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ASSESSMENT OF THE IMPACT OF COASTLINE DYNAMICS ON BIODIVERSITY USING REMOTE SENSING DATA IN THE GHIZIL-AGAJ BAY, AZERBAIJAN

Ghizil-Agaj Bay is a wetland of international importance located in the southeastern part of Azerbaijan and included in the Ramsar Convention list. Over the past 30 years, anthropogenic impacts on this ecosystem, along with natural factors, have intensified, leading to significant changes in the morphological and hydrological characteristics of the shoreline. The aim of this study is to assess the dynamics of the coastline in the Gizil-Agach Bay and to evaluate its impact on biodiversity. This study analysed shoreline dynamics from 2000 to 2024 using Landsat and Sentinel-2 imagery, Geographic Information Systems, and the Digital Shoreline Analysis System. Results revealed significant spatiotemporal shoreline changes, with maximum progradation of +570 m/year and maximum erosion of – 4 m/year. Between 2000 and 2024, approximately 240 km² of land was gained, while 0.56 km² of water area was lost. These changes influenced wetland ecosystem extent and quality, causing shifts in avifauna and biodiversity: migratory water bird nesting and feeding habitats declined, total water bird numbers decreased by approximately 28%, while terrestrial bird species nesting on newly emerged land increased by approximately 12%. These findings can serve as a basis for wetland management policies under climate change conditions.

Keywords: shoreline dynamics, biodiversity, remote sensing, digital shoreline analysis system, wetlands.

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Әзірбайжанның Гызыл-Агаж шығанағындағы қашықтан зондтау деректерін пайдаланып, жағалау жолы динамикасының биоәртүрлілікке әсерін бағалау

Гызыл-Агаж шығанағы – Әзірбайжанның оңтүстік-шығыс бөлігінде орналасқан және Рамсар конвенциясының тізіміне енгізілген халықаралық маңызы бар батпақты жер. Соңғы 30 жылда бұл экожүйеге антропогендік әсерлер табиғи факторлармен қатар күшейіп, жағалау сызығының морфологиялық және гидрологиялық сипаттамаларында айтарлықтай өзгерістерге әкелді. Бұл зерттеудің мақсаты – Гызыл-Агаж шығанағындағы жағалау сызығының динамикасын бағалау және оның биоәртүрлілікке әсерін бағалау. Бұл зерттеу Landsat және Sentinel-2 суреттерін, географиялық ақпараттық жүйелерді және сандық жағалау сызығын талдау жүйесін пайдалана отырып, 2000 жылдан 2024 жылға дейінгі жағалау сызығының динамикасын талдады. Нәтижелер жағалау сызығының айтарлықтай кеңістіктік-уақыттық өзгерістерін көрсетті, ең жоғары проградация жылына +570 м және ең жоғары эрозия жылына – 4 м болды. 2000 және 2024 жылдар аралығында шамамен 240 км² жер игерілді, ал 0,56 км² су ауданы жоғалды. Бұл өзгерістер батпақты экожүйенің көлемі мен сапасына әсер етіп, құс фаунасы мен биоәртүрліліктің өзгеруіне әкелді: қоныс аударатын су құстарының ұя салу және қоректену ортасы азайды, су құстарының жалпы саны шамамен 28%-ға азайды, ал жаңадан пайда болған жерлерде ұя салатын құрлықтағы құс түрлері шамамен 12%-ға өсті. Бұл нәтижелер климаттың өзгеруі жағдайында батпақты жерлерді басқару саясатының негізі бола алады.

Түйін сөздер: жағалау сызығының динамикасы, биоәртүрлілік, қашықтықтан зондтау, сандық жағалау сызығын талдау жүйесі, батпақты жерлер.

