

Investigation of Shoreline Change Rates and Prediction of Future Shoreline Position Using Remote Sensing and Geographic Information Systems (Case Study: Coasts from Jazireh Shomali to Bandar Rig, Bushehr Province, Iran)

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Abstract

The coastal zone is one of the most dynamic and sensitive geographical environments, constantly shaped by the combined effects of natural processes and human activities, which drive pronounced spatial and temporal variability. Monitoring and quantifying shoreline change are therefore essential for sustainable coastal management, hazard mitigation, infrastructure protection, and development planning. In this study, shoreline dynamics along the coastal stretch from Jazireh Shomali to Bandar Rig, in Bushehr Province, southern Iran, were analysed over a 30-year period (1993–2023) using multi-temporal Landsat satellite imagery (TM, ETM+, and OLI) within a remote sensing (RS) and geographic information system (GIS) framework. The images were subjected to radiometric and geometric corrections and processed using the Tasseled Cap transformation to accurately delineate shoreline positions. Shoreline change rates were then quantified with the Digital Shoreline Analysis System (DSAS) using Net Shoreline Movement (NSM), End Point Rate (EPR), and Linear Regression Rate (LRR) indices. The results reveal that coastal erosion is the predominant trend across large portions of the study area, with maximum shoreline retreat of approximately 1216 m, whereas only limited segments exhibit substantial accretion, with shoreline advance reaching up to 1528 m. Future shoreline evolution was simulated using a Kalman filter–based forecasting model, indicating that erosional trends are likely to persist over the next 10–20 years, particularly along the central and southeastern coastal sectors. Without appropriate management interventions, these areas may experience further shoreline retreat and increased exposure of coastal infrastructure to marine hazards. Overall, the findings provide a robust scientific basis for coastal risk assessment, shoreline protection planning, the design of coastal engineering structures, and evidence-based policymaking aimed at sustainable development along the Bushehr Province shoreline.

1. Introduction

Coastal zones are among the most dynamic and vulnerable environmental systems on Earth, continuously reshaped by the interaction between natural processes and human activities (Bamunawala et al., 2021; Alvarez-Cuesta et al., 2021; Dhiman et al., 2021; Le Cozannet et al., 2019; Dal Barco et al., 2024; Nicholls and Cazenave, 2010; Khurram et al., 2025). Coastal storms, tidal dynamics, sea-level rise, climate change, coastal engineering works, and the rapid expansion of human activities are key drivers of shoreline change. These processes can profoundly affect coastal ecosystems, natural resources, human settlements, and critical infrastructure, to the extent that shoreline erosion has emerged as one of the major environmental and socio-economic challenges facing many coastal regions worldwide in recent decades (Khurram et al., 2025).

To monitor and analyse coastal change trends, the integration of remote sensing (RS) and geographic information systems (GIS) provides an efficient and scientifically robust approach (Khurram et al., 2025). Remote sensing, through the acquisition of multi-temporal observations of the Earth's surface, offers an effective means for continuous monitoring of changes across extensive coastal areas (Yum et al., 2023; Zhao et al., 2022; García-Rubio et al., 2015). On the other hand, GIS, with its advanced analytical and

modeling capabilities, enables the extraction of spatial patterns, analysis of change trends, and simulation of future scenarios (Khurram et al., 2025; Yum et al., 2023; Zhao et al., 2022; García-Rubio et al., 2015). The combination of these two technologies is now widely recognised as the gold standard for shoreline change studies. Monitoring and analysis of shoreline changes in recent decades have attracted considerable attention as a key research field within coastal sciences, oceanography, geomorphology, and coastal zone management (Khurram et al., 2025; Ennouali et al., 2023; Ramachandran et al., 2025; Blais and Akhloufi, 2025). Increasing coastal erosion, sea-level fluctuations, urban and port development, excessive sediment extraction, climate change, and extreme events such as marine storms have driven researchers to investigate and predict the spatio-temporal patterns of shoreline change using advanced RS and GIS techniques. The availability of multi-temporal satellite image processing, open-access Landsat and Sentinel datasets, and the development of digital shoreline analysis tools (e.g., DSAS) have led to a significant growth in shoreline-related studies in recent years.

At the international level, a substantial body of research has focused on the use of multi-temporal Landsat satellite imagery in combination with the Digital Shoreline Analysis System (DSAS) for long-term shoreline change analysis. Studies such as Darwish and Smith (2023) and Sun et al. (2023) demonstrated that Landsat data, despite their moderate spatial resolution, are capable of extracting shoreline changes over periods of 30 to 40 years with acceptable accuracy. Similarly, Abd-Elhamid et al. (2023) employed remote sensing techniques and geographic information systems to investigate shoreline change trends in the Nile Delta, highlighting the effectiveness of satellite-based approaches in large and dynamic coastal environments. This group of studies has primarily emphasised the extraction and interpretation of key statistical indicators, including Net Shoreline Movement (NSM), End Point Rate (EPR), and Linear Regression Rate (LRR), which constitute the core analytical components of DSAS-based shoreline change assessments.

In very recent years, particularly during the period 2023–2025, research attention has increasingly focused on shoreline change analysis using multi-temporal datasets, machine learning algorithms, and advanced analytical frameworks such as DSAS. For example, Mahmoud et al. (2025) proposed an efficient approach for automated and high-precision shoreline extraction from satellite imagery by developing a deep learning framework based on semantic segmentation (U-Net) and boundary detection (BDCN). Their results demonstrated that the hybrid BDCN–U-Net model exhibited stable performance across satellite datasets with varying spatial resolutions, significantly improving shoreline extraction accuracy. In other studies, Zambrano-Medina et al. (2023) and Zhou et al. (2023) integrated multi-temporal satellite-based models with DSAS, showing that hybrid approaches can substantially enhance the accuracy of shoreline change analysis. These methodologies have attracted considerable attention in recent years and are increasingly recognised as a novel pathway for the development of advanced and intelligent analytical frameworks in coastal research.

In the field of shoreline position prediction, several recent studies have also been conducted. For example, in the Gulf of California, Zambrano-Medina et al. (2023) applied multivariate time-series models in combination with DSAS to predict shoreline changes over a 20-year horizon, demonstrating that

erosion rates can be reconstructed with satisfactory accuracy based on historical trends. Similarly, Khakhim et al. (2024) employed spatio-temporal frameworks and a Kalman filter approach to demonstrate the capability of future-oriented models in predicting long-term trends of shoreline morphological changes. Beyond classical DSAS-based approaches, some studies have utilised fuzzy clustering techniques, such as Fuzzy C-Means (FCM), to identify similarities in shoreline change patterns and to classify coastal segments exhibiting comparable erosional or accretional behaviours (Zorlu and Kuşak, 2025). Given the highly dynamic nature of coastal environments, the application of future-oriented models based on spatio-temporal and time-series analyses has become critically important and is increasingly recognised as a key methodological innovation in recent shoreline change studies.

Given the highly dynamic nature of shorelines and the increasing trend of coastal erosion along the northern coasts of Bushehr Province—particularly within the Jazireh Shomali to Bandar Rig coastal segment—conducting quantitative and long-term shoreline change analyses is of critical importance. Accordingly, the present study focuses on the spatio-temporal analysis of shoreline changes over 30 years (1993–2023) using multi-temporal Landsat satellite imagery and the analytical capabilities of geographic information systems (GIS). This study aims to provide an integrated and comprehensive evaluation of shoreline dynamics by examining the spatial and temporal variability of coastal erosion and accretion, and by elucidating the distinct responses of individual coastal segments using quantitative shoreline-change indicators. The findings of this study provide a scientific basis for risk reduction, coastal protection, and sustainable development policymaking in the region. Furthermore, the findings underscore the importance of continuous shoreline monitoring and the use of advanced geospatial techniques to support integrated coastal zone management. The novelty of this study lies in the integration of accurate shoreline extraction techniques with multi-indicator statistical analyses and spatio-temporal evaluation of shoreline change rates, combined with a future-oriented prediction framework. This approach provides an efficient and transferable methodology that can serve as a practical reference for long-term shoreline monitoring studies in other coastal regions of the Persian Gulf.

