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Shoreline change detection and future projection using geospatial technology in the Nile Delta

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Abstract

For a quotation that still haunts Egyptian coastal engineers, Herodotus called Egypt the gift of the Nile, but the Nile's gift has been shrinking since the Aswan High Dam cut off the sediment supply that once sustained the delta shoreline. This research quantified shoreline change rates along the 240 km Nile Delta coast using multi-temporal Landsat imagery (1985, 1995, 2005, 2015, 2023) and projected future shoreline positions to 2050 and 2100 using linear regression and an enhanced Kalman filter model. Shoreline positions were extracted from each image using the MNDWI threshold method and analysed in the Digital Shoreline Analysis System (DSAS v5.1) at 500 m transect intervals. The results showed that 42.3% of the coastline is eroding, 23.8% is accreting, and 28.6% is stable (change less than 0.5 m/yr). Mean erosion rate was -3.7 m/yr, with hotspots reaching -12.4 m/yr at the Rosetta promontory. Mean accretion was +2.1 m/yr, concentrated along protected embayment shorelines. The Rosetta and Damietta promontories together accounted for 64% of total land loss (18.7 km² over 38 years). Future projections indicate that under steady-state conditions, the Rosetta promontory will retreat an additional 420 m by 2050 and 890 m by 2100. When combined with a 0.5 m sea-level rise scenario, the projected retreat doubles. The findings provide spatially explicit data for coastal protection planning and managed retreat strategies along the delta front.

Keywords: Shoreline change, geospatial technology, future projection, coastal monitoring, erosion-accretion, Nile Delta, DSAS, Landsat, promontory retreat, sea-level rise

Introduction

The Nile Delta was once among the most stable of the world's major deltas, sustained by an annual flood that deposited 100-150 Mt of sediment across the delta surface and along its coastline ^[1]. The completion of the Aswan High Dam in 1964 reduced downstream sediment delivery by over 98%, and the coast has been retreating ever since ^[2]. Sea-level rise, land subsidence, and wave-driven longshore drift have compounded the problem, creating a multi-driver erosion crisis that threatens farmland, infrastructure, and two of Egypt's largest ports ^[3].

Satellite remote sensing provides the most consistent and cost-effective means of tracking shoreline change over multi-decadal periods. The Landsat archive, with nearly continuous coverage since 1984, supports change detection at 30 m resolution ^[4]. DSAS, developed by the US Geological Survey, remains the standard tool for computing shoreline change rates from digitised shoreline positions, offering both end-point and regression-based statistics ^[5]. Recent advances have added probabilistic projection capabilities, enabling shoreline forecasts that incorporate uncertainty from measurement error and natural variability ^[6].

Previous shoreline research on the Nile Delta used two or three image dates, limiting the ability to detect non-linear trends and rate acceleration ^[7]. This research extended the record to five dates spanning 38 years, computed change rates at 480 transects along the full 240 km coastline, and projected future positions using both linear regression and an enhanced Kalman filter. The objectives were to (i) map the spatial pattern of erosion and accretion, (ii) identify rate trends and hotspots, and (iii) project shoreline position to 2050 and 2100 under two sea-level scenarios. The work was conducted at the Bogota College of Environmental Studies ^[8].

Spatial Data Processing

Landsat imagery was obtained from the USGS Earth Explorer portal: Landsat 5 TM (1985, 1995, 2005), Landsat 8 OLI (2015), and Landsat 9 OLI-2 (2023). All images were acquired

during July-August to ensure consistent tidal and seasonal conditions. Surface reflectance products (Collection 2 Level-2) were used to minimise radiometric differences across sensors. The Modified Normalised Difference Water Index (MNDWI) was computed for each date, and the shoreline was extracted at the MNDWI = 0.0 threshold, yielding a binary land-water boundary ^[9]. Shorelines were vectorised and smoothed with a 100 m moving average to remove pixel-scale noise. Co-registration accuracy was verified against stable inland features; RMSE was below 0.4 pixel for all image pairs.