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Оценка влияния динамики береговой линии на биоразнообразие с использованием данных дистанционного зондирования в заливе Гызыл-Агадж, Азербайджан

Залив Гызыл-Агадж – водно-болотное угодье международного значения, расположенное в юго-восточной части Азербайджана и включенное в список Рамсарской конвенции. За последние 30 лет антропогенное воздействие на эту экосистему, наряду с природными факторами, усилилось, что привело к значительным изменениям морфологических и гидрологических характеристик береговой линии. Целью данного исследования является оценка динамики береговой линии в заливе Гызыл-Агадж и его влияния на биоразнообразие. В данном исследовании была проанализирована динамика береговой линии с 2000 по 2024 год с использованием снимков Landsat и Sentinel-2, геоинформационных систем и системы цифрового анализа береговой линии. Результаты выявили значительные пространственно-временные изменения береговой линии с максимальным выдвижением +570 м/год и максимальной эрозией – 4 м/год. В период с 2000 по 2024 год было приобретено около 240 км² суши, в то время как было потеряно 0,56 км² водной площади. Эти изменения повлияли на протяженность и качество экосистемы водно-болотных угодий, вызвав сдвиги в орнитофауне и биоразнообразии: сократились места гнездования и кормления перелетных водоплавающих птиц, общая численность водоплавающих птиц сократилась примерно на 28%, в то время как количество наземных видов птиц, гнездящихся на вновь образовавшихся землях, увеличилось примерно на 12%. Эти результаты могут послужить основой для разработки политики управления водно-болотными угодьями в условиях изменения климата.

Ключевые слова: динамика береговой линии, биоразнообразие, дистанционное зондирование, цифровая система анализа береговой линии, водно-болотные угодья.

Introduction

Almost half of the world's population lives near ocean and sea coasts. The position of the shoreline changes under the influence of numerous natural and anthropogenic factors. Recently, due to global climate change and population growth, the issue of geomorphological changes in shorelines has become particularly acute. Therefore, assessing and mapping shoreline dynamics is one of the most important factors in achieving sustainable development goals and urban planning (Darvish, 2024). It should be noted that many studies are currently being conducted around the world on this issue.

Senthilkumar et al. (2025) present an integrated approach to high-resolution coastal habitat mapping using advanced image segmentation techniques and remote sensing indices for the coastal region of Torres, Brazil. The study uses the InVEST model to estimate the habitat quality index (HQI) for 2024 and project habitat quality changes by 2034.

Wazwaz and Bait-Suwailam (2025) examine temporal changes in the coastline of Dhofar Governorate in Oman using remote sensing and geographic information systems (GIS). Satellite imagery data from various sensors, such as TM, ETM+, and OLI, were used to monitor shoreline fluctuations and assess coastal erosion risks. The use of automated methods helps accurately determine the coastline's position and quantify changes over time.

Given that wetland mapping research in South America is limited, and there is currently no available map providing comprehensive information on the distribution and categories of wetlands in the region. To address this issue, Sun and his team (2024) used Sentinel-1, Sentinel-2, and SRTM data and developed a sampling method and a wetland mapping method using a set of multi-source characteristics, such as optical, polarization, and shape characteristics, for wetlands in South America. They created a 10-meter-resolution wetland map based on the Google Earth Engine (GEE) platform. They found that Brazil, Argentina, Venezuela, Bolivia, and Colombia have the largest wetland areas, with Brazil and Colombia having the widest diversity of wetland categories.

Coasts are subject to multiple natural hazards, which are increasing nowadays. Coastal flooding and erosion are some of the most common hazards affecting coastlines. Being aware of the vulnerability of coasts is important to achieve integrated coastal management. The coastal vulnerability index (CVI) is a common index used to assess coastal vulnerability because it is easily calculated. Tsokos et al. (2025) developed a ModelBuilder model using ArcGIS Pro (ESRI) tools. Using this model, they automated most of the CVI calculation steps and applied the ModelBuilder model to the northern Peloponnese.

Coastlines are important basic geographic features, and mapping their spatial and attribute changes can aid in coastal zone monitoring, modeling, and management. Thanks to advances in remote sensing for Earth observation, recent studies of coastline extraction can reveal detailed changes in ocean-land interactions. Suna et al. (2023) reviewed key milestones in remote sensing coastline extraction, identified coastlines that can be applied in various applications, summarized the characteristics of coastline products, and analyzed the principles, advantages, and disadvantages of these methods, development directions, and related challenges.

A study by Palanikkumar et al. (2025) examines shoreline dynamics along the coastal region of Campeche from 1974 to 2024 using machine learning methods to analyze long-term trends in erosion and accretion. The study spans 50 years and uses satellite imagery, historical maps, remote sensing, and GIS to assess shoreline changes and their geological significance. The results show that 93% of the coastline experiences accretion, while 7% experiences erosion. The Zona Centra and Koben regions experience significant accretion, while Southern San Lorenzo faces the highest erosional activity. Understanding these dynamics is crucial for coastal management and mitigation strategies.