2. Study Area

The study area encompasses the coastal stretch between Jazireh Shomali and Bandar Rig, located in the northern part of Bushehr Province along the northern shoreline of the Persian Gulf (Fig. 1). This coastal segment forms part of the northern Bushehr coastline and is strongly influenced by Zagros-derived alluvial deposits and sediments supplied by seasonal rivers draining the southern flanks of the Zagros Mountains. The shoreline in the study area is predominantly sandy to muddy–sandy, and sediment redistribution driven by wave action, tidal currents, and prevailing west to north-westerly winds plays a decisive role in controlling the regional coastal morphodynamics. The climate of the region is hot and arid, characterised by long, extremely hot summers, mild winters, high evaporation rates, and low annual precipitation. In most years, saltwater intrusion and environmental instability, particularly near seasonal river mouths and low-lying coastal zones, are highly pronounced. These geomorphological and climatic characteristics make the study area particularly susceptible to rapid shoreline changes across

multiple temporal scales, highlighting its suitability for long-term spatio-temporal shoreline change analysis and future-oriented coastal assessment.

3. Materials and Methods

3.1. Data and Satellite Imagery

To monitor long-term shoreline change trends and predict future shoreline positions, multi-temporal satellite imagery from the Landsat mission was employed. Four representative epochs—1993, 2002, 2013, and 2023—were selected to provide a consistent 30-year temporal coverage (1993–2023) suitable for analysing historical shoreline dynamics and long-term coastal evolution. The dataset includes images acquired by Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI sensors, which offer appropriate spatial resolution and long-term continuity for shoreline change studies. All images were obtained from the United States Geological Survey (USGS) archive. Following the delineation of the study area in ArcGIS, the corresponding Landsat path/row was identified using the USGS EarthExplorer platform, and satellite images with minimal cloud cover and favourable acquisition conditions were selected to ensure reliable shoreline extraction. Details of the satellite images used in this study—including acquisition year, satellite platform, sensor type, image identification code, spatial resolution, and data source—are summarised in Table 1. The integration of these multi-temporal datasets enables robust quantitative analysis of shoreline displacement and supports subsequent statistical and predictive modeling.

Table 1
Specifications of the Landsat satellite images used in this study

Year	Satellite	Sensor	Image ID	Spatial Resolution	Data Source
1993	Landsat-5	TM	LT05_L1TP_164039_19930824	30 m	USGS
2002	Landsat-7	ETM+	LE07_L2SP_164039_20020724	30 m (15 m pan)	USGS
2013	Landsat-8	OLI	LC08_L1TP_164039_20130730	30 m (15 m pan)	USGS
2023	Landsat-8	OLI	LC08_L1TP_164039_20230726	30 m (15 m pan)	USGS

3.2. Image Pre-processing

Radiometric, geometric, and atmospheric corrections were applied to all satellite images before shoreline extraction. Surface reflectance products were derived based on sensor-specific calibration coefficients to ensure radiometric consistency among the multi-temporal datasets. To minimise the effects of clouds and cloud shadows, the internal quality assessment (QA) and cloud masking algorithms provided by the USGS were employed. Subsequently, all images were co-registered to a common spatial reference framework to ensure spatial consistency across different acquisition dates.

These pre-processing steps significantly enhanced the positional accuracy of the extracted shorelines and reduced potential uncertainties associated with multi-temporal shoreline change analysis.

3.3. Spectral Indices and Water-Land Separation

To enhance the contrast between water and terrestrial features, the Tasseled Cap Transformation (TCT)—specifically the Wetness component—was utilised. This index is particularly effective for the muddy and sedimentary environments of the Persian Gulf, due to its high sensitivity to moisture content and shallow water surfaces (Tamassoki et al., 2014; Shamsuzzoha and Ahamed, 2023). After standardising the Wetness layer, an optimal thresholding technique was applied to generate a binary water-land mask. Additionally, the Normalised Difference Water Index (NDWI) was calculated in specific cases to cross-validate and ensure the consistency of the delineation results.

3.4. Shoreline Extraction

The classified raster layers were subjected to morphological filtering and noise removal, and subsequently converted into vector format. The boundary between land and water was defined as the shoreline and independently extracted for each study year. Visual quality control was conducted using high-resolution Google Earth imagery and a digital elevation model (DEM) to reduce misclassification in turbid or sun-glitter-affected areas.

3.5. Shoreline Change Analysis using DSAS

Quantitative shoreline change analysis was conducted using the Digital Shoreline Analysis System (DSAS) version 5.0 implemented in the ArcMap environment. Multi-temporal shoreline vectors extracted for different years were imported into DSAS, which was developed by the USGS for shoreline change assessment (Danforth and Thieler, 1992; Himmelstoss et al., 2018, 2021). A baseline was first established along the general orientation of the coast, and transects were generated perpendicular to the baseline at intervals of 50 to 100 m. DSAS computed standard statistical indicators, including Net Shoreline Movement (NSM), End Point Rate (EPR), Linear Regression Rate (LRR), and Weighted Linear Regression (WLR). These metrics enabled the identification and spatial-temporal analysis of erosional and accretional trends along the study coastline.

- **Statistical Indices of Shoreline Change**

In this study, five principal statistical indices were employed to quantify shoreline change. Net Shoreline Movement (NSM) represents the distance, in meters, between the oldest and the most recent shoreline positions. Shoreline Change Envelope (SCE) measures the maximum distance between the two farthest shoreline positions at each transect, regardless of their temporal order. The End Point Rate (EPR) calculates the rate of shoreline change by dividing the NSM by the time elapsed between the oldest and most recent shoreline positions. The Linear Regression Rate (LRR) estimates the shoreline change rate by fitting a linear regression line to the distances of shoreline positions from the baseline over time. The Weighted Linear Regression Rate (WLR) is similar to LRR; however, shoreline positions are weighted

according to their positional uncertainty, thereby providing a more robust estimate of shoreline change rates.

3.6. Predictive Modeling and Future Projections

To forecast shoreline positions over the next 20 years, a Kalman filter model was implemented. This recursive mathematical algorithm was selected for its robustness in modeling dynamic coastal processes and its ability to handle noisy time-series data. The model integrated historical shoreline positions and shoreline change rates derived from DSAS to generate predicted shoreline coordinates for the year 2043. The outputs include both the projected spatial position of the coastline and a potential risk map highlighting zones with higher predicted shoreline displacement and erosional susceptibility.

3.7. Accuracy Assessment and Uncertainty Analysis

The predictive models' performance was evaluated using Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE). To quantify the total positional uncertainty (E_{total}), which represents the positional error, both the spatial resolution of the Landsat imagery (± 15 m) and the user-induced digitising error were incorporated into the overall error budget. These assessments enhanced the reliability and robustness of the shoreline change analysis and future projections. Finally, all spatial analyses, statistical computations, and visualisations were performed using ArcGIS Pro, ArcMap, MATLAB, and Microsoft Excel.

