

P-ISSN: 2706-7483
E-ISSN: 2706-7491
IJGGE 2024; 6(1): 552-556
www.geojournal.net
Received: 06-01-2024
Accepted: 09-02-2024

Mei Liu
Department of Geology,
Shanghai College of
Environmental Studies,
Shanghai, China

Hua Li
Department of Geology,
Shanghai College of
Environmental Studies,
Shanghai, China

Bo Huang
Department of Geology,
Shanghai College of
Environmental Studies,
Shanghai, China

Corresponding Author:
Mei Liu
Department of Geology,
Shanghai College of
Environmental Studies,
Shanghai, China

Assessment of coastal erosion patterns along the dalmatian shoreline using remote sensing

Mei Liu, Hua Li and Bo Huang

DOI: <https://doi.org/10.22271/27067483.2024.v6.i1g.544>

Abstract

An estimated 70% of the world's sandy shorelines have retreated over the past five decades, yet site-specific erosion data for the eastern Adriatic remain fragmentary. This research assessed spatial and temporal patterns of coastal erosion along a 320 km stretch of the Dalmatian shoreline in Croatia, covering the period from 1990 to 2022. Four epochs of Landsat imagery (TM, ETM +, and OLI sensors) were processed to extract shoreline positions using a normalised difference water index (NDWI) threshold approach. The Digital Shoreline Analysis System (DSAS) generated 1,640 shore-perpendicular transects at 200 m spacing, from which net shoreline movement (NSM) and end-point rate (EPR) were calculated. Transect-level results showed that 45.9% of the coast experienced net retreat, 28.6% was stable within $\pm 0.5 \text{ m yr}^{-1}$, and 25.5% recorded net advance. The mean EPR for eroding segments was -1.17 m yr^{-1} , with localised peaks exceeding -3.4 m yr^{-1} near river-mouth deflection zones south of Split. Accretion was concentrated around engineered harbours and groin fields where longshore sediment had been trapped. A supplementary analysis of 30-m SRTM elevation data identified low-lying back-beach areas vulnerable to future storm overwash under projected sea-level rise scenarios. Results indicated that lithological control—specifically the contrast between resistant limestone headlands and erodible flysch embayments—was the dominant factor governing spatial variability, while inter-decadal changes in wave energy flux modulated the rate of retreat. The research provides a baseline dataset for coastal management planning along the Croatian Adriatic and demonstrates that freely available satellite archives can yield erosion assessments comparable in resolution to ground-based surveys when combined with rigorous geometric correction and tidal normalisation.

Keywords: Coastal erosion, remote sensing, shoreline change, GIS mapping, coastal management, Dalmatian coast, DSAS, Landsat, NDWI, Adriatic Sea

Introduction

Between 1984 and 2016, roughly 28,000 km² of the world's coastline converted from land to water, a net loss that exceeded new land formation by nearly 16,000 km² according to the Global Surface Water dataset ^[1]. In the Mediterranean basin, where tourism infrastructure often crowds narrow coastal strips, even modest rates of shoreline retreat can carry outsized economic and social consequences ^[2]. The Croatian segment of the eastern Adriatic, known as the Dalmatian coast, presents a particularly complex erosion setting because its deeply indented karst topography juxtaposes hard carbonate headlands with pocket beaches developed on softer flysch and Quaternary alluvium ^[3].

Traditional methods of monitoring shoreline change—beach profiling, cadastral surveys, and aerial photograph interpretation—are labour-intensive and often discontinuous in time and space ^[4]. Satellite remote sensing overcomes many of these constraints by offering repeated, synoptic coverage at spatial resolutions now adequate for decadal-scale change detection. The Landsat programme, with its unbroken archive stretching back to 1972, is especially suited to multi-decadal assessments because its 30-m multispectral bands permit consistent water-land discrimination across sensor generations ^[5].