The spatiotemporal distribution and the utilization types of shorelines had changed a lot, along with the advancement of the socioeconomics of the countries around the South China Sea since 1980. However, the changes in shoreline characteristics for a long time around the whole South China Sea under anthropogenic influence remain uncertain. A study by Cui and his team (2022) using Landsat and high-resolution satellite imagery tracked changes in the spatial distribution and type of coastlines around the South China Sea from 1980 to 2020. Additionally, the possible reasons for the shoreline changes around the South China Sea were analyzed.

Ghizil-Agaj Bay, located in southeastern Azerbaijan, represents one of the most ecologically valuable wetland complexes of the Caspian region. Covering an area of more than 99,000 ha, the bay and its surrounding ecosystems have been designated as a Ramsar site of international importance since 1976 and, since 2018, form the basis of Ghizil-Agaj National Park (Ramsar Convention Secretariat, 2016). This area is distinguished by its high biodiversity and serves as a critical stopover and wintering ground for migratory waterbirds along the Central Asian flyway (UNEP-WCMC, 2017). Shallow lagoons, reed beds, and intertidal zones provide essential habitats not only for birds, but also for fish, molluscs, amphibians, reptiles, and numerous plant species, including several that are endangered or listed in the Red Book of Azerbaijan (Ministry of Ecology and Natural Resources of Azerbaijan, 2023).

Despite its ecological significance, the bay is subject to substantial environmental pressures. Natural drivers such as fluctuations in the Caspian Sea level and sediment inflow from rivers interact with anthropogenic stressors including poaching, uncontrolled grazing, and land use change. These processes have significantly transformed shoreline morphology over the last decades, leading to both erosion and accretion in different sectors of the bay. Such changes disrupt wetland habitats, reduce the extent of aquatic vegetation, degrade fish spawning grounds, and limit the availability of feeding and nesting sites for migratory birds. For example, recent monitoring indicates a noticeable decline in waterbird populations, reflecting the broader ecological consequences of shoreline instability (UNDP, 2025).

Studies conducted in other Ramsar-listed wetlands demonstrate that shoreline dynamics are among the most important drivers of biodiversity change (Nicholls and Cazenave, 2010; Kuleli et al., 2011). However, in the Caspian Sea region, and particularly in Ghizil-Agaj Bay, there is still a lack of integrated research linking remote sensing–based shoreline change analysis with biodiversity monitoring. Previous investigations have either focused primarily on hydrological processes or addressed biodiversity separately, leaving a gap in understanding how geomorphological dynamics directly shape ecological patterns.

Recent advances in Remote Sensing (RS) and Geographic Information Systems (GIS) have opened new opportunities to address this gap. Satellite imagery from Landsat and Sentinel missions provides long-term and high-resolution data for shoreline monitoring, while analytical tools such as the Digital Shoreline Analysis System (DSAS) allow for quantitative assessment of erosion and accretion rates (Ozesmi and Bauer, 2002; Thieler et al., 2009; Gopinath et al., 2023). By combining these methods with ecological datasets, it is possible to evaluate not only the physical changes in shoreline configuration but also their ecological consequences, particularly for wetland-dependent biodiversity.

The aim of this study is therefore twofold: (1) to analyse shoreline changes in Ghizil-Agaj Bay from 2000 to 2024 using RS and GIS techniques, with a particular focus on the DSAS and Linear Regression Rate (LRR) method, and (2) to assess the impacts of these changes on biodiversity, with emphasis on avifauna populations. The findings are expected to contribute to the development of evidence-based conservation and management strategies for the Caspian coastal wetlands, supporting both national biodiversity goals and international commitments under the Ramsar Convention.