4. Results

4.1. Shoreline Changes in the Jazireh Shomali to Bandar Rig Area (1993–2023)

Rig Port, the administrative centre of Rig District in Genaveh County, is located approximately 17 km southeast of Genaveh Port along the northern coast of the Persian Gulf. The shoreline changes within the Jazireh Shomali to Bandar Rig sector over the period from 1993 to 2023 are illustrated in Fig. 2, where shorelines corresponding to different years are delineated using distinct colours for visual comparison. The results indicate that this coastal segment has been predominantly affected by erosional processes over the past three decades. The observed spatio-temporal pattern reflects an unstable shoreline behaviour, characterised by considerable landward and seaward shifts at different locations along the coast. A clear spatial discrepancy is evident among the extracted shorelines for the years 1993, 2002, 2013, and 2023, highlighting pronounced positional changes over time. Erosional zones are particularly prominent in the central and southeastern sections of the study area, where shoreline retreat is more extensive and spatially continuous. These findings suggest that the coastal dynamics of this sector are governed by persistent erosional tendencies, likely driven by the combined effects of hydrodynamic processes and local geomorphological conditions.

4.1.1. Net Shoreline Movement (NSM) Analysis in the Jazireh Shomali to Bandar Rig Sector

The Net Shoreline Movement (NSM) results for the Jazireh Shomali to Bandar Rig sector reflect the combined influence of erosional and accretionary processes along this coastal stretch. As illustrated in Figs. 3 and 4, accretional conditions are observed at the initial part of the study area; however, shoreline erosion dominates most sections of the coastline thereafter. The maximum shoreline retreat reaches -1216.54 m, whereas the maximum shoreline advancement attains $+1528.01$ m. Furthermore, the mean values of shoreline retreat and advancement are -425.52 m and $+408.56$ m, respectively. These results indicate a marked spatial variability in shoreline behaviour, with erosion prevailing across large portions of the study area despite localised accretional zones.

4.1.2. End Point Rate (EPR) Analysis in the Jazireh Shomali to Bandar Rig Sector

The End Point Rate (EPR) index was employed to quantify the average shoreline displacement over the 30 years from 1993 to 2023. As illustrated in Fig. 5, most portions of the coastline are characterised by erosional trends, while localised accretion occurs primarily at the northern part of the study area.

According to the EPR results (Fig. 6), the maximum shoreline retreat reaches -40.66 m yr⁻¹, whereas the maximum shoreline advance attains $+51.07$ m yr⁻¹. The mean erosion and accretion rates are -21.23 m yr⁻¹ and $+13.41$ m yr⁻¹, respectively. Spatially, sedimentation dominates in the initial sector of the study area, transitioning to widespread erosion along most of the coastline thereafter.

The EPR spatial pattern is highly consistent with the NSM results, confirming that approximately 70% of the shoreline is dominated by erosional processes. This trend underscores the influence of hydrodynamic factors, particularly onshore currents and southwestward-approaching waves, which contribute significantly to sediment removal in this coastal region.

4.1.3. Linear Regression Rate (LRR) Analysis in the Jazireh Shomali to Bandar Rig Sector

The Linear Regression Rate (LRR) was applied to assess the long-term trend and to provide a more robust prediction of future shoreline position within the study area. As illustrated in Figs. 7 and 8, the maximum shoreline retreat recorded by this indicator is -43.71 m yr⁻¹, while the maximum shoreline advance reaches $+43.33$ m yr⁻¹. The average erosion and accretion rates are -17.43 m yr⁻¹ and $+9.22$ m yr⁻¹, respectively.

The overall shoreline change statistics derived for the Jazireh Shomali – Bandar Rig sector are summarised in Table 2, which compiles the maximum and mean values of erosion and accretion calculated from the three indices—NSM, EPR, and LRR. The comparison clearly confirms the dominance

of erosional processes along most of the coastline, consistent with the spatial patterns identified in the previous analyses.

Table 2
Shoreline change rates in the Jazireh Shomali to Bandar Rig coastal sector

Index	Mean Accretion	Maximum Accretion	Mean Erosion	Maximum Erosion	Range of Change
LRR (m yr ⁻¹)	+ 9.22	+ 43.33	-17.43	-43.71	Linear regression–based change rate
EPR (m yr ⁻¹)	+ 13.41	+ 51.07	-21.23	-40.66	End-point shoreline change rate
NSM (m)	+ 408.56	+ 1528.01	-425.52	-1216.54	Net shoreline displacement

4.2. Prediction of Future Shoreline Position

Shoreline predictions were performed using the Kalman filter model, based on the time-series of EPR and LRR outputs derived from the DSAS analysis. This approach enables the filtering of noise and the estimation of future shoreline positions by integrating historical trends with stochastic variability. The prediction results for each coastal segment are presented below.

- **Predicted Shoreline Changes in the Jazireh Shomali to Bandar Rig Sector**

The predicted shoreline position for the study area is illustrated in Fig. 9. The results indicate a maximum shoreline advance of + 19.66 m and a maximum shoreline retreat of – 104.49 m within the prediction horizon. These findings suggest the continued dominance of erosional processes, accompanied by localised and intermittent accretionary phases along limited sections of the coastline. Overall, the predicted patterns demonstrate a repetition of shoreline change trends observed in the historical analysis, particularly in relation to erosion and sedimentation processes. The obtained predictions provide a quantitative basis for coastal management, supporting informed decision-making for shoreline protection, land-use planning, and sustainable coastal development in the study area.

4.3 Accuracy Assessment of Predictive Models

To evaluate the accuracy of shoreline predictions, statistical metrics such as the Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE) were employed. These analyses assessed the reliability and precision of projections generated by the EPR and LRR models, measuring the uncertainty of long-term shoreline predictions over a 20-year time frame. The primary objective of this evaluation was to identify the suitability of these models in representing shoreline trends and quantifying their predictive uncertainty. Based on the statistical analyses performed, the Linear Regression Rate (LRR) exhibited consistently superior accuracy compared to the End Point Rate (EPR) in both MAPE and RMSE criteria. This result highlights the effectiveness of LRR in capturing long-term shoreline behaviour,

compared to EPR's focus on short-term changes. Therefore, LRR provides a more reliable basis for future shoreline predictions, and its application is recommended for precise modeling of coastal dynamics. By emphasising long-term trends, the LRR model demonstrates an improved capacity to predict the future shoreline position compared to the episodic changes detected by EPR methods. This outcome underlines the importance of using long-term trend-based approaches for coastal management and planning, ensuring more accurate projections of shoreline evolution.

5. Discussion

The results of this study indicate that the shoreline of the investigated area along the northern coasts of Bushehr Province has undergone substantial changes over the past three decades, with a predominantly erosional trend observed across many coastal segments. This pattern reflects the geomorphological instability of the northern Bushehr coastline and is consistent with both national and international studies emphasising the combined influence of natural processes and human activities on accelerating shoreline instability (Chen et al., 2023; Khurram et al., 2025).

Time-series analysis of shorelines extracted from Landsat imagery, using the Tasseled Cap–Wetness spectral index in conjunction with the DSAS tool, revealed that the Jazireh Shomali to Bandar Rig sector exhibits higher erosion rates compared to other parts of the study area. This spatial pattern aligns well with previous investigations conducted along the Bushehr coastline and other southern Iranian coasts, highlighting the role of low-slope coastal morphology and the hydrodynamic conditions of the Persian Gulf in intensifying shoreline retreat rates. Similar findings have also been reported for the coasts of Morocco, where shallow nearshore environments experienced the highest magnitudes of shoreline retreat (Hakkou et al., 2018).

At the same time, the observation of localised accretion patterns in certain coastal segments indicates that shoreline behaviour in the study area is not uniform, but is instead influenced by the complex interaction of hydrodynamic forces, coastal topography, and alluvial sediment inputs. These results are consistent with studies conducted along the coasts of Kuwait and other regions of the Persian Gulf, which have reported the dual role of natural processes and human activities in driving shoreline changes (Aladwani, 2022).

The role of human activities, particularly the construction of piers, breakwaters, and coastal infrastructure developments, in altering nearshore current regimes and sediment transport patterns is also evident in the results of this study. These interventions have intensified erosional processes in adjacent coastal sections in certain areas, a phenomenon that has been widely reported in global studies as one of the primary drivers of coastal instability (Kanwal et al., 2020; Natesan et al., 2015).