The DSAS extension for ArcGIS has become a standard tool for quantifying shoreline movement, translating digitised shoreline positions into statistical rates of change along evenly spaced transects ^[6]. When coupled with spectral indices such as the NDWI, which exploits the contrast between near-infrared and green reflectance to delineate the water boundary, DSAS analyses can be automated to a degree that makes coast-wide inventories

feasible for data-scarce regions ^[7]. Earlier remote-sensing work on the Adriatic focused on the Italian side or on limited Croatian segments near Dubrovnik, leaving the central Dalmatian stretch between Zadar and the Neretva delta without a comprehensive erosion baseline ^[8].

Several physical drivers shape erosion patterns along this coast. Waves approach predominantly from the south-southeast, with significant wave heights averaging 0.6 to 1.2 m but occasionally reaching 4 m during bora and sirocco storm events ^[9]. Tidal range is micro-tidal, seldom exceeding 0.4 m, so wave action and storm surge are the main agents of morphological change ^[10]. Longshore sediment transport is modest and highly compartmentalised by headlands, meaning that pocket beaches depend almost entirely on local cliff and river sources ^[3].

This research pursued three objectives: first, to map shoreline positions at four time steps (1990, 2000, 2010, 2022) along a 320 km Dalmatian reach; second, to quantify rates and spatial patterns of erosion and accretion; and third, to relate observed changes to lithological, hydrodynamic, and anthropogenic controls. The work was carried out through the Department of Geology at the Shanghai College of Environmental Studies, Shanghai, China, between June 2021 and November 2022. Findings are intended to support evidence-based coastal zone management and to fill a gap in the Adriatic shoreline-change literature.

Research Area Description

The research area extends along the Dalmatian coast of Croatia from Zadar (44.12° N, 15.23° E) southward to the Neretva River mouth (43.02° N, 17.43° E), covering approximately 320 km of mainland shoreline excluding offshore islands. The coast is classified as a longitudinal (Dalmatian-type) coast, where structural folds run parallel to the shore, producing elongated islands and narrow channels ^[3]. Bedrock along the mainland consists of Cretaceous and Eocene limestone in headland zones and Eocene-Oligocene flysch (marls, siltstones, and sandstones) in embayment areas. Quaternary alluvial and colluvial deposits mantle the lower slopes and form narrow beach strips at the base of cliffs. The climate is Mediterranean (Csa), with hot, dry summers and mild, wet winters. Mean annual precipitation at Split-Marjan station is 788 mm, concentrated between October and March. The Adriatic Sea in this sector has a micro-tidal regime (mean spring range 0.31 m) and a fetch-limited wave climate dominated by south-southeasterly swells ^[9]. Coastal land use is dominated by tourism infrastructure, residential settlement, and agriculture on alluvial flats.

Materials and Methods

Materials

The research was based at the Department of Geology, Shanghai College of Environmental Studies, Shanghai, China, and ran from June 2021 to November 2022. Ethical review was not required as no human subjects were involved. Satellite imagery consisted of 16 cloud-free Landsat scenes (four per epoch: 1990, 2000, 2010, 2022) acquired during summer months (June–August) to minimise sun-glint and seasonal vegetation effects. Scenes were

downloaded from the USGS Earth Resources Observation and Science (EROS) Center. A 30-m SRTM DEM (version 3.0) provided elevation context for back-beach vulnerability mapping. Tidal predictions for the Split tide gauge were obtained from the Croatian Hydrographic Institute to correct image-derived shorelines to mean sea level. Ancillary data included the 1:100,000 geological map sheets of Croatia published by the Croatian Geological Survey, high-resolution Google Earth imagery for visual validation, and wave climate statistics from the Copernicus Marine Environment Monitoring Service (CMEMS) reanalysis product for the Adriatic basin ^[9].

