Surveillance of coastal erosion and marine habitat degradation using remote sensing and GIS

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Received: 03 February 2025; Revised: 13 March 2025; Accepted: 29 March 2025; Published: 20 May 2025

Abstract

Accurately identifying coastal regions affected by historical, current, and prospective erosion is essential for effective coastal risk mitigation. In this context, satellite imagery is a significant synoptic and multi-temporal input source. The study employed Geographic Information System (GIS) and satellite imagery tools to map and model coastline change. The long-term patterns of advancement and retreat of the shoreline were assessed using Landsat imagery from the mid-1970s to 2025, followed by predicting and validating a short-term scenario over three years. Two distinct coastal ecosystems, Oceanic and Mediterranean, were examined. Initially, various proxies were examined, facilitating a multi-proxy study. The findings indicated that the approach yielded more precise results in high-energy situations (oceanic) and in areas where the shoreline is not urbanized. The findings underscored the significance of conducting multi-proxy analysis in specific research regions to more accurately delineate shoreline models. Significantly, the studies focused on evaluating uncertainty, essential when research outputs are contemplated for managerial purposes.

Keywords: Coastal erosion, Marine habitat degradation, Remote sensing, Surveillance

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DOI: 10.70102/IJARES/V5I1/5-1-16

Introduction

Coastal zones are delicate and dynamic ecosystems vulnerable to disasters, climate change impacts, and human activities (Roy *et al.,* 2023). Given that over 42% of the global population resides in coastal regions, these places are frequently highly urbanized, resulting in significant vulnerability and elevated risk levels. It is imperative to utilize long-term management strategies and instruments within this structure, considering the intricacies of coastal events and their effects on ecosystems. Integrated Coastal Management (ICM) (Fang *et al.*, 2021) focuses on the long-term growth of coastal areas, encompassing risk adaptation and mitigating techniques. The examination of spatiotemporal shoreline alterations is critically significant in this setting. Coastal risk mitigation (Zanin *et al.*, 2023) is enhanced by monitoring and forecasting, which offer valuable insights for managers and participants to address present and potential coastal hazards influenced by their evolution.

A prevalent evaluation technique for beach degradation and temporal shoreline development involves mapping shoreline positions with multi-temporal sources of information, such as aerial photographs, satellite imaging, Geographic Information System (GIS) (Shahriar, Atiquzzaman and Ivancic, 2011; Weerasingha and Ratnayake, 2022), and survey information. Linear and nonlinear approaches are typically employed to (1) estimate historical shoreline change rates from uniformly distributed shore-perpendicular routes and (2) forecast scenarios for the future. The findings indicate that linear models are predominantly utilized in coastal planning because of their simplicity. They yield precise results provided that the assumption of proportionality remains unviolated during the evaluated timeframe (Foster, Kharouba and Smith, 2022). This approach posits that natural events influencing shoreline position can be categorized into (a) long-term shifts or patterns (i.e., the signal), primarily resulting from solid transport shifts and represented as a function of duration, such as through a linear approach; and (b) an arbitrary component impacting the signal (i.e., noise), predominantly attributable to recent wave measures depicted as coastline fluctuations.

Spaceborne remote sensing offers comprehensive and multi-temporal data that facilitates the consistent collection and evaluation of coastal indicators, even in isolated regions (Wasehun, Hashemi Beni and Di Vittorio, 2024). The Landsat archive, offering optical data from 1975, is the most extensive continuous collection of Earth observation information among openly available satellite picture databases. It constitutes an essential tool for multi-temporal and time-series investigations and change detection studies. Although the accuracy of the data is limited to 35 m, this repository serves as a critical resource for mapping coastline positions and examining long-term evolutionary movements.

GIS-Based Shoreline Assessment Methodology

The system has five stages: (A) data preparation, (B) proxies extraction, (C) computation of past shoreline rates of modifications, (D) formulation of the shoreline predicting situation, and (E) uncertainty evaluation.