In the prediction component, the application of the Kalman filter model indicated that the erosional trend is likely to persist over the next 20 years within the study period, although its intensity is not spatially uniform along the shoreline. This finding is consistent with results reported from studies conducted along the coasts of India and the Mediterranean, which emphasise the necessity of employing time-

series-based models for analysing shoreline changes in regions characterised by high sedimentary variability (Abd-Elhamid et al., 2023).

Furthermore, uncertainty assessment of the models using the MAPE and RMSE indices demonstrated that the Linear Regression Rate (LRR) provides more stable performance and higher accuracy than the End Point Rate (EPR) in the analysis and prediction of long-term shoreline changes. This result is consistent with the findings of Thieler et al. (2009) and recent studies based on multi-decadal shoreline analyses. Overall, the results of this study emphasise the necessity of continuous shoreline monitoring and the application of quantitative approaches based on remote sensing and GIS as effective tools for risk management and sustainable coastal planning along the northern coasts of Bushehr Province.

6. Conclusions

The present study employed multi-temporal Landsat satellite data, image processing techniques, the Tasseled Cap spectral index, and the Digital Shoreline Analysis System (DSAS) to evaluate and analyse shoreline change trends along the coastal stretch extending from Jazireh Shomali to Bandar-e-Rig over 30 years (1993–2023) with satisfactory accuracy. The results indicate that this coastal zone has been predominantly affected by continuous erosion over the past three decades, while localised accretion has occurred in certain segments. This pattern reflects the high dynamism and geomorphological sensitivity of the northern coasts of Bushehr Province. Analysis of the NSM, EPR, and LRR indices further revealed that the dominant shoreline change pattern is characterised by persistent erosion accompanied by spatial variability in the intensity of changes along the coastline.

The application of the Kalman filter model in the subsequent analyses indicated that the continuation of erosional trends over the next 10–20 years is highly likely. In the absence of appropriate management interventions, certain coastal segments may experience more pronounced shoreline displacements. These findings underscore the necessity of coastal structure management, control of sediment extraction, and scenario-based planning grounded in future shoreline evolution. The novelty of this study lies in the integrated use of the Tasseled Cap spectral index, long-term time-series analysis, and Kalman filter-based predictive modeling, which together enable a more robust interpretation of spatio-temporal shoreline dynamics and provide more reliable estimates of future coastal change trends.

Overall, the findings of this study indicate that the northern coasts of Bushehr Province, along the stretch from Jazireh Shomali to Bandar-e-Rig, are highly vulnerable to both natural and anthropogenic changes, and that the continuation of current trends may pose a serious threat to coastal infrastructure, shore-based economic activities, and regional ecosystems. Therefore, integrating the results of this research within the framework of Integrated Coastal Zone Management (ICZM) can contribute to risk reduction, enhancement of coastal resilience, and support for informed decision-making. It is recommended that future studies incorporate higher-spatial-resolution datasets, such as Sentinel-2 and UAV imagery, as well as advanced machine-learning approaches, to further improve the accuracy of shoreline extraction and the prediction of future shoreline changes.

Declarations

Author Contribution

A: data collector B: Supervisor, writer, data analysis C: Advisor, writer, discussion