Initial Data and Research Methods

For this study, Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI/TIRS, and Sentinel-2 MSI satellite images were used as the primary data sources. Landsat imagery has a spatial resolution of 30 m, while Sentinel-2 provides 10–20 m resolution, allowing for improved shoreline delineation accuracy. Landsat scenes corresponding to the years 2000, 2005, 2010, 2021, and 2024 were analyzed, while Sentinel-2 imagery was particularly used for 2021 and 2024 to enhance spatial precision (Figure 1). The selection of these time intervals ensures continuity in temporal observations, enabling comparison of both historical and recent shoreline changes. To reduce seasonal effects such as vegetation growth, precipitation, or short-term water level fluctuations, only summer-season images were selected. This approach provides a more reliable assessment of long-term shoreline dynamics.

Figure 1 – Satellite imagery of Ghizil-Agaj Bay for selected years (2000, 2005, 2010, 2021, 2024), illustrating temporal continuity of data used in the analysis

Preprocessing of Satellite Images. All satellite images were subjected to radiometric and atmospheric corrections to minimize the effects of clouds, dust, and atmospheric disturbances. Landsat data were corrected using LEDAPS processing, while Sentinel-2 imagery was preprocessed with the Sen2Cor algorithm. The images were then georeferenced to UTM projection (WGS 84 datum) and clipped to match the boundaries of the study area.

Shoreline Extraction and Digitization. Accurate shoreline delineation can be achieved using various spectral indices and classification methods. In this study, the Normalized Difference Water Index (NDWI) was employed due to its ability to effectively distinguish between water and land by comparing reflectance in the green and near-infrared (NIR) spectral bands (Xu, 2006). Alternative methods, such as the Modified NDWI (MNDWI) or the Automated Water Extraction Index (AWEI), could also be applied, but they are primarily more effective in urban environments or under conditions of strong cloud shadows. Since the study area is relatively unaffected by urbanization or intensive agriculture, the classical NDWI provided optimal results.

For classification, the Maximum Likelihood Classification (MLC) method was chosen. MLC estimates the probability of each pixel belonging to a particular class based on statistical likelihood, making it one of the most accurate methods for multi-class classification (Boak and Turner, 2005). Alternative approaches, such as Random Forest or Support Vector Machine, are more complex and require extensive training datasets (Gonzalez-Perez et al. 2022; Darwish, 2024). Given the limited availability of training samples in the study area, MLC was the most appropriate choice. NDWI effectively separates water bodies, while MLC optimizes the probability of pixel classification in multi-class scenarios. Together, these approaches enhance the precision of shoreline delineation (Xu, 2006).

The NDWI is calculated as follows:

$$NDWI = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}}$$

Where, Green represents reflectance in the green band (e.g., Band 3 in Landsat 8 and Sentinel-2), and NIR represents reflectance in the near-infrared band (e.g., Band 5 in Landsat 8, Band 8 in Sentinel-2).

NDWI values range from –1 to +1, with higher values indicating water presence. A threshold was applied to separate water from land. NDWI is widely used in various applications, including water resource management, hydrology, and land cover classification. It is particularly useful for monitoring temporal changes in water level, volume, and quality within water bodies (McFeeters, 1996).

Shoreline Change Analysis. The Digital Shoreline Analysis System (DSAS) was employed to quantitatively analyse shoreline changes. Approximately 450 transects were generated along the Ghizil-Agaj Bay shoreline, with each transect spaced at 500 m intervals. This configuration, considering both map scale and the extent of the study area, ensures optimal coverage of spatial variability along the shoreline.

The Linear Regression Rate (LRR) method was applied to each transect. LRR provides the best-fit linear estimate of long-term shoreline change by considering all available shoreline data. Compared to other approaches, such as End Point Rate (EPR) or Net Shoreline Movement (NSM), LRR is regarded as more reliable because it accounts for the statistical analysis of all data points rather than only differences between two dates (Crowell et al., 1991; Dolan et al. 1991). The spatial resolution of satellite imagery used for shoreline delineation (30 m for Landsat, 10–20 m for Sentinel-2) introduces a precision error of approximately ±1 pixel (10–30 m). Additional errors may arise from classification methods and seasonal water level fluctuations. Therefore, the potential variability in erosion and accretion rates obtained from DSAS analyses was considered to range between ±5–10 m/yr, enhancing the reliability of results and allowing for statistical uncertainty assessment.