Methods

All Landsat scenes were radiometrically calibrated to top-of-atmosphere reflectance and then atmospherically corrected using the FLAASH module in ENVI 5.6. Scenes were co-registered to a common UTM Zone 33N (WGS 84) grid, with root-mean-square error (RMSE) kept below 0.5 pixels (15 m). Shoreline positions were extracted by computing the NDWI (green minus near-infrared, divided by their sum) and applying an empirically determined threshold of 0.18 to separate water from land ^[7]. Extracted raster boundaries were vectorised and smoothed using a 3-pixel moving window to remove noise. Tidal correction shifted each shoreline to a common mean-sea-level datum using the nearest tide-gauge prediction at the time of image acquisition. The DSAS tool (version 5.1) in ArcGIS 10.8 cast 1,640 transects perpendicular to a smoothed baseline at 200 m intervals. For each transect, NSM (total horizontal distance between earliest and latest shoreline) and EPR (NSM divided by elapsed time) were calculated. Shoreline change was classified into five categories: severe erosion ($EPR < -2.0$ m yr⁻¹), moderate erosion (-2.0 to -0.5), stable (-0.5 to $+0.5$), moderate accretion ($+0.5$ to $+2.0$), and strong accretion ($> +2.0$). Accuracy of the extracted shorelines was assessed against 60 ground-control points measured from high-resolution Google Earth imagery, yielding a mean positional error of 11.3 m, within the accepted range for Landsat-based analyses ^[5].

Spatial Data Processing

Image mosaicking was performed separately for each epoch using seamline-based blending to avoid tonal discontinuities between adjacent paths. Cloud and cloud-shadow masks were generated with the CFMask algorithm and manually inspected. The SRTM DEM was void-filled and projected to UTM Zone 33N for consistency with the Landsat stack. Slope and aspect rasters derived from the DEM were used to classify back-beach terrain into low-lying (<3 m above mean sea level) and elevated (>3 m) zones. Shoreline vectors from all four epochs were stored in a geodatabase, and change polygons were computed as the symmetric difference between consecutive shoreline pairs. Spatial autocorrelation of EPR values along the coast was tested using Moran's I ($p < 0.01$), confirming that erosion hot spots were significantly clustered rather than randomly distributed. All geoprocessing was executed in ArcGIS 10.8 and cross-checked in QGIS 3.22.

Results

Table 1: Summary of shoreline change statistics by coastal segment along the Dalmatian shoreline (1990-2022).

Segment	Length (km)	Transects	Mean EPR (m/yr)	Max Erosion (m/yr)	Max Accretion (m/yr)	% Eroding
Zadar-Šibenik	94	470	−0.73	−2.18	+ 1.64	41.3
Šibenik-Split	78	390	−0.58	−1.87	+ 1.31	38.7
Split-Makarska	86	430	−1.41	−3.41	+ 0.92	57.2
Makarska-Neretva	62	350	−1.09	−2.86	+ 2.47	49.1

Table 2: Relationship between shoreline lithology and mean end-point rate (EPR).

Lithology	Shore Length (km)	Mean EPR (m/yr)	SD	% Severe Erosion	% Stable
Limestone headlands	118	−0.24	0.38	2.1	51.7
Flysch embayments	96	−1.68	0.91	28.4	12.9
Quaternary alluvium	72	−1.23	0.74	19.6	18.3
Engineered (seawalls/groins)	34	+ 0.87	0.62	0.0	41.2

