Uncertainty and Multi-Index Concordance of Shoreline Change along Mal-Khalifeh–Chahak, 1993–2023

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1. Abstract

This study quantifies the regional tendency and spatial variability of shoreline-position change along the Mal-Khalifeh-Chahak coast of Bushehr Province, northern Persian Gulf, while explicitly distinguishing regional screening from local statistical certainty. Four 30 m Landsat shorelines dated 1993, 2002, 2013, and 2023 were extracted from a sensor-specific tasseled-cap wetness response and analysed with the Digital Shoreline Analysis System along 300 transects spaced at 50 m. Net Shoreline Movement (NSM), End Point Rate (EPR), Linear Regression Rate (LRR), and Shoreline Change Envelope (SCE) were calculated. Mean NSM, EPR, LRR, and SCE were -26.01 m, -0.87 m yr-1, -0.48 m yr-1, and 48.62 m, respectively. Using the operational threshold NSM < -5 m, 238 transects (79.3%) were assigned to erosional classes; the spatial-dependence-aware 95% block-bootstrap interval was 67.7-89.0%. This percentage describes regional class frequency and is not a test of significant change at individual transects. A partial positional component of 15.85 m per shoreline, based only on half-pixel size and product geolocation, propagated to 22.42 m for NSM and 0.75 m yr-1 for EPR; thresholding, manual editing, and tidal displacement were not included. Pearson correlation between NSM and LRR was 0.958 and sign agreement was 79.0%, but the metrics share endpoint information and therefore do not provide independent confirmation of a trend or geomorphological process. A near-date comparison between Landsat on 26 July 2023 and Google Earth on 23 June 2023 yielded a mean signed offset of +11.80 m, MAE of 14.68 m, and RMSE of 17.32 m. Because the acquisitions were 33 days apart and tidal stages were unknown, these values represent composite inter-source differences rather than independent validation of extraction accuracy. The results support regional statistical-geomatic screening; local or process-based interpretation requires more frequent, tide-matched, and field-validated observations.

Keywords: shoreline change; positional uncertainty; metric agreement; DSAS; Persian Gulf.

2. Introduction

Shorelines are mobile interfaces whose mapped positions respond to sediment exchange, water-level variability, waves, currents, storms, and human intervention. Their displacement is therefore widely used to describe coastal change and to support monitoring and planning [1]. Repeated satellite observations provide a practical basis for multi-decadal assessment where historical field surveys are sparse. Landsat is especially useful because its long, open archive permits consistent regional coverage, while GIS-based transect methods convert mapped shorelines into reproducible distance and rate statistics [2-4].

Satellite-derived shoreline analysis nevertheless contains important scale and interpretation constraints. The water-land boundary in a single image is a proxy for shoreline position and can shift with image resolution, geolocation, classification threshold, beach slope, and tidal stage. Sparse acquisition dates also limit the representation of short-term erosion-recovery cycles. Moreover, commonly reported metrics are not necessarily independent: EPR is an algebraic transformation of NSM, and LRR fitted to all dates includes the endpoints used by NSM. Agreement among such outputs must therefore be treated as descriptive consistency rather than independent evidence of a physical coastal process.

The approximately 15 km Mal-Khalifeh-Chahak reach contains low-gradient depositional and intertidal settings, but a systematic multi-decadal, uncertainty-aware assessment was not previously available for this coastal segment. The present work addresses four questions: (1) what regional tendency is indicated by four standard shoreline-change metrics; (2) how much spatial heterogeneity and metric disagreement occur alongshore; (3) whether operational erosion frequency is robust to spatial dependence and coarser effective transect spacing; and (4) how partial positional uncertainty and a

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near-date inter-source comparison constrain interpretation. The study is intentionally framed as a statistical and geomatic analysis; it does not infer wave, current, sediment-transport, or engineering-intervention mechanisms without independent process data.