Data Preprocessing

A preprocessing step was necessary to get a multi-temporal database that was mathematically and radiometrically co-registered. This is essential for precisely extracting coherent proxies in both space and duration. The Landsat images were acquired as Level 1T products (Standard Terrain Corrections) and georeferenced to the Universal Transverse Mercator perspective scheme. Images were supplied with information, encompassing leftovers of ground control points utilized for orthorectification (Dhileepkumar *et al.,* 2023). The accuracy of spatially co-registration among pictures within the same database was assessed using a geometric Root Mean Square Error (RMSE) method (Ye *et al.,* 2021). The databases' most significant geometrical RMSE modeling values were 4.5 m for American Standards Association (ASA) and 6.8 m for Marine Safety Authority (MSA) (Kerfouf *et al.,* 2023; Akyol and Capape, 2024). Considering the high spatial detail of Landsat, these values were deemed sufficient, being less than half a pixel width; hence, no additional spatial co-registration of the pictures was performed. Regarding image radiography, the top of atmospheric radiance was computed from numerical values using the specified coefficients and formulas. Landsat eight pictures were processed using the environmental tool "Radiometric Calibration," followed by a two-step radiometric adjustment (Venkatesh *et al.,* 2022).

Proxy Retrieval

Before proxy extraction, research locations were categorized into three thematic groups: natural regions, neighborhoods, and rocks, by visually inspecting the high-resolution baseline map available in the program. The standards for these categories define natural areas as coastline beach segments where shoreline development is presumed primarily governed by "natural" processes, devoid of direct human impact (Robbe *et al.,* 2021). In contrast, urban areas are identified as beach sections adjacent to urban coastal communities, where protective structures like groins and barriers significantly influence coastal dynamics. In ASA, any beaches adjacent to urban populations were designated as urban zones, while in MSA, the stretch of coastline was classed similarly. Studies were not conducted along coastline cliffs, situated exclusively within ASA, as the mechanisms of shoreline alteration in these regions exhibit distinct dynamics compared to sandy coasts. In ASA, cities were omitted from evaluations, henceforth referred to as vegetation-based substitutes, due to the destruction of dune vegetation and its replacement by urban infrastructure.

Assessment of Historical Coastline Alteration Rates

The time sequence of shoreline roles, expressed as proxy vector data, was utilized to compute rates for variation along equidistant (100 m) transects oriented parallel to the coast using the Digital Shoreline Analysis Systems (DSAS). This freely accessible application operates within the ESRI ArcGIS software. DSAS facilitated the computation of the Linear Regression Ratio (LRR) for all routes, indicative of the proxy annual displacement rate (m/year). For each route, the LRR was determined as the slant of the least-squares regression line representing the location of the shorelines. DSAS supplied, for each route, (1) the factor of correlation (R-squared - R2) and (2) the uncertainty related to each LRR, computed as the 95.5% Confidence Intervals (CI) of the observed frequency.

It is essential to highlight that the examines employed the Weighted Linear Regression (WLR) method (i.e., LRR and LCI) due to (1) the constancy of resolution error across both records and (2) the assumption of constant mathematical error inside each database, as the standard errors of the mean mathematical RMSE system values are negligible about the geographic detail of the Landsat archives. Suppose these requirements remain unmet (e.g., an elevated standard deviation rendering it significant, or the utilization of disparate satellite imagery with varying spatial decisions) (Khojasteh *et al.*, 2016). In that case, the WLR and the Water CI (WCI) must be employed in the DSAS to compute historical rates of change and assess uncertainty. Figure 1 is a comprehensive graphical depiction of the steps.

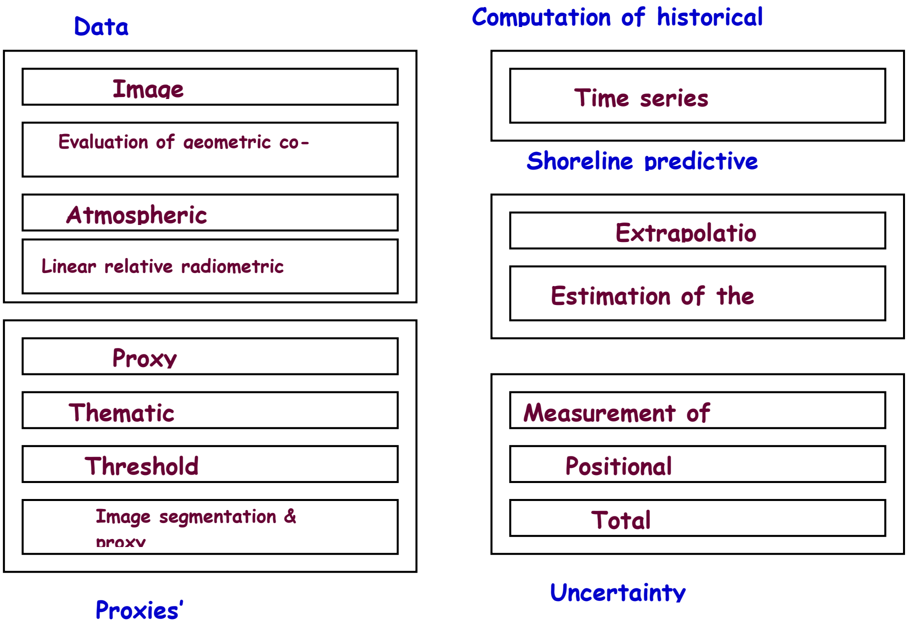

Figure 1: System workflow.