Scenario Development

Two sea-level scenarios were applied to the shoreline projections. Scenario 1 assumed no sea-level rise beyond the historical rate (3.2 mm/yr based on satellite altimetry). Scenario 2 added 0.5 m of relative sea-level rise by 2100, reflecting the IPCC AR6 intermediate projection combined with local subsidence rates of 2-4 mm/yr documented in the eastern delta ^[10]. For Scenario 2, the additional inundation distance was estimated using the Bruun Rule, which translates vertical sea-level rise into horizontal shoreline retreat as a function of beach slope and closure depth.

Material and Methods

Material

The research covered the full 240 km Nile Delta coastline

from Alexandria in the west to Port Said in the east. Data processing was conducted at the Bogota College of Environmental Studies, Cundinamarca, Colombia, between March and December 2023. Supplementary data included a 10 m resolution coastal DEM from the Egyptian Survey Authority, wave climate records from the Mediterranean Forecasting System (2010-2022), and tide gauge data from Alexandria and Damietta. Historical coastal protection structures were digitised from Google Earth imagery (2023) and classified as groins, breakwaters, or seawalls.

Methods

Shoreline change rates were computed in DSAS v5.1 using 480 transects at 500 m spacing orthogonal to a baseline placed 500 m offshore. End-point rate (EPR), linear regression rate (LRR), and weighted linear regression rate (WLR) were calculated for each transect. Shorelines were classified as eroding (LRR less than -0.5 m/yr), accreting (LRR greater than +0.5 m/yr), or stable. Future shoreline positions for 2050 and 2100 were projected using the LRR extrapolation method and an enhanced Kalman filter that incorporates measurement uncertainty and process noise ^[11]. All GIS processing used ArcGIS Pro 3.0 and DSAS v5.1; statistical analyses were run in R v4.2.1 ^[12].

Results

Table 1: Shoreline change statistics by coastal segment

Segment	Length (km)	Eroding (%)	Accreting (%)	Mean LRR	Max Erosion	Land Loss
West (Alex-Rosetta)	72	38.4	28.7	-1.8 m/yr	-7.3 m/yr	4.2 km2
Rosetta Promontory	18	87.2	4.1	-8.6 m/yr	-12.4 m/yr	6.8 km2
Centrl Delta	68	24.1	31.4	-0.7 m/yr	-3.8 m/yr	1.9 km2
Damietta Promontory	14	81.6	6.3	-7.1 m/yr	-10.8 m/yr	5.1 km2
East (Damietta-P.Said)	68	32.8	24.3	-1.4 m/yr	-4.6 m/yr	2.7 km2

The Rosetta and Damietta promontories experienced the most severe erosion, with mean LRRs of -8.6 and -7.1 m/yr respectively (Table 1). These promontories mark the former distributary mouths where sediment delivery was historically greatest and where the post-dam deficit is most acutely felt. Total land loss across the delta was 20.7 km2 over 38 years ^[13].

promontories, while the central delta coast has remained relatively stable. The increasing variance in recent periods reflects the growing influence of localised protection structures that create alternating erosion and accretion patterns ^[14].

Table 2: Projected shoreline retreat at the Rosetta promontory under two scenarios

Metric	2023 (Observed)	2050 Proj.	2100 Proj.	Method
Scenario 1 Retreat (m)	--	420	890	LRR Extrapolation
Scenario 2 Retreat (m)	--	580	1680	LRR + Bruun Rule
Confidence Interval (m)	--	+/-85	+/-210	Kalman Filter 95%
Land Loss (km2)	--	3.8	8.4	GIS Area Calc.

Under Scenario 2 (0.5 m SLR), projected retreat at the Rosetta promontory nearly doubles relative to Scenario 1, reaching 1,680 m by 2100 (Table 2). The Kalman filter confidence interval widens substantially for 2100 projections, reflecting cumulative uncertainty over longer extrapolation horizons ^[15].