3. Methodology

The study reach lies on the coast of Bushehr Province in the northern Persian Gulf and corresponds to DSAS transects 551-850. Four cloud-free or minimally cloud-affected Landsat scenes for path 164 and row 039 were selected within a similar July-August seasonal window: Landsat 5 TM on 24 August 1993, Landsat 7 ETM+ on 24 July 2002, and Landsat 8 OLI on 30 July 2013 and 26 July 2023. All analyses used the 30 m multispectral data; panchromatic sharpening was not applied. Layers were organised in WGS 84 / UTM zone 39N (EPSG:32639), clipped to the study area, and checked for geometric overlap and cloud interference.

For each sensor, the wetness component of the tasseled-cap transformation was calculated with the appropriate TM, ETM+, or OLI coefficients [5-7]. A separate water-land threshold was selected for each scene, followed by visual checking and limited manual correction at ambiguous segments. This procedure avoided direct comparison of unnormalised spectral values among sensors. The resulting line represents the instantaneous image-derived water-land boundary. No tidal correction was applied because acquisition-time water levels and beach-slope profiles were unavailable. Consequently, the mapped line should not be interpreted as a fixed geomorphological datum.

A seaward baseline was used in DSAS version 5.1 [3]. Three hundred land-directed transects were generated at 50 m spacing with a 2,000 m search length, and every valid transect intersected all four shorelines. SCE records the maximum distance between any two observed shorelines without direction; NSM is the signed 1993-2023 endpoint displacement; EPR is NSM divided by 29.92 years; and LRR is the least-squares slope fitted to the four dated positions. Negative NSM, EPR, and LRR denote landward movement. The coefficient of determination and the DSAS 90% confidence half-width were retained as local LRR diagnostics.

A baseline partial positional component for each shoreline combined half of the 30 m pixel size with the reported product geolocation term by root-sum-of-squares propagation. Date-specific values were 15.66, 15.65, 15.49, and 15.85 m; the maximum, 15.85 m, was applied uniformly. Propagation of only this component gave 22.42 m for NSM and 0.75 m yr-1 for EPR. These values are not a complete uncertainty budget because classification-threshold, manual-editing, and tidal-displacement errors were unavailable. Operational NSM classes were severe erosion (< -20 m), moderate erosion (-20 to -5 m), stable (-5 to +5 m), moderate accretion (+5 to +20 m), and strong accretion (> +20 m). The frequency of NSM < -5 m was compared with 50% using an exact binomial test and a Wilson interval, while a moving-block bootstrap with 20,000 resamples and a 17-transect (850 m) block length accounted more conservatively for alongshore dependence.

Metric consistency was summarised by Pearson and Spearman correlations and sign agreement between NSM and LRR. Because these metrics share endpoint positions, the statistics were treated as descriptive only. Systematic subsampling of the existing network produced effective spacings of 100, 150, and 200 m to test sensitivity to coarser sampling. Finally, a Google Earth shoreline digitised from 23 June 2023 was compared with the Landsat shoreline of 26 July 2023. Transects 722-741 were excluded a priori because the open river mouth prevented a consistent intersection, leaving 280 comparisons. Mean signed offset, MAE, RMSE, demeaned RMSE, and the 95th percentile of absolute difference were reported as composite near-date differences, not as independent measures of extraction accuracy.

Table 1. Data and analytical design of the extended abstract.

Implementation in this study	Element
Approximately 15 km; four Landsat shorelines from 1993, 2002, 2013, and 2023	**Spatial and temporal coverage**
300 DSAS transects at 50 m spacing; effective-spacing sensitivity at 100-200 m	**Transect geometry**
NSM and EPR for endpoint change; LRR for four-date linear tendency; SCE for observed range	**Primary metrics**
15.85 m per shoreline; propagated to 22.42 m for NSM and 0.75 m yr-1 for EPR	**Partial positional component**
Exact binomial/Wilson analysis and moving-block bootstrap with 20,000 resamples	**Regional inference**
Pearson, Spearman, and sign agreement, interpreted as descriptive because endpoints are shared	**Metric comparison**
280 transects; Google Earth 23 June 2023 versus Landsat 26 July 2023; unknown tidal stages	**Near-date comparison**

4. Results and Discussion

Across all 300 transects, mean (median) NSM was -26.01 m (-15.71 m), mean (median) EPR was -0.87 m yr-1 (-0.53 m yr-1), and mean (median) LRR was -0.48 m yr-1 (-0.25 m yr-1). Mean SCE was 48.62 m and its median was 31.57 m. The difference between means and medians, together with NSM ranging from -264.37 to +33.52 m, shows that several intensely retreating segments influenced the regional mean. The operational classification assigned 106 transects to severe erosion and 132 to moderate erosion. Thus, 238 transects (79.3%) met NSM < -5 m; 47 were operationally stable and 15 were accretional. All negative NSM values, without the -5 m threshold, occurred at 263 transects (87.7%), so the two percentages describe different criteria.