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Figures

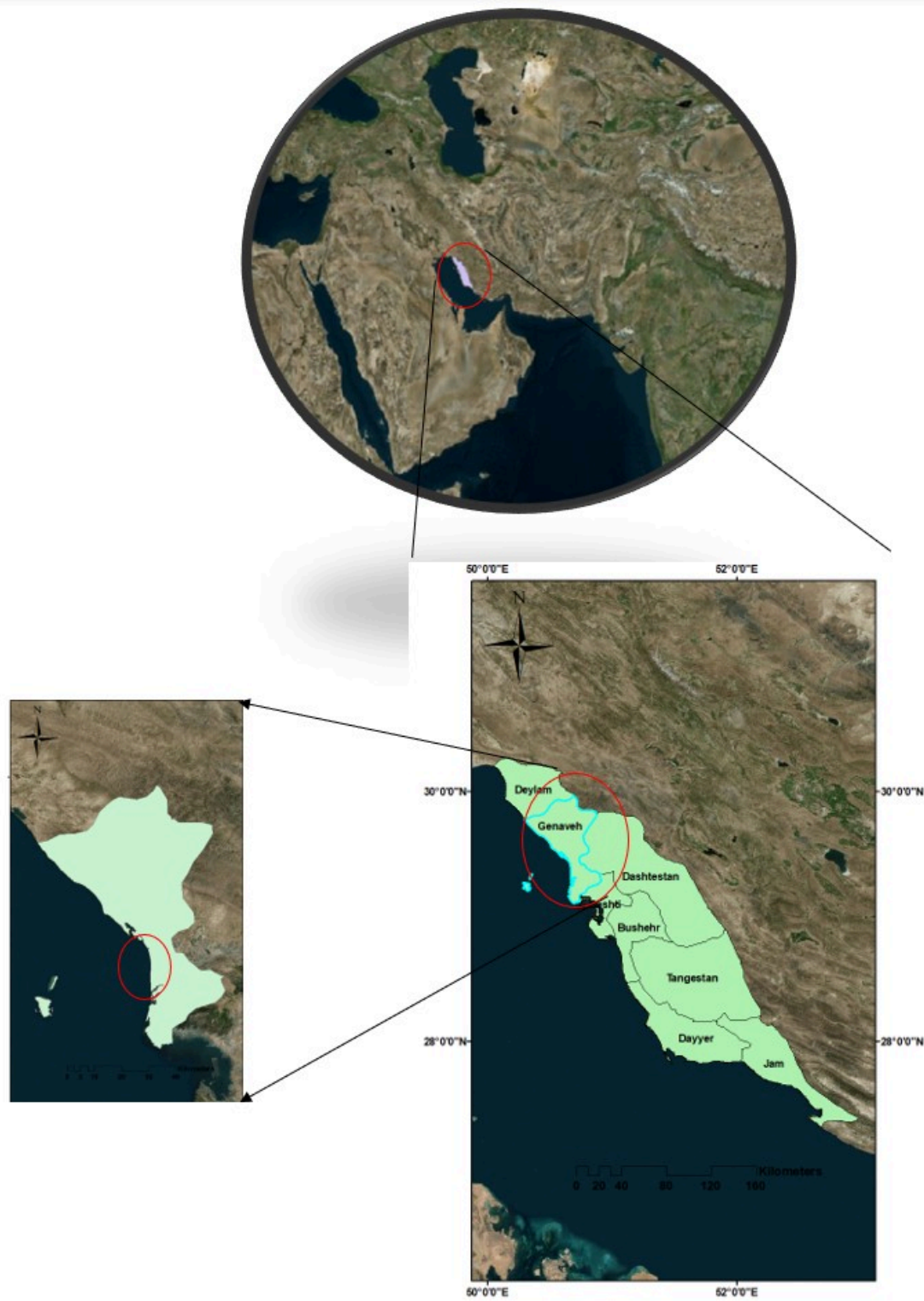


Figure 1

Location of the study area

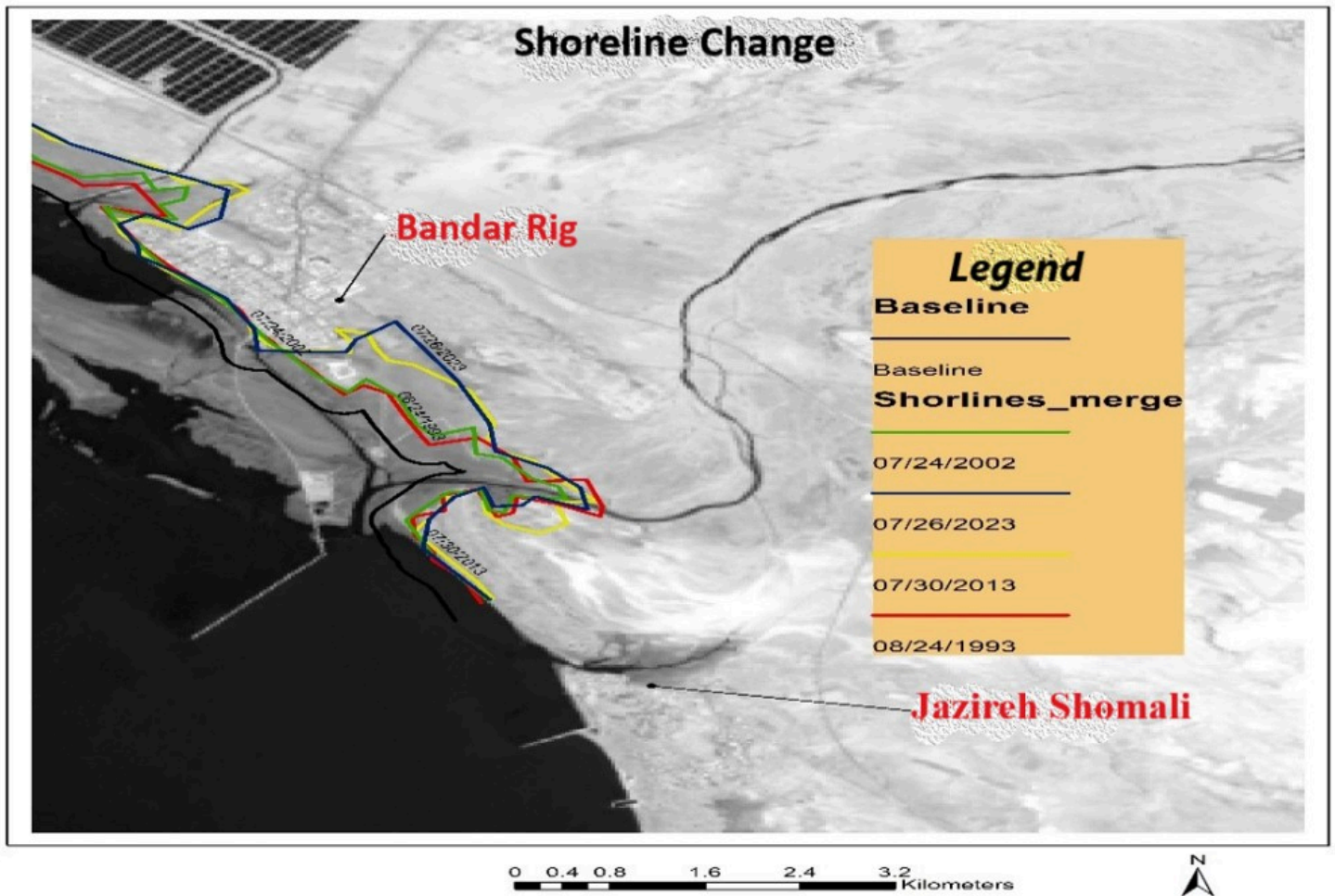


Figure 2

Shoreline changes along the coastal stretch from Jazireh Shomali to Bandar-e-Rig during the period 1993–2023.

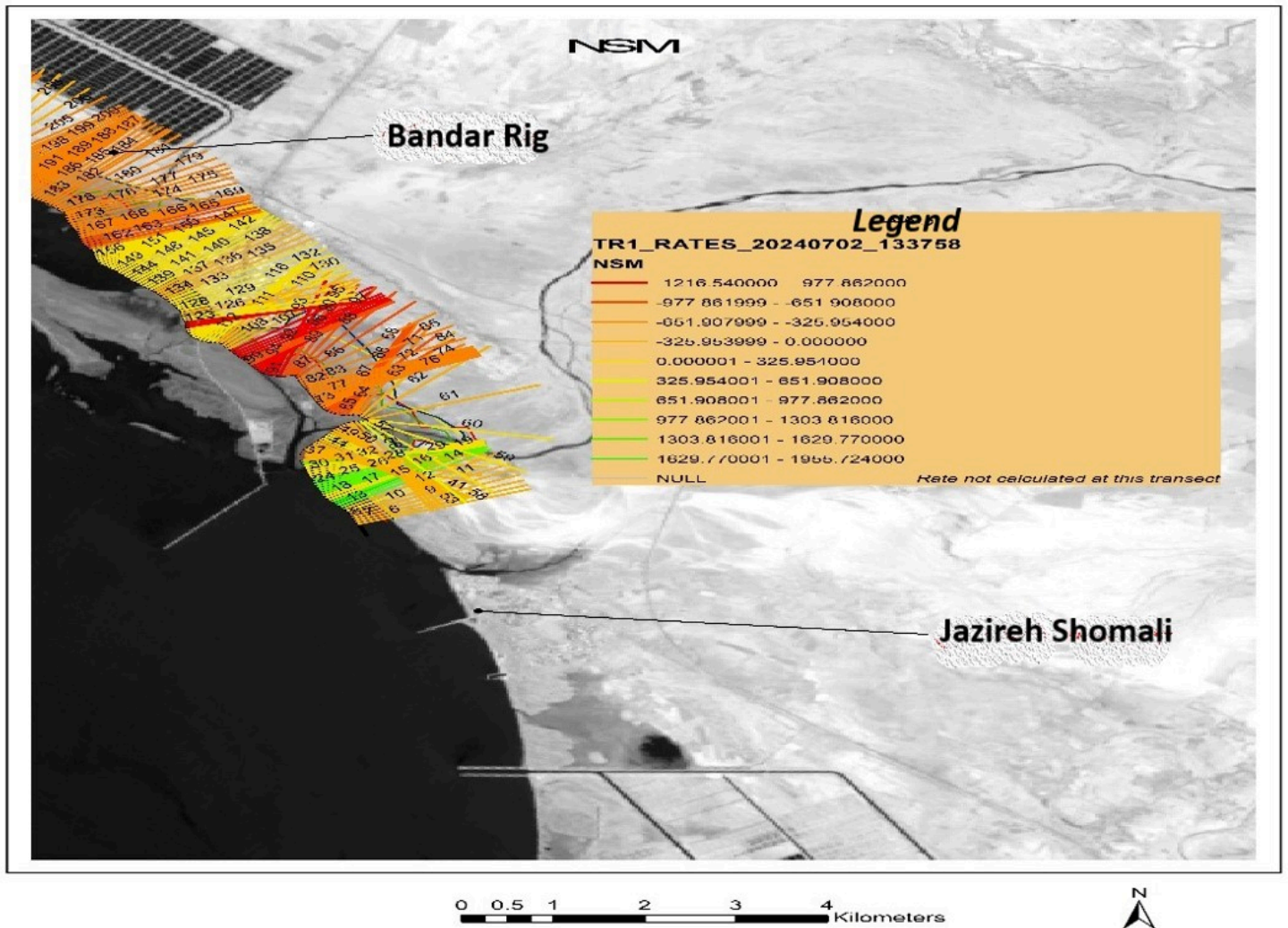


Figure 3

Net Shoreline Movement (NSM) along the coastal stretch from Jazireh Shomali to Bandar-e-Rig for the period 1993–2023.

