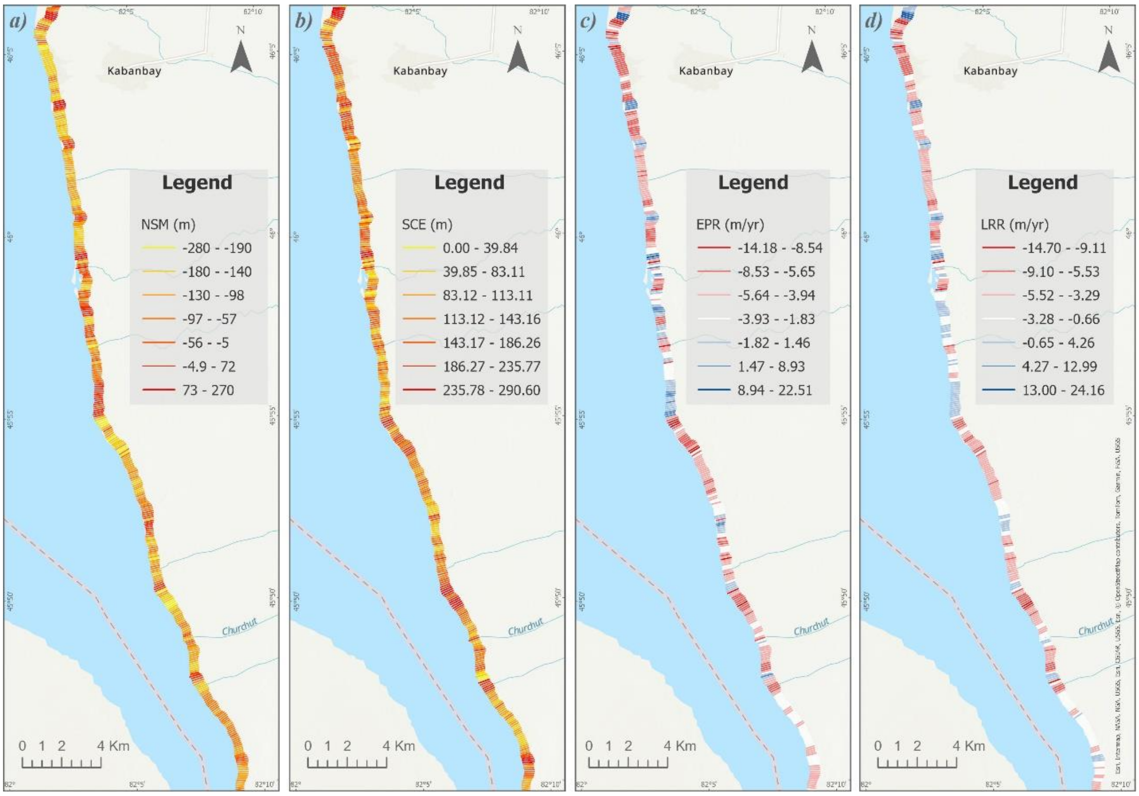

Figure 6. a) NSM, b) SCE, c) EPR and d) LRR indicators of the eastern shore of Lake Alakol

The SCE's measurements showed that the longest distance of 235-290 metres corresponded to the area of recreational facilities in the village of Kabanbay on the eastern shore of Lake Alakol. According to the EPR indicator, the annual change of the shoreline near the village of Kabanbay had a high index value of -14.18 - - 8.54 m compared to other regions.

The analysis of the WLR rates across 463 transects reveals valuable insights into shoreline dynamics. The overall average rate of shoreline changes stands at -2.67 meters per year, indicating a predominant erosional trend (Figure 6). However, this average rate comes with a notable uncertainty of ±0.66 meters per year, calculated based on a reduced number of independent transects (n=54). Among the transects, 82.51% exhibit erosional behaviour, with an average erosion rate of -3.95 meters per year. This erosional trend is further emphasized by the fact that 55.08% of all transects demonstrate statistically significant erosion, with the most significant erosion observed at -14.7 meters per year on Transect ID 28. Conversely, 17.49% of the transects display accretional behaviour, albeit at a lower frequency. Despite this, only 2.16% of transects show statistically significant accretion, with the highest accretion rate recorded at 24.16

meters per year on Transect ID 22. These findings underscore the dynamic nature of coastal environments, with erosional processes dominating over accretional ones in this study area (Figure 7).