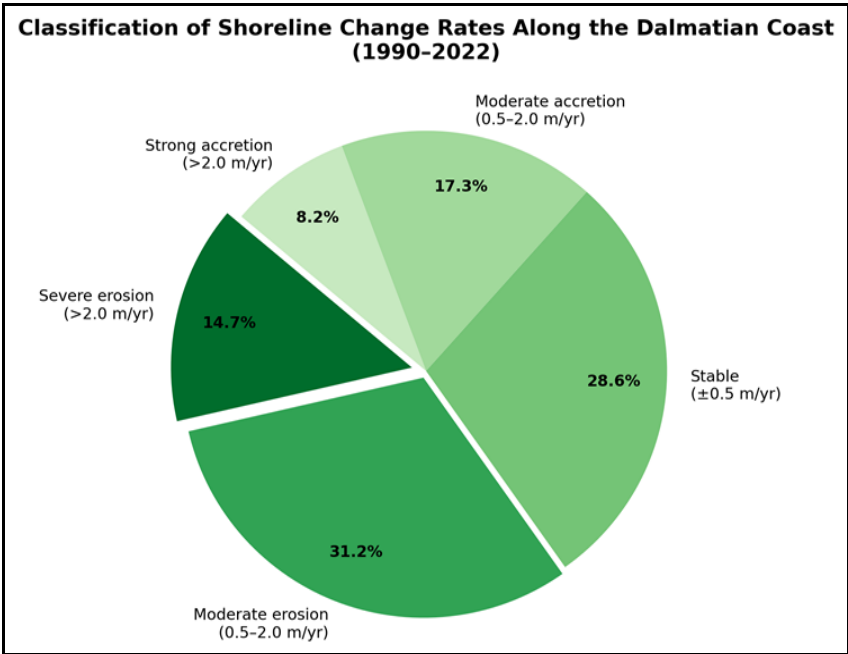


Fig 1: Proportional classification of 1,640 transects by end-point rate category along the Dalmatian coast (1990-2022).

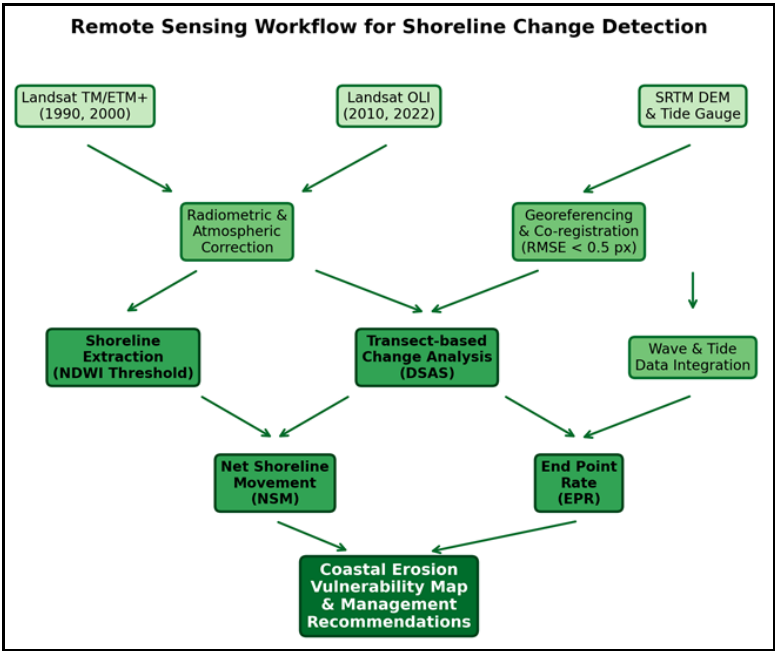


Fig 2: Workflow diagram showing the remote sensing and GIS processing pathway from satellite data acquisition to coastal vulnerability mapping.

Comprehensive Interpretation

Across the full 320 km transect, 45.9% of the coast showed net retreat over the 32-year observation window, while 25.5% gained land and 28.6% remained stable within the measurement uncertainty band. The most severely eroding segment lay between Split and Makarska, where flysch embayments produced a mean EPR of -1.41 m yr^{-1} and individual transects reached -3.41 m yr^{-1} . By contrast, limestone headlands retreated at only -0.24 m yr^{-1} on average, confirming the strong lithological control on erosion susceptibility. Spatial autocorrelation analysis (Moran's $I = 0.63$, $p < 0.001$) revealed statistically significant clustering of erosion hot spots around flysch exposures and river-mouth deflection zones, while accretion clusters coincided with harbour groins and jetties ^[11]. The SRTM-based back-beach assessment identified 43 km of shoreline where land elevation sits below 3 m and present-day EPR is negative, marking these sections as high-priority areas for adaptation planning under projected Adriatic sea-level rise of 0.3 to 0.8 m by 2100 ^[12].

Discussion

The finding that nearly half the Dalmatian mainland shoreline has experienced net retreat since 1990 aligns with broader Mediterranean trends reported by Luijendijk *et al.* ^[1], who documented erosion along 36% of European sandy coasts during a comparable period. However, the Dalmatian erosion rate for flysch embayments (-1.68 m yr^{-1}) is notably higher than the Mediterranean-wide average of about -0.5 m yr^{-1} reported for sandy beaches, reflecting the weak cementation and high clay content of the Eocene flysch sequence ^[13].