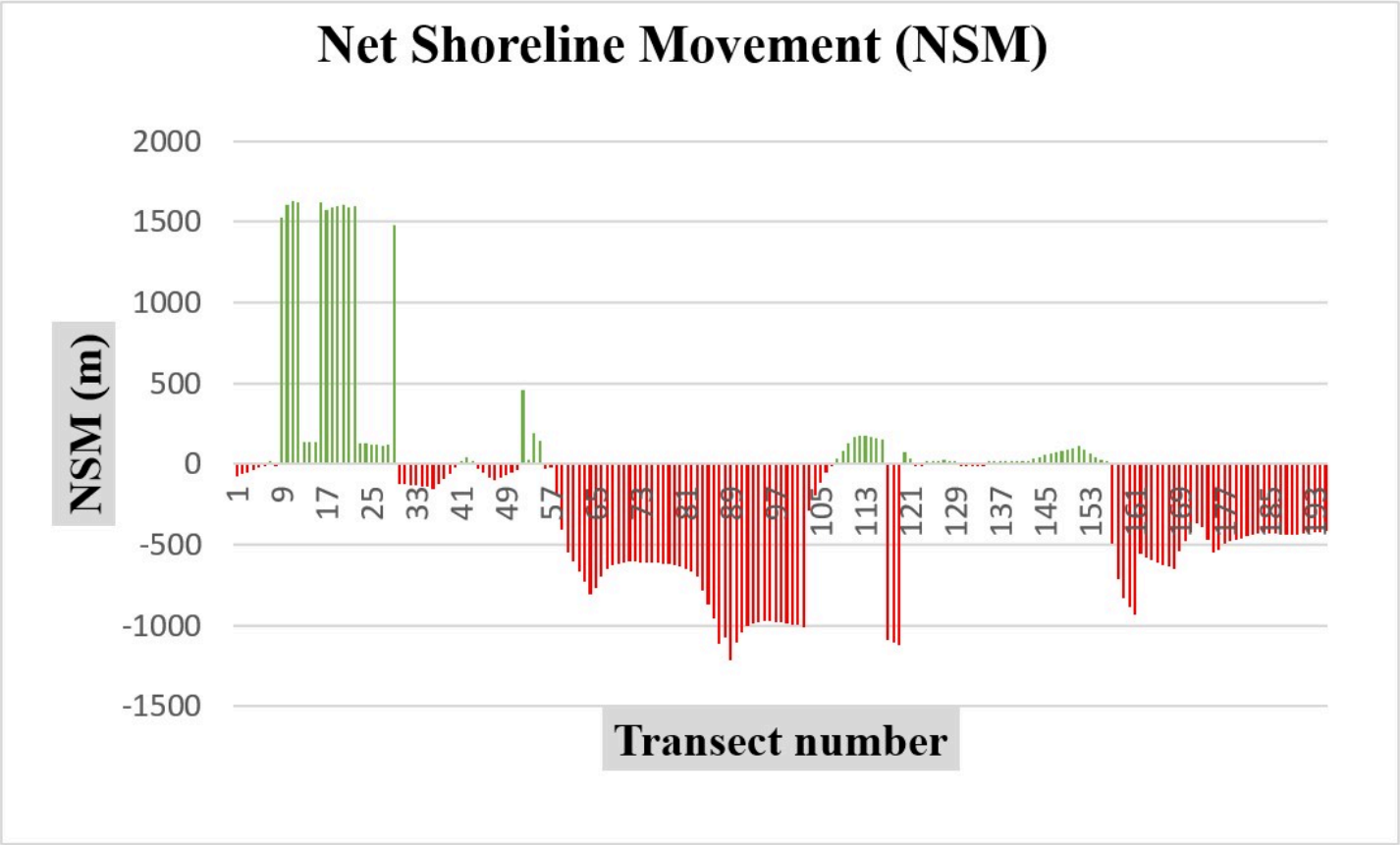


Figure 4

Spatial distribution of Net Shoreline Movement (NSM) values along the study coastline (1993–2023).

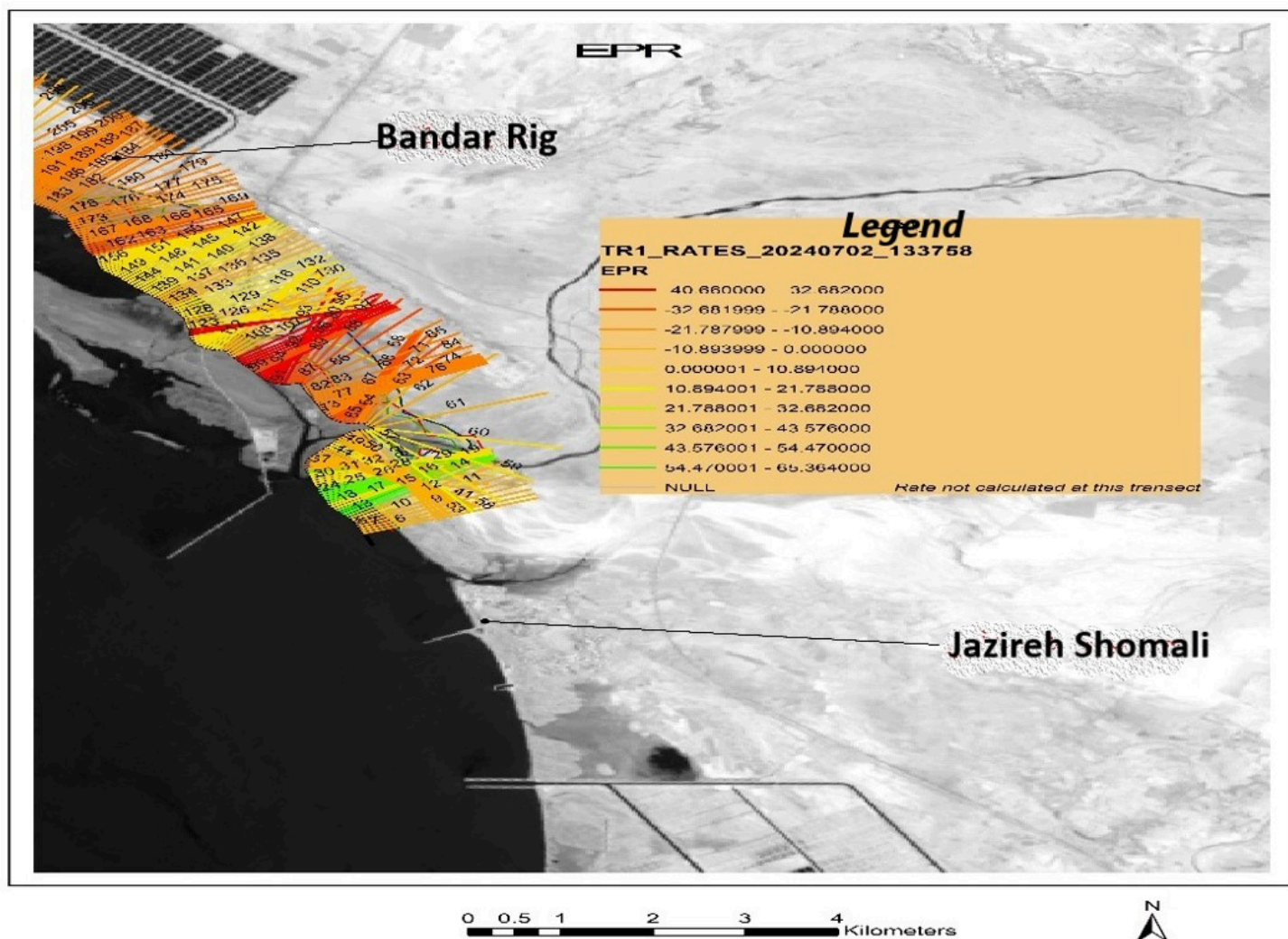


Figure 5

End Point Rate (EPR) of shoreline change along the coastal stretch from Jazireh Shomali to Bandar-e-Rig during 1993–2023.