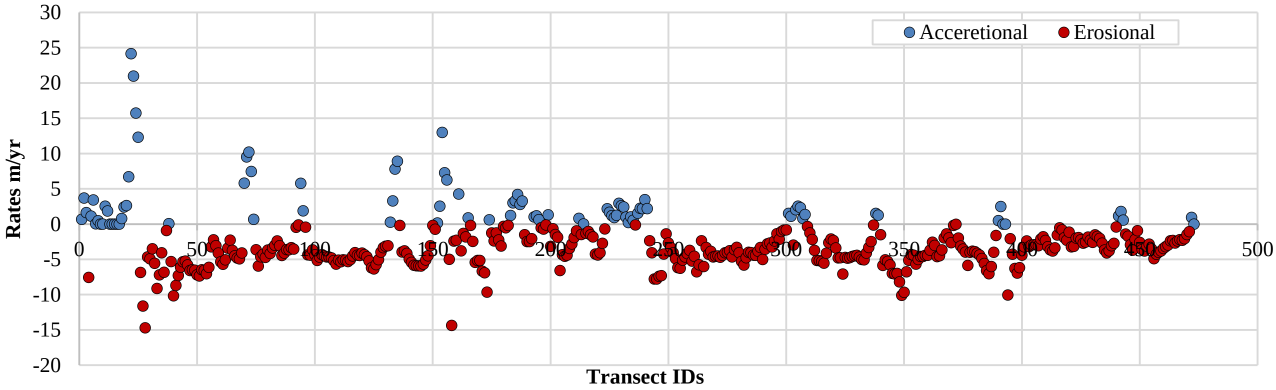

Figure 7. WLR rates along transect

The distance of the shoreline from the baseline has fluctuated over time, with the most recent measurement in 2023 showing (Figure 8) a distance of 169.76 meters, while in 1999 it reached its peak at 306.61 meters.

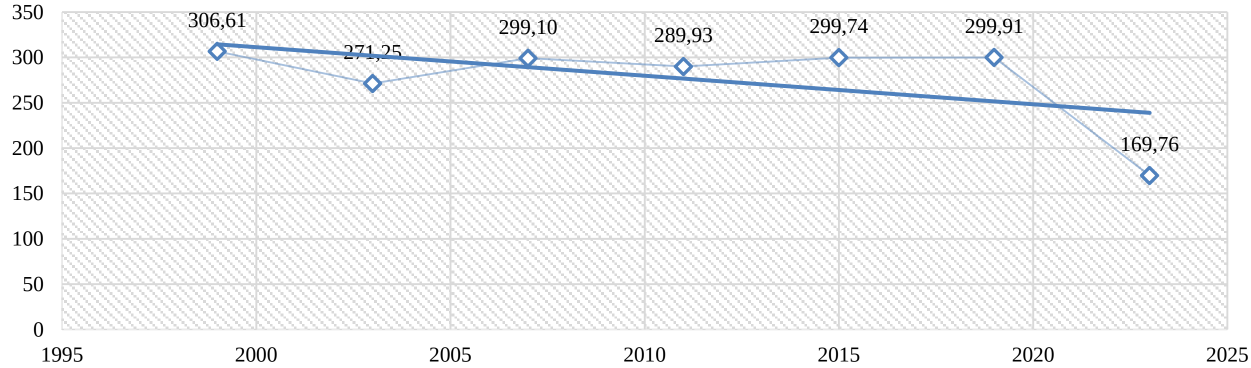

Figure 8. Changes in the distance of the shortelinе from the baseline

The analysis of shoreline changes conducted on the dataset extracted from DSAS Summary Transects reveals significant insights into the coastal dynamics of the studied area. Various rate types were examined, including SCE, NSM, EPR, and LRR. Transects were spaced at 100-meter intervals, with a smoothing distance of 2500 meters. The analysis, conducted with a confidence interval of 90 and default uncertainty of 10, revealed both erosional and accretional trends. EPR indicated an average erosional rate of -3.68 meters/year, with 89.01% of transects exhibiting erosion and 10.99% exhibiting accretion. LRR showcased an average erosional rate of -2.67 meters/year, with 82.51% of transects displaying erosion and 17.49% displaying accretion. These findings provide valuable insights for coastal management and conservation efforts in the studied region. Wind conditions and waves have a great influence on the formation of the coast (Velichko & Spasskaya, 2002). Wave power is considered to be the main factor affecting the change of the Alakol lake shoreline (Mikhailova & Loginovskaya, 2012). The wave height of Lake Alakol during the hurricane season reaches 9-10 meters. This poses a serious threat to the territory where the recreation area is located, and there is a high risk of erosion of roads and recreation centers. The main force of this wave is the wind.