Computation and Analysis of Coastline Variation Rates

DSAS computes discrepancies in coastal positions over specified intervals. This provides the fundamental data necessary to calculate shoreline alterations. Indicators of coastal shape determine the historical pattern of shoreline changes. The framework regulates coastal attributes: coastline alteration, historic shoreline motion, cliff retreats and erosion, gull evolution and growth, and coastal computation and modeling. DSAS generates transects parallel to the standard at user-specified intervals along the coastline. The crossings of the transect shoreline along this starting point are utilized to calculate the rate of change of the data. According to the logical parameters in DSAS, 6k transects have been established, positioned parallel to the baseline at intervals of 60 meters along the Qingdao shoreline. DSAS 5.0 comprises six statistical methodologies for assessing variances. This study employed Net Shore Motion (NSM), End Point Ratio (EPR), and LRR methodologies.

NSM quantifies net coastline change based on distance rather than average value. NSM pertains to date and necessitates only two coastlines, specifically the distance between the earliest and latest shore in each survey. The EPR was chosen as the statistical metric to characterize the spatial distribution of shoreline alteration. EPR quantifies the shift in shoreline by calculating the distance between the coastline's first and most recent positions.

LRR utilizes the current data to compute the long-term rate of change. The LRR, EPR, and NSM values that are positive or negative indicate the seaward and landward shifts of the shoreline, respectively. Baseline historical coastlines and shoreline uncertainties are input data provided to the model throughout the modeling phase. The intervals between transects adjacent to the standard and the lengths of the traverses were delineated according to the coastline design.

Results

The study region can be segmented into three portions of significant size and complexity. In coastline variability evaluation, segmenting the research region facilitates a deeper understanding of the findings. The study area was divided into three portions for inspection to achieve this objective.

Extended Timeframe Analysis

The shoreline alteration from 2000 to 2025 was assessed utilizing the LRR methodology. This program calculates the data change rate by applying least squares regression to all coastline points, from the oldest to the most recent, for each transect. The findings exhibit the overall rates of coastal variation derived from the examination. Positive numbers show the progradation of the coastline, whereas low numbers are associated with coastal erosion. This image illustrates the locations of erosional and accretional components.

Over 19 years, the LRR total average indicates a progressive trend of coastal accretion throughout all three sections. The average LRR rates for segments 1, 4, and 5.6 are 6.2 million per year, 3.7 million per year, and 14.6 million per year, correspondingly. Overall averages indicate that the Qingdao coastline is predominantly experiencing accretion. The most excellent accretion length is 127.8 meters per year, with an average rate of 12.6 meters yearly. The highest erosion distance of -8.4 m/yr is observed in segment 2.

Analysis of Short Period

The coastal position change rates assessed by the NSM and EPR methodologies throughout this period demonstrate that the coastline is primarily undergoing aggradation. This overarching trend fluctuates across the three sections delineated along the coast, demonstrating geographic diversity in shoreline dynamics. The aggregate mean EPR rates for all sections exhibit an increasing trend, with rates of 2.12, 0.25, and 2.87 m/yr for section-1, section-2, and section-3. The NSM length values exhibit consistent trends, measuring 23.4, 1.7, and 26.2 m for sections 1, 4, and 6. The most incredible accretion distances for NSM are 832.7, 989.6, and 1186.8m for sections 1, 4, and 6, while the highest deposition EPR rates for the sections, in the same place, are 85.7, 98.2, and 126.2 m/yr. The most incredible erosion distances for NSM are 389.2, -878.3, and -745.5m for sections 1, 4, and 6, while the EPRs are -37.2, -89.3, and -85.7m/yr for the same sections in that order.

