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MULTI-TEMPORAL ASSESSMENT OF DELTAIC ISLANDS IN THE HUGLI AND MEGHNA ESTUARIES

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Abstract: Understanding of coastal erosion and accretion processes in dynamic estuarine contributes in coastal risk mitigation strategies. The island-area dynamics across multiple estuaries within the same delta region requires significant research attention. This study analyses shoreline changes characteristics of Nayachar and Ghoramara islands (Hugli estuary, India) and Hatia and Nijhum islands (Meghna estuary, Bangladesh) of the Ganga–Brahmaputra Delta using Landsat-MSS, TM, and OLI data from 1973 to 2024. Multi-temporal island shoreline overlay analysis was applied to quantify island area dynamics at each time step for a period of 51 years. Manual digitalization from the satellite images has done to quantify the shoreline accretion and erosion rates. Linear extrapolation was applied to project future island-area trends to 2044. In the Hugli estuary, Nayachar shows overall accretion while Ghoramara erodes from all directions. In the Meghna estuary, Hatia faces erosion in the northern portion, while Nijhum shows northward area gain through sediment deposition. Accretion rates for Nayachar and Nijhum (0.57 km²/yr and 0.41 km²/yr) exceed projected sea-level rise of 0.43–0.84 m by 2100 under IPCC SSPs, yet any SLR increase will raise flood frequency. The erosion rates of Ghoramara and Hatia (0.09 km²/yr and 1.52 km²/yr) signal severe vulnerability to future sea level rise, storm surge and flooding. If historical trends continue, island areas by mid-21st century will be 67.40, 40.67, 287.98 and 1.53 km² for Nayachar, Nijhum, Hatia and Ghoramara respectively; actual areas under SLR will be smaller. The study suggests shoreline protection zoning for eroding islands, mangrove restoration and integrated island specific management as immediate priorities.

Keywords: Hugli estuary, Landsat, Meghna estuary, sea level rise, shoreline change

Introduction

Estuaries represent transitional environments where riverine and oceanic processes converge, creating semi-enclosed water bodies of significant ecological and geomorphological complexity. Among the world's great delta systems, the Ganga–Brahmaputra Delta (GBD) stands out for its exceptional scale, covering approximately 123.5×10^3 km² and delivering annual sediment loads exceeding 1×10^9 t yr^{-1} (Bandyopadhyay, 2007). This combination of prolific river discharge, substantial sediment supply, vigorous tidal forcing, and recurring cyclonic disturbances renders the GBD one of the most geomorphologically active coastal zones on Earth. Within this system, the Hugli Estuary (India) and the Meghna Estuary (Bangladesh) constitute the two principal outlets through which sediment and water reach the Bay of Bengal. The dynamic interplay of these processes has, over centuries, facilitated the emergence, growth, and in some cases disappearance of estuarine islands (Uddin et al., 2024).

Island area change serves as a tangible indicator of sediment redistribution, tidal regime shifts, and the cumulative effects of climate-driven sea-level rise. By comparing islands exhibiting opposite geomorphic

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trajectories accretion versus erosion within the same deltaic framework, it becomes possible to isolate the factors governing coastal vulnerability and resilience. The research studies have examined individual island assessments of single estuaries. The study focuses on cross-estuary comparative analysis to address the gap.

The present study undertakes such a comparative analysis across two estuaries, aiming (i) to quantify deltaic island area change over a century from 1973 to 2024 using multi-temporal Landsat imagery (ii) to project future island extents until 2024 assuming continuous historical trends, and (iii) to discuss the implications of these trends under IPCC AR6 projected sea-level rise scenarios to recommend safeguards for vulnerable island communities.

Literature Review

1. Prior works

The geomorphological dynamism, tidal interplay and island area change have been a focal area of research over the Ganga-Brahmaputra Delta. Rudra (2018) reflected on a comprehensive overview of the rivers such as Ganga, Bhagirathi, and Meghna and their river system, documenting historical channel migration and their relation with sediment budget. Bandyopadhyay (2007) establishes the sediment dynamics of the delta.