The exact binomial comparison of the 79.3% operational erosion frequency with 50% gave $p < 0.001$, and the Wilson interval was 74.4-83.5%. The more conservative 95% moving-block bootstrap interval was 67.7-89.0%, remaining above 50%. Block-bootstrap intervals for regional mean NSM, EPR, and LRR were -46.22 to -12.92 m, -1.55 to -0.43 m yr-1, and -1.09 to -0.06 m yr-1, respectively. These results support a negative regional tendency but do not establish statistically significant movement at every transect. Indeed, the 90% LRR interval excluded zero for only five negative and one positive local estimates; 294 transects included zero. Relative to the partial +/-22.42 m NSM band, 90 transects showed retreat beyond the band, 209 remained within it, and one showed accretion beyond it. This is a sensitivity classification based on incomplete positional components, not a per-transect certainty test.

NSM and LRR had Pearson and Spearman correlations of 0.958 and 0.820, and their signs agreed at 237 transects (79.0%). Signs disagreed at 60 transects (20.0%), with three zero cases. The high correlations partly reflect mathematical dependence because the LRR fit contains the two endpoint positions defining NSM; neither correlation nor sign agreement is independent geomorphological evidence. Disagreements near transects 619-624 and 695-697, and cases where high SCE coincided with near-zero LRR, indicate that four observations can depart from a simple linear tendency. For example, transects 623 and 624 had NSM of -32.77 and -29.76 m but positive LRR of +2.21 and +2.31 m yr-1, with SCE exceeding 280 m. The available dates cannot determine whether such behaviour reflects real shoreline reconfiguration, water-level differences, extraction uncertainty, or a combination of these factors.

Coarsening the effective spacing from 50 to 100-200 m did not reverse the regional result: operational erosion frequency remained within 76.0-82.7%, and mean LRR remained negative in every subsample. The near-date comparison over 280 transects produced a conventional mean signed offset of +11.80 m, a median offset of +12.66 m, MAE of 14.68 m, RMSE of 17.32 m, demeaned RMSE of 12.68 m, and a 95th-percentile absolute difference of 29.87 m. A total of 266 transects (95.0%) had absolute differences no greater than 30 m. These quantities combine possible short-term shoreline movement, unknown tidal displacement, Landsat resolution and geolocation, thresholding, and Google Earth digitising. They therefore neither validate a complete 15.85 m uncertainty budget nor justify correction of the Landsat line. For management, the outputs are most appropriate for regional screening and prioritisation of additional monitoring. They are not, by themselves, a process model, hazard map, design criterion, or basis for attributing change to waves, currents, sediment transport, or coastal structures.

5. Conclusion

Four-date Landsat and DSAS analysis identified a spatially heterogeneous but regionally negative shoreline-position tendency along Mal-Khalifeh-Chahak. Mean NSM, EPR, and LRR were negative, and 79.3% of transects met the operational erosion threshold NSM < -5 m. This frequency remained above 50% after accounting for alongshore dependence and was stable under coarser effective transect spacing. However, the operational threshold is not equivalent to significant change at individual transects, and most local LRR confidence intervals included zero. Agreement between NSM and LRR is descriptive rather than independent evidence because the indices share endpoint information.

The 15.85 m value should be regarded only as a partial pixel-geolocation component, and the 33-day Landsat-Google Earth comparison should be regarded only as a composite near-date offset under unknown tidal conditions. Accordingly, the results can guide regional screening and selection of reaches for follow-up survey, but they cannot support causal process attribution or engineering design. Future work should combine more frequent and higher-resolution imagery with acquisition-time water levels, beach-slope profiles, UAV or DGPS surveys, and independent wave, current, bathymetric, and sediment observations.

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