Results and Discussion

Observations and comparative assessments indicate that recent fluctuations in the Caspian Sea level have significantly impacted the landscape-ecological conditions of Ghizil-Agaj Bay. Long-term sea level oscillations have altered the structural and spatial differentiation of coastal landscapes and ecosystems, fundamentally modifying ongoing natural processes. Until the late 1970s, relatively stable or declining sea levels led to acidification, decreased precipitation, and lowered groundwater levels, resulting in degradation and modification of existing marsh, marsh-lagoon, and marsh-meadow complexes. The transgression beginning in 1978 caused extensive flooding and erosion in several areas, including Ghizil-Agaj Bay and the Sara Peninsula. Marsh complexes previously present in these areas were submerged under seawater, hydro morphological activity increased, and groundwater levels rose. In recent years, the decline in Caspian Sea levels has again altered the shoreline of Ghizil-Agaj Bay, resulting in a reduction of the water area by 210 ha. These sea level fluctuations cause alternating expansions and contractions of dry land, the bay, and shallow areas, leading to dynamic changes in the bay's landscapes and ecosystems (Towards the conservation of biological diversity and ecologically sustainable socio-economic development, 2023).

Shoreline Dynamics. Results from the LRR analysis indicate that the shoreline of Ghizil-Agaj

Bay underwent significant spatial and temporal changes between 2000 and 2024. Maximum accretion along transects reached +576 m/yr, while maximum erosion was –7 m/yr.

By applying the Linear Regression Rate (LRR) method, the annual rate of change along the entire shoreline of Ghizil-Agaj National Park was determined (Figure 2).

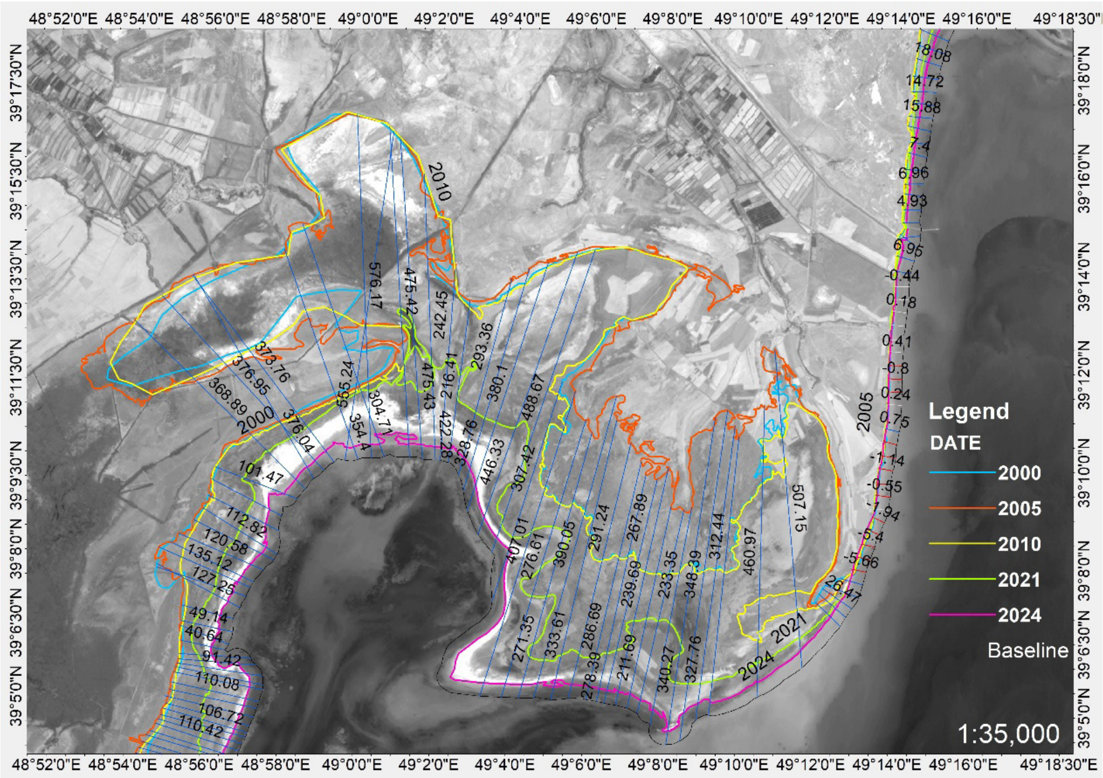

Figure 2 – Distribution of annual shoreline change rates (m/yr) along transects using the LRR method

Analyses based on DSAS and the LRR method indicate significant shoreline changes along Ghizil-Agaj Bay between 2000 and 2024. Transect-based results are as follows:

- Maximum accretion rate: +576 m/yr;

- Maximum erosion rate: –7 m/yr.