Shoreline dynamics of the delta relied on remote sensing over the past decades. Paul et al. (2023) contributed to the spatio-temporal change of Nayachar Island, confirming the sediment accretion of the island driven by tidal activity. Previously, studies on Ghoramara island have identified the severe area island and a shrinking in the island's area by more than 60% of its 1970s extension due to wave attack, river flow direction and relative sea level rise (Karapurkar et al., 2025). In the Meghna Estuary, Anwar and Rahman (2021) discuss morphological changes at East Bhola Island, indicating tidal currents, cyclonic events and the dynamic interplay of sediment discharge from the river system contributing to a spatially complex pattern of accretion and erosion within the individual island.

Remote sensing and GIS based tool and actively contributing to shoreline change analysis at the global scale (Ankrah eta., 2022). Application of multi-temporal satellite images has become a standard practice among researchers for quantifying shoreline migration and projecting future trends. The advancement of remote sensing is contributing to the large-scale assessment of the island to take safety measures and actively contribute to integrated coastal management (Vitousek et al, 2023).

Zhang et al. (2025), in their global-scale analysis of coastline dynamics in relation to sea level rise, established the threat of sea level rise on low-lying deltaic coasts. Sorna et al. (2025) developed a relation between relative sea level rise through geodetic-hydrodynamic fusion, contributing local relative sea level rise estimates for the Meghna Estuary.

The present study addresses the research gap of a cross estuary comparison of long-term island area dynamics in Hugli and Meghna Estuaries using a multi-temporal dataset. Existing studies focus on individual islands or specific single estuaries. The study fills the gap by analysing islands situated at the estuary mouth of both estuaries over the period of 1973 to 2024.

2. Study Area

Nayachar and Ghoramara from the Hugli Estuary (India) and Hatia and Nijhum islands, Meghna Estuary (Bangladesh) of the GBD have been selected for the study. This selection, spanning two countries and two distinct estuarine systems, enables a meaningful cross-comparison of shoreline dynamics under varying sedimentary and hydrodynamic conditions.

The Hugli Estuary is one of the most active deltas of GBD. The domination of a micro-tidal regime, moderate wave energy and fluvial sediment deposit develops the upper Ganga Basin. Nayachar is located at the mouth of the estuary, which occupies a significantly progressive sediment accumulation (Paul et al., 2023). Ghoramara experiences a heightened wave energy, storm surge, and channel migration, rendering it one of the severely eroded islands of the estuary (Pramanick et al., 2022).

The Meghna Estuary carries and deposits discharges from the Ganga, Brahmaputra and Meghna river systems. The estuary is characterised by an active macro-tidal regime, frequent tropical cyclone landfall and high suspended sediment concentration. Hatia Island, located at the mouth of the Meghna estuary, has experienced net erosion despite active sediment accretion in the 1973-1988 (Faisal, 2024). The tidal dynamics, flow direction of the river system and frequent cyclone landfall are active drivers of the island erosion. Nijhum, on the other hand, is more sheltered in terms of sediment deposition, showing a significant increase in its island area.