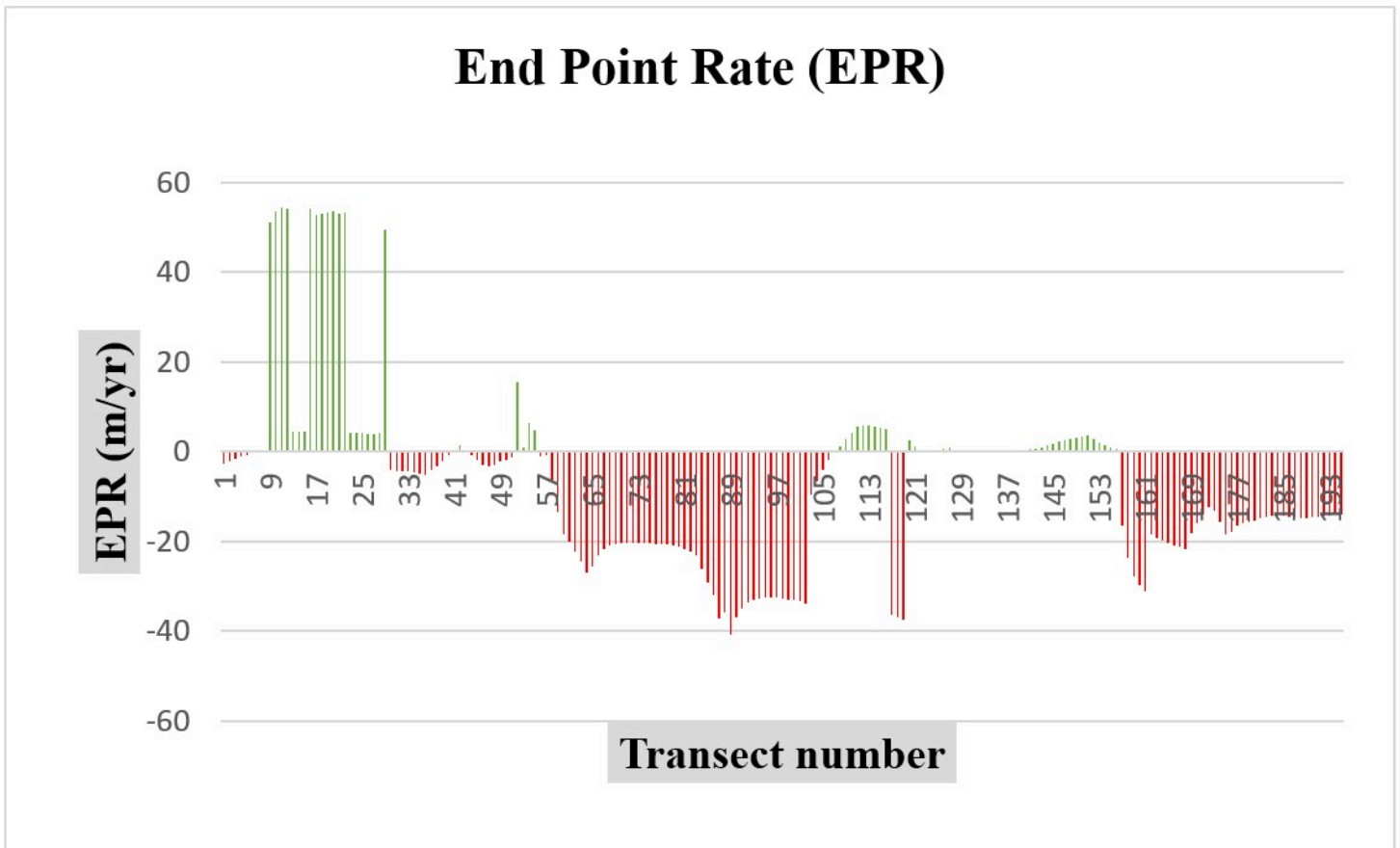


Figure 6

Spatial distribution of End Point Rate (EPR) values along the study coastline (1993–2023).

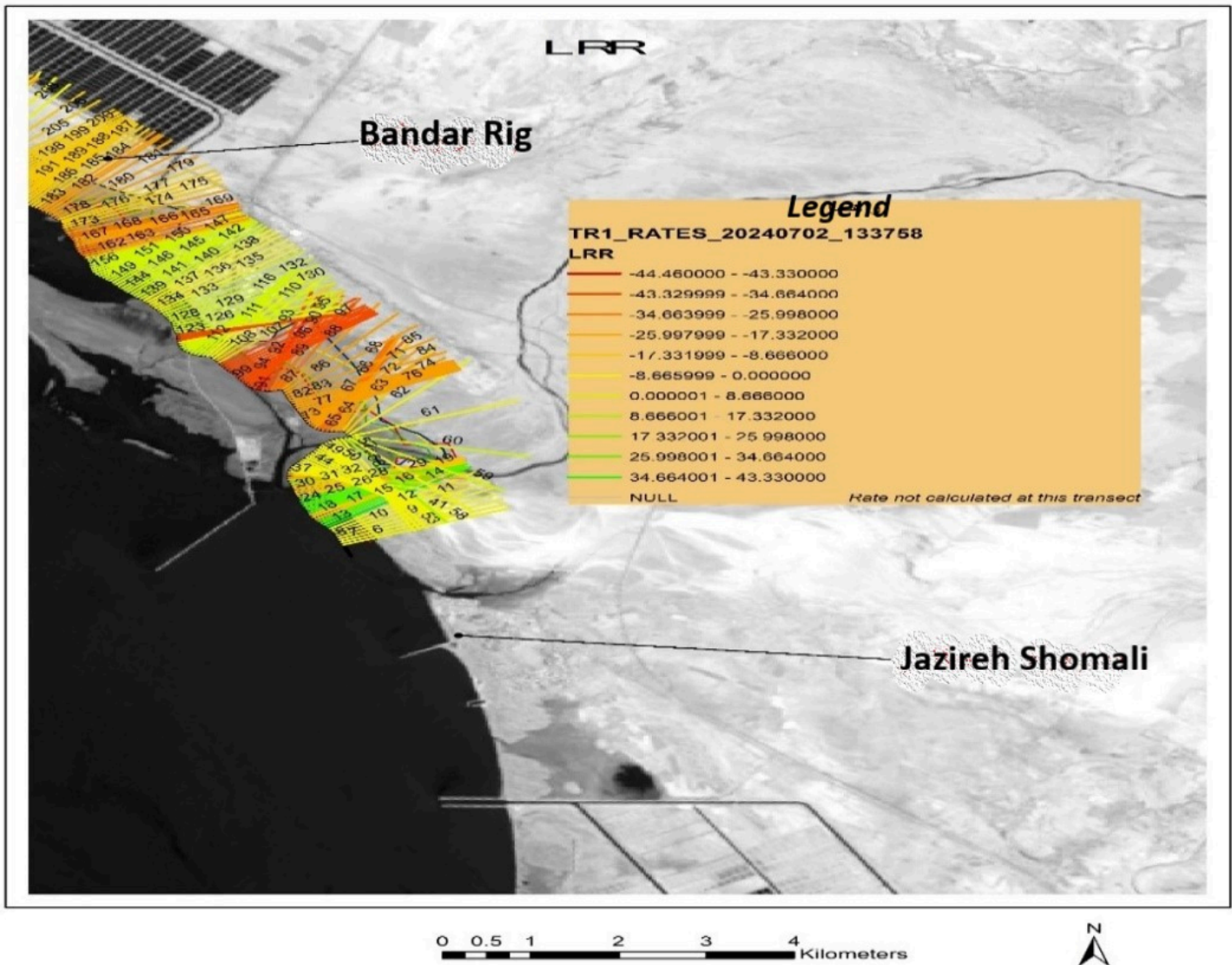


Figure 7

Linear Regression Rate (LRR) of shoreline change along the coastal stretch from Jazireh Shomali to Bandar-e Rig for the period 1993–2023.