Calculation of Land Losses and Field Gain

The Qingdao shoreline is undergoing alterations over time due to processes of accretion and attrition. The entire coastal region has predominantly undergone accretion, while erosion has occurred to some extent. Between 2000 and 2025, most accretion occurred, resulting in a net area increase of 54.4 sq. km, despite a coastline loss of around 15.2 sq. km. The fluctuating distribution of landmass across different intervals is illustrated in Figure 2. During the initial interval (2000 - 2025), the shoreline expanded by 36.4 km² over a decade, while it experienced a loss of merely 17.2 km². In the subsequent interval, the shoreline extended by roughly 43.6 km² in 9 years, with a loss of only 10.6 km².

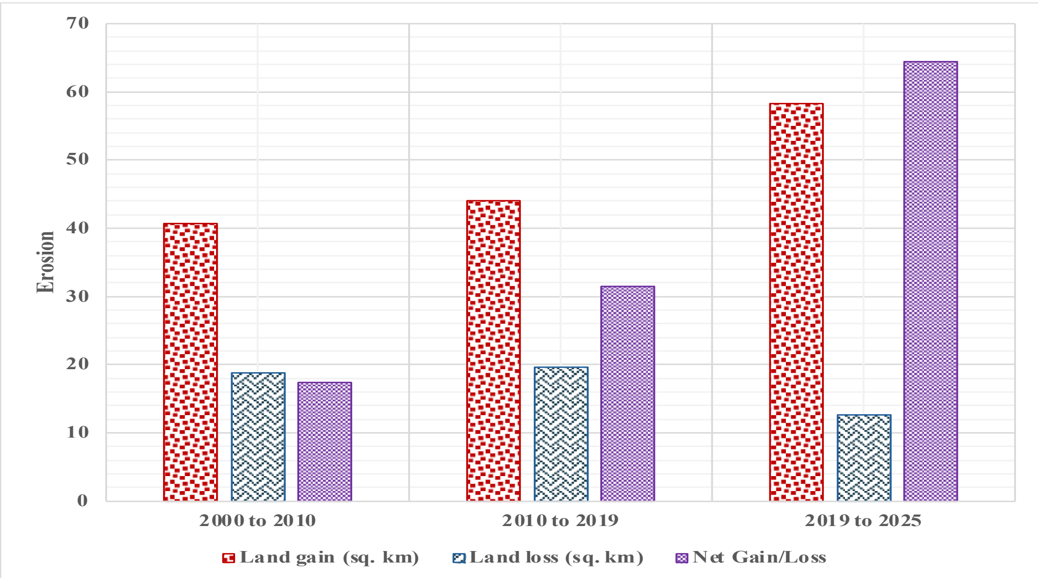

Figure 2: Erosion analysis.

Conclusion

This work introduced an enhanced iteration of a straightforward, resilient, and reproducible method, enabling the integration of GIS and remote sensing tools to visualize the locations of shoreline proxies and analyze their temporal evolution. The objective was to delineate a comprehensive processing pipeline of satellite imagery to identify historical, current, and prospective regions susceptible to shoreline erosion at regional and subregional levels, thereby aiding coastal risk mitigation. The Landsat archives served as the input data;

the methodology can be readily adapted to any satellite imagery. The system facilitated precise and uniform extraction of shoreline samples that were spatially and temporally coherent. These proxies were then employed to compute historical coastal rates of advance and retreat utilizing a linear framework that facilitated the extrapolation of future situations. The latter were corroborated by juxtaposing the modeled situation with the data collected, with results subjected to statistical analysis and evaluated within a coastal risk mitigation paradigm. The analysis concentrated on two distinct study locations to assess the capacities in varying coastal situations: ASA (high energy) and MSA (low energy). Findings indicated that the technique yielded valid outcomes, demonstrating greater accuracy in non-urbanized coastal regions (i.e., natural regions) and when the shoreline alteration signal is more pronounced (i.e., ASA). Significant enhancements are anticipated, particularly in MSA-like situations, when extensive and uninterrupted time series of measurements from satellites with improved spatial accuracy are utilized to mitigate geometric error, which substantially influences method uncertainty.

The multi-proxy evaluation technique is crucial for an in-depth knowledge of coastal processes affecting a specific littoral zone and for determining the most credible proxy in a particular study region. The findings indicated that proxies derived from stable coastal characteristics yield more precise outcomes due to reduced uncertainty and diminished susceptibility to daily or seasonal variations. Extrapolations based on solid coastal characteristics demonstrate greater accuracy when forecasting short-term situations utilizing long-term retreat costs.

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