The results of this study underline several key advantages of the project. One of the most significant is the direct relationship between its findings and the potential for sustainable tourism development in the Alakol Lake region. By identifying critical erosion risks and shoreline dynamics, the project supports the strategic planning of tourism infrastructure and recreational areas, ensuring their resilience and appeal for future visitors. Moreover, the integration of this project with other regional and national initiatives—such as ecological monitoring programs, tourism development plans, and innovative remote sensing applications—creates a cohesive framework for addressing environmental challenges. This synergy will enable the adoption of cutting-edge technologies and methodologies, amplifying the impact of this research and fostering long-term regional growth. The findings of this study highlight the significant changes in shoreline dynamics along the eastern coast of Lake Alakol, with implications for both environmental management and regional development. The predominant trend of shoreline retreat towards land reflects the combined influence of natural processes such as wave action, wind dynamics, and geological factors. This underscores the importance of understanding the interaction between these variables to design effective strategies for shoreline protection.

One of the key takeaways from this study is the vulnerability of critical recreational areas, such as the village of Kabanbay, which are central to the region's tourism economy. The high erosion rates observed near this area not only threaten infrastructure but also pose a challenge to sustainable tourism development. Proactive measures, including the implementation of coastal protection infrastructure and ecosystem-based solutions, are essential to mitigate these risks.

For example, integrating vegetative barriers and reinforcing natural features along the shoreline can provide cost-effective and environmentally friendly alternatives to traditional methods of erosion control.

The study also emphasizes the value of advanced remote sensing technologies, such as the DSAS, in monitoring and analyzing shoreline changes. The ability to process and visualize long-term data using satellite imagery enables researchers and policymakers to make informed decisions regarding environmental conservation and development planning. While this approach offers significant advantages in terms of cost-efficiency and scalability, it is important to address the limitations of lower-resolution satellite data by incorporating high-resolution imagery and other advanced geospatial tools in future studies. Another important aspect is the potential for cross-border collaboration with China, given the proximity of Lake Alakol to the Chinese border. Environmental challenges in the region, such as shoreline erosion, are not confined to national boundaries and call for cooperative approaches to address shared ecological and hydrological systems. Joint initiatives with Chinese institutions could enhance data sharing, resource management, and the development of innovative solutions to mitigate environmental risks. This study also sheds light on the need to align shoreline management with broader regional goals, including sustainable tourism and biodiversity conservation. Lake Alakol's unique natural features and its role as a key recreational hub for Kazakhstan present an opportunity to promote eco-friendly tourism initiatives. Incorporating nature-based tourism activities that focus on the lake's biodiversity and landscape can simultaneously enhance visitor experiences and support conservation efforts. Additionally, integrating this project with other regional initiatives, such as water resource management and climate resilience planning, can create a synergistic framework for sustainable development.

CONCLUSION

In conclusion, this comprehensive study of shoreline dynamics along the eastern coast of Lake Alakol, situated near the border of Kazakhstan and China, has provided valuable insights into the complex interactions between environmental factors and coastal processes. By analyzing satellite imagery and applying advanced GIS tools such as DSAS software, significant changes in shoreline morphology and behavior have been identified over the studied period.

The findings revealed a predominant trend of shoreline retreat towards land, with erosional processes outweighing accretional ones. High rates of erosion, particularly near the village of Kabanbay, underscore the vulnerability of coastal areas to environmental changes and the urgent need for effective management strategies. The influence of wind conditions and wave power on shoreline dynamics further emphasizes the importance of incorporating these factors into coastal planning and conservation efforts. Beyond coastal management, these results hold significant implications for the development of sustainable tourism in the region. Protecting the natural assets of Lake Alakol, such as its unique shoreline and recreational areas, is essential for ensuring the long-term viability of tourism activities. By integrating this research with regional tourism planning, stakeholders can enhance visitor experiences while safeguarding the ecological integrity of the lake.

Future initiatives should prioritize the alignment of tourism development with conservation goals, incorporating nature-based tourism events and activities that highlight the lake's natural beauty and ecological significance. Moreover, the project serves as a foundation for integrating advanced technologies and methodologies into broader environmental monitoring and resource management initiatives. Given Lake Alakol's proximity to China, the findings also offer potential for cross-border collaborations on environmental protection and sustainable resource use. Continuous monitoring and collaborative efforts between policymakers, researchers, and local communities will be critical to ensuring the sustainability of the lake's ecosystem and its role as a key driver of regional economic growth. These actions will not only mitigate erosion risks but also pave the way for sustainable development that balances environmental conservation with socio-economic progress.

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