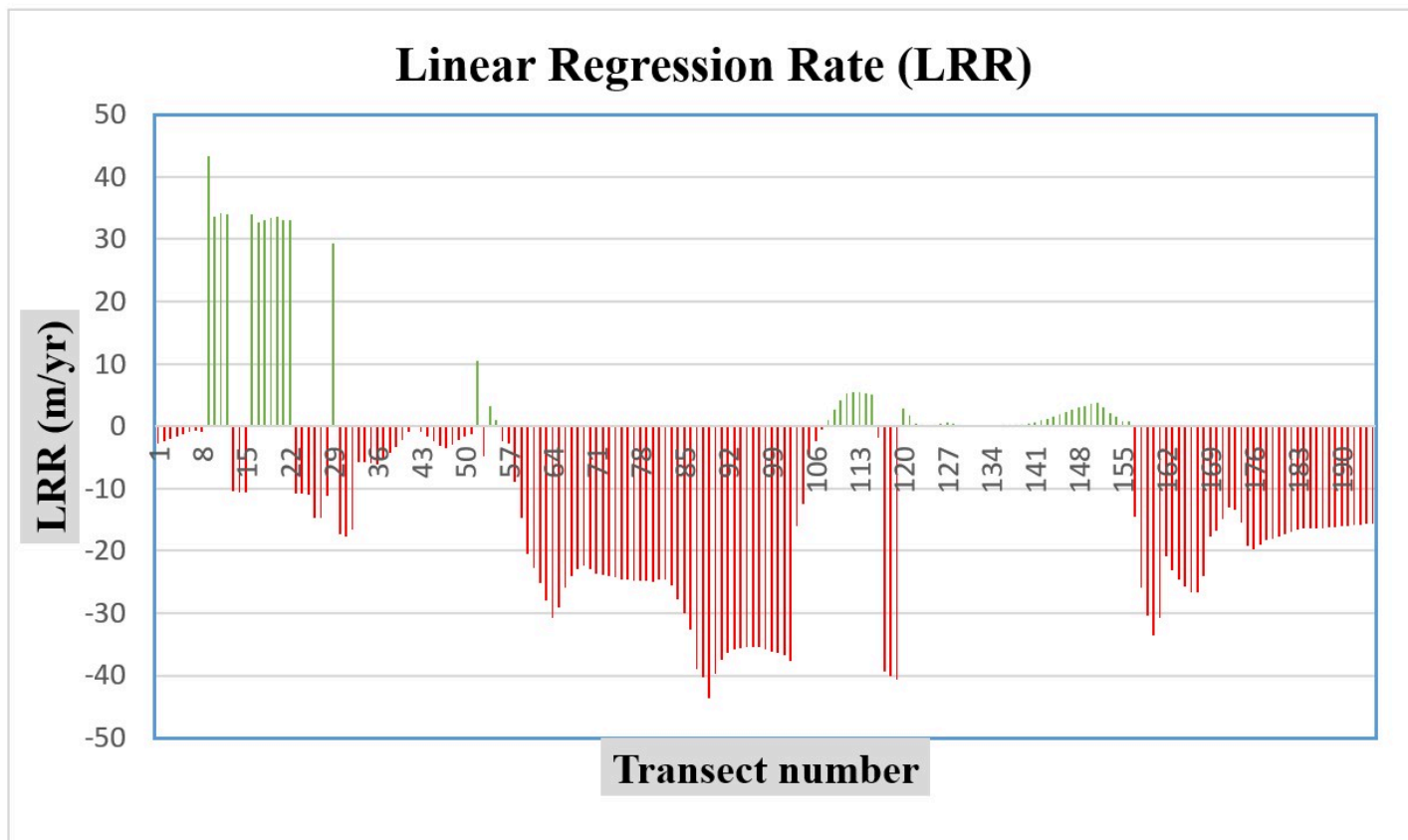


Figure 8

Spatial distribution of Linear Regression Rate (LRR) values along the study coastline (1993–2023).

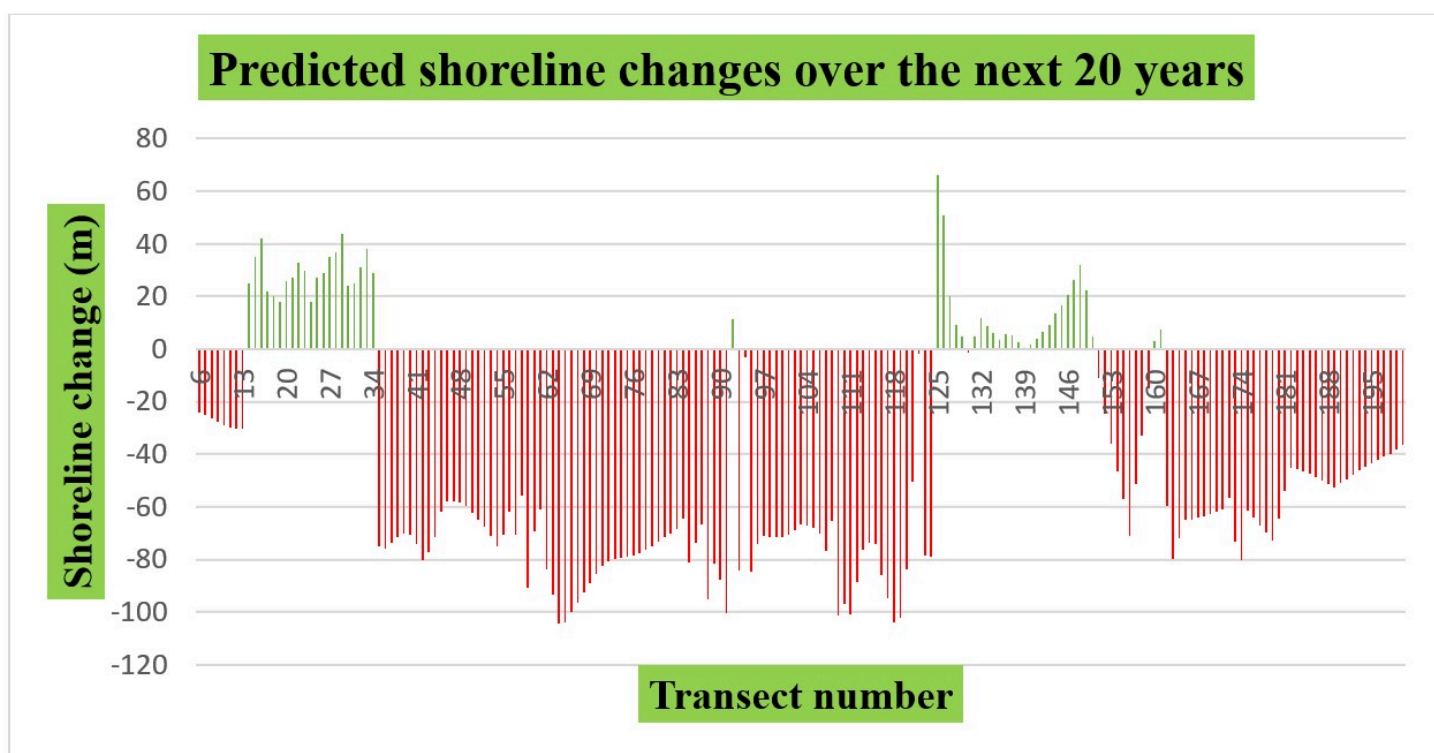


Figure 9

Predicted shoreline changes over the next 20 years along the coastal stretch from Jazireh Shomali to Bandar-e Rig, based on the Kalman filter model.