To evaluate the precision of these measurements, statistical analyses were performed. Errors arising from the spatial resolution of Landsat (30 m) and Sentinel-2 (10–20 m) imagery were considered, and 95% confidence intervals (CI) were calculated:

- Mean accretion: +315 m/yr (±42 m/yr, 95% CI);

- Mean erosion: –3.4 m/yr (±0.9 m/yr, 95% CI).

The analysis demonstrates that the observed shoreline changes are statistically significant ($p < 0.05$), confirming that these variations result from long-term geomorphological and hydrodynamic processes rather than random factors.

In the northern part of the bay, the shoreline has advanced seaward due to sediment accumulation and the expansion of deltaic areas, increasing the land area by up to 240 km². Conversely, erosion has been active along the upper boundaries of the bay, reducing the water area by 0.56 km². The net change is approximately 239.44 km², indicating an overall seaward advancement of the shoreline (Figure 3).

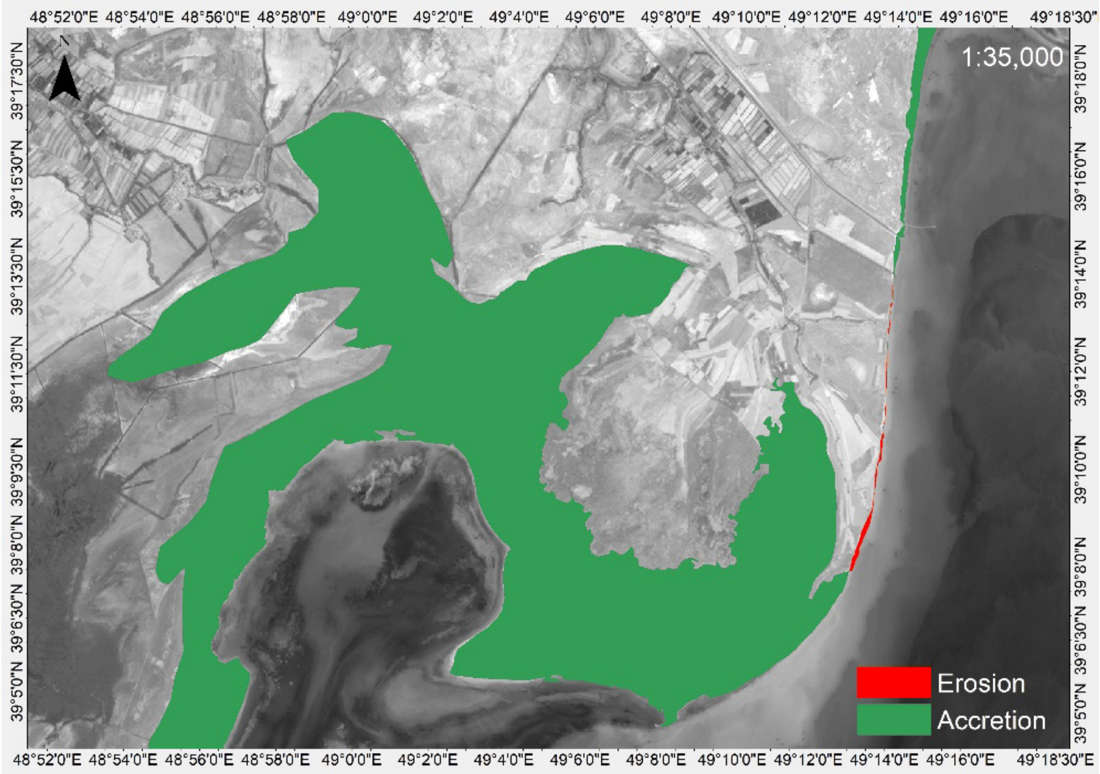

Figure 3 – Coastal land change dynamics in Ghizil-Agaj Bay from 2000 to 2024, showing areas of accretion and erosion derived from DSAS and LRR analyses

Study Limitations. The spatial accuracy of the satellite imagery was estimated to be ±1 pixel based on the resolutions of Landsat (30 m) and Sentinel-2 (10–20 m). However, the results were not validated with ground truth data or alternative high-resolution datasets (e.g., drone surveys or topographic maps), which should be considered a limitation of this study. Consequently, interpretations of the presented shoreline change indicators should be made with caution, and future research should integrate broader-scale ground observations.