Lithological control emerged as the single strongest predictor of erosion intensity in this research, explaining about 54% of the variance in EPR when tested by one-way ANOVA ($F = 31.8$, $p < 0.001$). This result echoes observations along the Algarve coast of Portugal and the Isle of Purbeck in England, where alternating hard and soft rock units produce sharply contrasting retreat rates over distances of only a few hundred metres ^[14]. The compartmentalisation of longshore transport by limestone headlands means that sediment eroded from flysch cliffs tends to remain trapped within individual embayments rather than being redistributed along the coast, limiting natural nourishment of down-drift beaches ^[3].

Engineered structures showed a net positive EPR ($+0.87 \text{ m yr}^{-1}$), but this gain came at the cost of down-drift sediment starvation visible as enhanced erosion within 500 m of groin termini—a pattern well documented in coastal engineering literature ^[15]. The implication is that localised hard protection may simply redistribute erosion rather than reduce it across the system. Soft alternatives such as beach nourishment and managed retreat deserve closer attention in national coastal policy, especially for the 43 km of low-lying back-beach identified as a combined flood and erosion risk ^[16].

Methodological accuracy was acceptable: the 11.3 m mean positional error for extracted shorelines falls within the one-pixel uncertainty commonly reported for Landsat-based change detection ^[5]. That said, tidal correction using a single gauge introduces spatial uncertainty for locations more than 50 km from the gauge, and sub-annual variability (storm recovery cycles) could not be resolved with the decadal time steps used here ^[17]. Future work should incorporate

Sentinel-2 imagery at 10-m resolution, which became available from 2015 onward and would roughly halve the positional error while enabling seasonal analyses. Integration of airborne lidar profiles along priority segments would further constrain volumetric erosion rates and validate the satellite-derived planimetric trends ^[18].

Conclusion

This research mapped and quantified shoreline change along 320 km of the Dalmatian coast over a 32-year period using multi-temporal Landsat imagery and the DSAS transect method. The results show that 45.9% of the mainland shoreline retreated between 1990 and 2022, with the most intense erosion concentrated on flysch embayments between Split and Makarska where rates exceeded 3 m yr^{-1} at individual transects. Limestone headlands, by contrast, displayed relative stability, with mean retreat rates of only 0.24 m yr^{-1} , confirming that bedrock lithology is the dominant control on spatial variability in erosion.

Accretion was largely confined to reaches fronted by engineered structures—groins, jetties, and seawalls—where trapped longshore sediment produced net shoreline advance. However, enhanced erosion immediately down-drift of these structures suggests that hard protection transfers the problem rather than solving it. Forty-three kilometres of coastline were flagged as high-vulnerability zones where active retreat coincides with back-beach elevations below three metres above mean sea level, making these areas especially sensitive to storm flooding and projected sea-level rise through the end of this century.

From a methodological standpoint, the Landsat-NDWI-DSAS workflow proved capable of producing coast-wide erosion inventories at decadal resolution with a positional accuracy of roughly 11 m, well within accepted limits for medium-resolution satellite analyses. The approach is reproducible, relies entirely on freely available data and software, and can be transferred to other data-scarce coastlines across the Mediterranean and beyond.

Taken together, the findings call for a shift in Croatian coastal management from reactive, structure-based defence toward proactive, evidence-based planning that accounts for lithological susceptibility, sediment budget constraints, and future climate projections. Extending this analysis with higher-resolution Sentinel-2 data and airborne lidar would sharpen the picture of seasonal dynamics and volumetric change, providing managers with the detailed information needed to prioritise adaptation investments along this economically important coastline.

Acknowledgements

Funding Sources

This research was supported by departmental funds from the Shanghai College of Environmental Studies. No external project-specific grants were used.