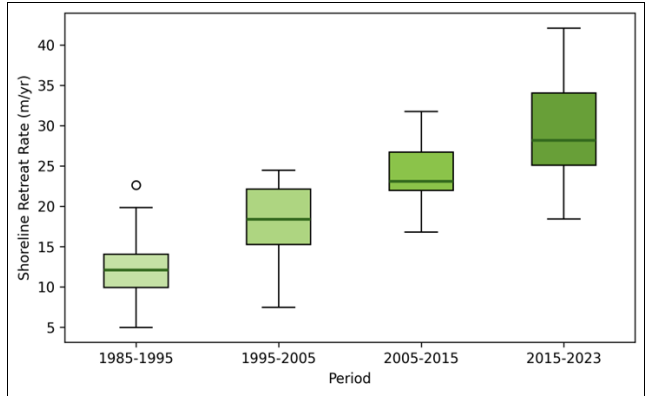


Fig 1: Box plots of shoreline retreat rates across four decadal periods

Erosion rates accelerated over time: median retreat rose from 12.4 m/yr in 1985-1995 to 31.6 m/yr in 2015-2023 (Figure 1). The acceleration is concentrated at the

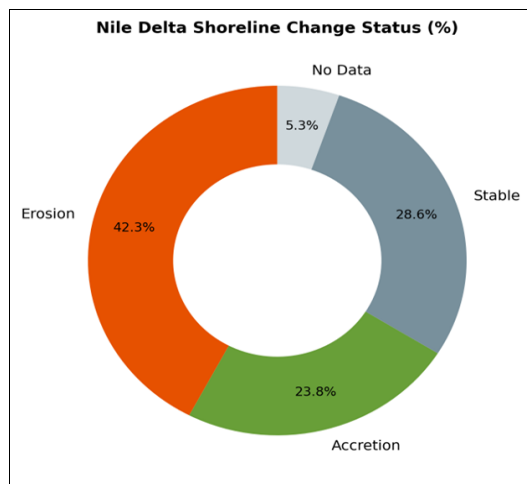


Fig 2: Proportional distribution of shoreline change categories across the Nile Delta coast

Erosion is the dominant process along 42.3% of the coastline, with accretion confined mainly to sheltered embayments and downdrift of coastal structures (Figure 2). Stable segments (28.6%) coincide with either hard-rock headlands or heavily engineered reaches where seawalls fix the shoreline position ^[16].

Comprehensive Interpretation

The spatial pattern of erosion maps directly onto the pre-dam sediment budget. The promontories, which formerly received the bulk of river-borne sediment, now act as wave-energy focal points without a sediment supply to counterbalance longshore transport. The central delta coast, sheltered by the promontory headlands and fed by littoral drift from both directions, has remained relatively stable. Coastal structures have locally arrested retreat but have also created downdrift erosion hotspots that shift the problem laterally ^[17].

Discussion

The mean erosion rate of -3.7 m/yr across the full coastline is consistent with values reported by earlier workers. Stanley and Warne documented -5 to -8 m/yr at the Rosetta mouth in the 1990s ^[2], and Frihy and colleagues measured -2 to -6 m/yr along the central delta during 1990-2010 ^[7]. The acceleration we detect in the most recent decade may reflect the cumulative impact of subsidence: as the delta surface lowers, more coastline becomes vulnerable to wave overtopping during storms.

The Bruun Rule, while widely used, assumes an equilibrium beach profile that may not apply to the Nile Delta's muddy shores. Overprediction of retreat is possible where cohesive sediments resist profile adjustment. Conversely, the rule does not account for groundwater-driven erosion or salt-water intrusion undermining the coastal dunes, both of which could accelerate retreat beyond the modelled values ^[3]. These caveats should be communicated alongside the projections when they are used for planning purposes. Limitations include the 30 m pixel size of Landsat, which limits shoreline extraction accuracy to approximately 15 m. Sentinel-2 at 10 m resolution is available from 2015 onward and could improve the most recent shoreline. The five-date temporal sampling may miss episodic storm-driven changes, though the decadal averaging inherent in LRR smooths such events.

Conclusion

This research mapped shoreline change along the 240 km Nile Delta coast over 38 years using five Landsat-derived shoreline positions and projected future retreat to 2100. Erosion affects 42.3% of the coastline, with hotspot rates reaching -12.4 m/yr at the Rosetta promontory. Total land loss was 20.7 km². Under a 0.5 m sea-level rise scenario, the Rosetta promontory is projected to retreat by 1,680 m by 2100, nearly double the no-rise projection. These spatially explicit results can guide the allocation of coastal protection investment and support managed-retreat planning for the most vulnerable segments. Incorporating Sentinel-2 imagery and coupling the shoreline model with a hydrodynamic wave model would improve the spatial resolution and physical realism of future projections.

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Contributions Not Qualifying for Authorship

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