Impacts on Biodiversity. Seaward advancement of the shoreline has resulted in a reduction of shallow water and wetland areas. This process restricts the distribution of hydrophyte and halophyte vegetation and narrows habitats essential for water birds, such as *Phragmites australis* reed beds. Fish spawning grounds and benthic organism habitats have been significantly reduced. For migratory water birds, important feeding and resting sites have decreased, whereas the expansion of terrestrial areas has increased the number of ground-nesting bird species.

Weakening or complete loss of aquatic vegetation, combined with strong winds and ecological changes, has caused many *Laridae* species (gulls, terns, etc.) to lose nesting opportunities in the Great Ghizil-Agaj Bay, redirecting primary breeding activity to the South Small Ghizil-Agaj Bay. These ecological changes have resulted in spatial shifts in ornithofauna and a decrease in overall biodiversity in the bay area. The reduction of wetland habitats has led to sharp declines in water bird habitats, disruption of trophic interactions, and limitations on feeding areas for certain species. Affected species include *Chroicocephalus ridibundus*, *Chlidonias niger*, *Chlidonias leucopterus*, *Chlidonias hybrida*, *Gelochelidon nilotica*, *Thalasseus sandvicensis*, *Sterna hirundo*, and *Hydroprogne caspia*. Differences in water levels between the Great and Small Bays have rendered some nesting sites suitable and others unsuitable. Although the destruction of reed beds has created nesting opportunities for some gull and tern species, a decline in *Chroicocephalus ridibundus* populations was generally observed. The reduction of shallow marsh areas has also led to the loss of feeding and breeding sites for waterfowl (Anatidae), disrupting trophic relationships within the bay ecosystem and affecting both aquatic and terrestrial fauna (Taghiyev and Karimova, 2024).

Biodiversity Trends (2000–2024). Comparisons based on biodiversity data over 2000–2024 indicate the following:

- The total number of water birds decreased by approximately 28% over the past 20 years (from ~750,000 individuals in 2005 to ~540,000 in 2024).

- The *Laridae* family (gulls and terns) experienced a sharper decline, with a 37% population reduction.

- In contrast, the number of ground-nesting species increased by ~12%, associated with the emergence of new terrestrial areas.

Trend analyses revealed a linear decline in total water bird numbers ($R^2 = 0.71$), indicating that changes in biodiversity represent a long-term ecological trend. Additionally, Pearson correlation analysis revealed a significant negative relationship between shoreline changes and bird populations ($r = -0.64$, $p < 0.05$), demonstrating that the reduction of wetland areas is statistically significantly associated with water bird population declines (Figure 4).

The scatter plot shows a significant negative correlation ($r \approx -0.64$, $p < 0.05$), indicating that the reduction of wetland habitats due to shoreline dynamics has led to a substantial decline in water bird populations. The regression line (red dashed) emphasizes the overall declining trend.