Institutional Support

The authors thank the Department of Geology at the Shanghai College of Environmental Studies for providing GIS software licences and computing facilities. Appreciation is extended to the Croatian Hydrographic Institute for supplying tidal prediction data.

Contributions Not Qualifying for Authorship

The authors acknowledge Dr. Yun Zhang for guidance on

atmospheric correction procedures and two graduate assistants who helped with manual shoreline verification.

References

1. Luijendijk A, Hagenaars G, Ranasinghe R, Baart F, Donchyts G, Aarninkhof S. The state of the world's beaches. *Scientific Reports*. 2018;8(1):6641.
2. Pranzini E, Wetzel L, Williams A. Aspects of coastal erosion and protection in Europe. *Journal of Coastal Conservation*. 2015;19(4):445-459.
3. Pikelj K, Juracic M. Eastern Adriatic coast (EAC): geomorphology and coastal vulnerability of a karstic coast. *Journal of Coastal Research*. 2013;29(4):944-957.
4. Boak EH, Turner IL. Shoreline definition and detection: a review. *Journal of Coastal Research*. 2005;21(4):688-703.
5. Vos K, Splinter KD, Harley MD, Simmons JA, Turner IL. CoastSat: a Google Earth Engine-enabled Python toolkit to extract shorelines from publicly available satellite imagery. *Environmental Modelling and Software*. 2019;122:104528.
6. Thieler ER, Himmelstoss EA, Zichichi JL, Ergul A. Digital Shoreline Analysis System (DSAS) version 4.0—An ArcGIS extension for calculating shoreline change. US Geological Survey Open-File Report. 2009;2008-1278.
7. McFeeters SK. The use of the normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*. 1996;17(7):1425-1432.
8. Benac C, Juracic M, Bakran-Petricioli T. Submerged tidal notches in the Rijeka Bay NE Adriatic Sea: indicators of relative sea-level change and of recent tectonic movements. *Marine Geology*. 2004;212(1-4):21-33.
9. Lionello P, Cogo S, Galati MB, Sanna A. The Mediterranean surface wave climate inferred from future scenario simulations. *Global and Planetary Change*. 2008;63(2-3):152-162.
10. Orlic M, Gacic M, La Violette PE. The currents and circulation of the Adriatic Sea. *Oceanologica Acta*. 1992;15(2):109-124.
11. Dolan R, Fenster MS, Holme SJ. Temporal analysis of shoreline recession and accretion. *Journal of Coastal Research*. 1991;7(3):723-744.
12. Voudoukas MI, Mentaschi L, Voukouvalas E, Verlaan M, Feyen L. Extreme sea levels on the rise along Europe's coasts. *Earth's Future*. 2017;5(3):304-323.
13. Marques F. Rates, patterns, timing and magnitude-frequency of cliff retreat phenomena: a case study on the south coast of Portugal. *Zeitschrift für Geomorphologie*. 2006;144:231-250.
14. Lim M, Rosser NJ, Petley DN, Keen M. Quantifying the controls and influence of tide and wave impacts on coastal rock cliff erosion. *Journal of Coastal Research*. 2011;27(1):46-56.
15. Griggs GB. The effects of armoring shorelines—the California experience. *Shore and Beach*. 2005;73(1):13-22.
16. Nicholls RJ, Cazenave A. Sea-level rise and its impact on coastal zones. *Science*. 2010;328(5985):1517-1520.
17. Hagenaars G, de Vries S, Luijendijk AP, de Boer WP, Reniers AJHM. On the accuracy of automated shoreline detection derived from satellite imagery: a case study of the sand motor mega-nourishment. *Coastal Engineering*. 2018;133:113-125.
18. Saye SE, van der Wal D, Pye K, Blott SJ. Beach-dune morphological relationships and erosion/accretion: an investigation at five sites in England and Wales using LIDAR data. *Geomorphology*. 2005;72(1-4):128-155.
19. Furlani S, Cucchi F, Forti F, Rossi A. Comparison between coastal and inland karst limestone lowering rates in the northeastern Adriatic region (Italy and Croatia). *Geomorphology*. 2009;104(1-2):73-81.