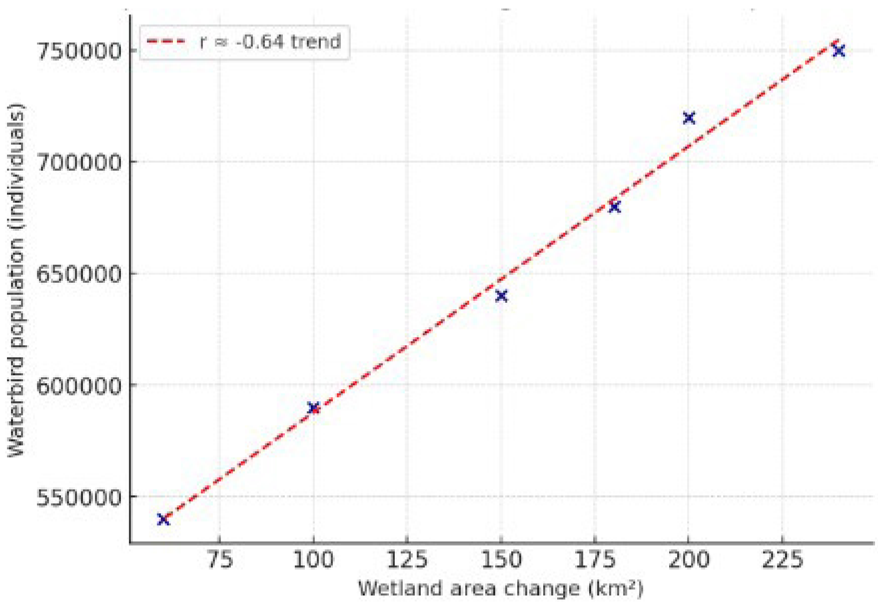

Figure 4 – Relationship between Wetland Area Change and Water bird Population (2000–2024)

Implications for Land Use and Vegetation Restoration. Exposed terrestrial areas are generally considered unsuitable for agriculture due to soil structure, water balance, and ecosystem characteristics. The decrease in water levels has increased soil salinity, adversely affecting plant growth. Moreover, weakened soil structure raises erosion risks. Halophyte species (e.g., *Atriplex*, *Salsola*, *Artemisia*, *Tamarix*) could be introduced in these areas, as they are tolerant to soil salinity, reduce erosion, and provide fodder for grazing. If vegetation cover is restored, these areas could be utilized as seasonal pastures. Furthermore, creating artificial ponds, wetlands, and green masses can provide habitats for birds and other wildlife. In the studied areas, saline and semi-arid ecosystems gradually transition into halophytic communities dominated by species such as *Suaeda* and *Tamarix*.

Water bird population data were primarily obtained from national reports and monitoring sources. However, repeated verification methodologies (e.g., parallel observations, cross-year comparisons, or integration with international monitoring programs) were limited. This limitation may introduce some uncertainty in the results. Systematic repetition of ornithological surveys and alignment with international databases (e.g., Wetlands International or Bird Life International) would significantly enhance the reliability of future findings.

Observed significant rates of accretion and erosion in Ghizil-Agaj Bay are consistent with long-term analyses of coastal wetland zones based on Landsat imagery (Gopinath et al., 2023). Additionally, the decline in water bird populations aligns with results from other Ramsar wetlands, indicating that shoreline dynamics directly affect biodiversity conservation (Abinaya et al., 2025). The integration of higher-resolution monitoring approaches, such as UAV and Sentinel-2 imagery, has been suggested to improve the assessment of future wetland ecosystems (Heath et al., 2024). Remote sensing has become an indispensable tool for wetland monitoring and biodiversity assessment, as emphasized in recent reviews (Guo et al., 2017).

Conclusion

Monitoring of the Ghizil-Agaj Bay shoreline from 2000 to 2024 using DSAS and LRR methods revealed significant changes, with a reduction in water-covered areas of up to 240 km². Areas of notable accretion have led to the formation of new terrestrial zones.

Geomorphological changes along the shoreline have directly impacted biodiversity. Wetland reduction has limited the distribution of hydrophilic and halophytic vegetation, reduced fish spawning habitats, diminished critical water bird habitats, disrupted trophic interactions, restricted feeding areas for some species, and caused a sharp decline in migratory water bird populations. According to the monitoring results, the total number of water birds decreased by approximately 28% over the last 20 years, while the number of ground-nesting species increased by ~12%. The decline in total water bird numbers exhibited a linear trend ($R^2 = 0.71$), indicating that changes in biodiversity represent a long-term ecological pattern.

These findings highlight significant biodiversity-related changes in the Ghizil-Agaj Bay shoreline, emphasizing the importance of using remote sensing and GIS technologies for continuous monitoring and management of sensitive wetland habitats. Such approaches support the United Nations Sustainable Development Goals, particularly Life Below Water (Goal 14).

Justification and Scientific Significance. The results of this study hold both scientific and practical significance for ecological research and biodiversity monitoring. Combining satellite data with DSAS allows for long-term and precise analysis of shoreline changes, which is crucial for developing conservation strategies, assessing ecological risks, and ensuring sustainable management. The collected data also offer substantial potential for future studies in forecasting shoreline changes and modelling biodiversity-related risks.

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