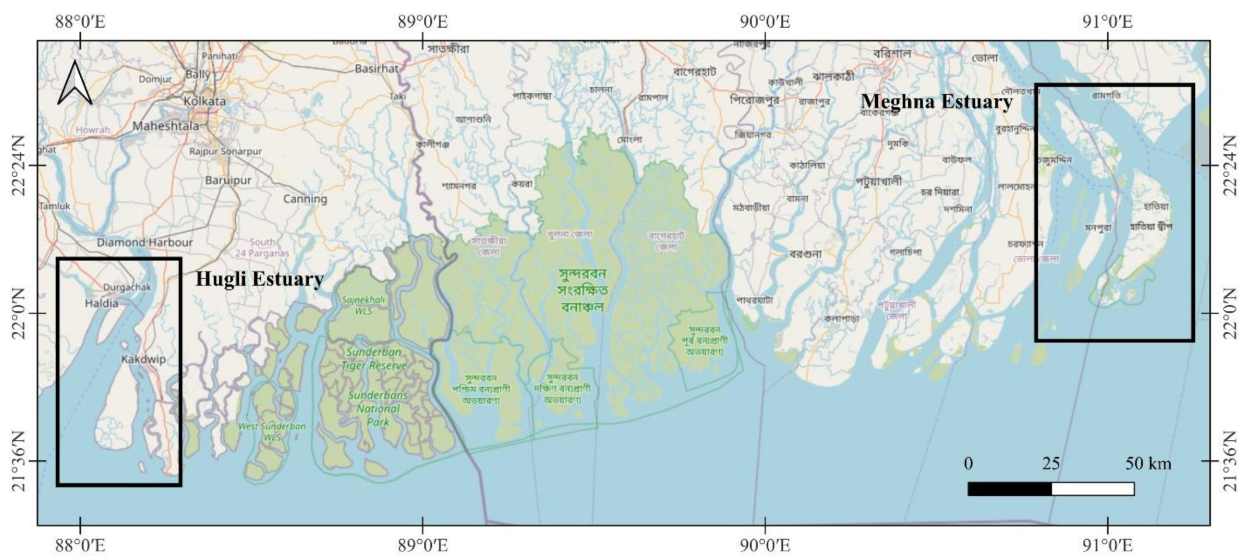

Figure 1: Location map delineating the Hugli and Meghna estuaries

Data and Methodology

A. Satellite Data Acquisition

Cloud-free Landsat satellite images were acquired for each estuary, for the period from 1973 to 2024 and encompassing the MSS, TM, and OLI sensor generations (Table 1). Images were downloaded from the USGS Earth Explorer archive (https://earthexplorer.usgs.gov). To minimise the influence of ephemeral intertidal features such as sandbars, mudflats, and exposed tidal flats, high-tide imagery was prioritised wherever archive availability permitted (Costa et al., 2023). All four images were geometrically corrected to the Universal

Transverse Mercator coordinate system referenced to the WGS-84 ellipsoid, ensuring spatial consistency across epochs. Positional uncertainty arising from the resolution of 60 m (MSS) and 30 m (TM/OLI) is acknowledged as a methodological limitation.

Table 1: Specifications of multi-temporal satellite images

Study Area	Satellite	Sensor	Acquisition Date	Path	Row	Resolution (m)
Hugli Estuary	Landsat 1	MSS	17th Jan 1973	149	45	60
	Landsat 5	TM	26th Dec 1988	138	45	30
	Landsat 5	TM	27th Dec 2000	138	45	30
	Landsat 8	OLI	13th Dec 2024	138	45	30
Meghna Estuary	Landsat 1	MSS	5th Dec 1973	147	45	60
	Landsat 5	TM	9th Oct 1988	136	45	30
	Landsat 5	TM	29th Dec 2000	136	45	30
	Landsat 9	OLI	23rd Dec 2024	136	45	30

B. Shoreline Extraction and Area Calculation

Shorelines for the years 1973, 1988, 2000, and 2024 were extracted through manual digitisation using false-colour composite (bands 4-3-2 for MSS and bands 5-4-3 for TM/OLI) to maximise the contrast between land and water. The land-water boundary, considering the high water line, has been delineated. Vector polygons were generated for each of the four islands, using Q-GIS software. Specific colours (yellow for 1973, blue for 1988, green for 2000, and red for 2024) were applied for shoreline overlay to ensure clear identification of shoreline migration through time.

C. Rate of Change and Future Projection

Island area changes ($km^2\ yr^{-1}$) were computed by dividing the net area change between 1973 and 2024 by the 21-year study period. Future island areas to 2044 were projected to 2044 by linear extrapolation. Projected $Area_{2044} = Area_{2024} + (Rate \times 20\ years)$. The method assumes continuation of linear historical trend and does not account for non-linear potential sea-level rise, policy intervention or episodic cyclonic events. These projections are best interpreted as indicative baseline estimates rather than deterministic forecasts.

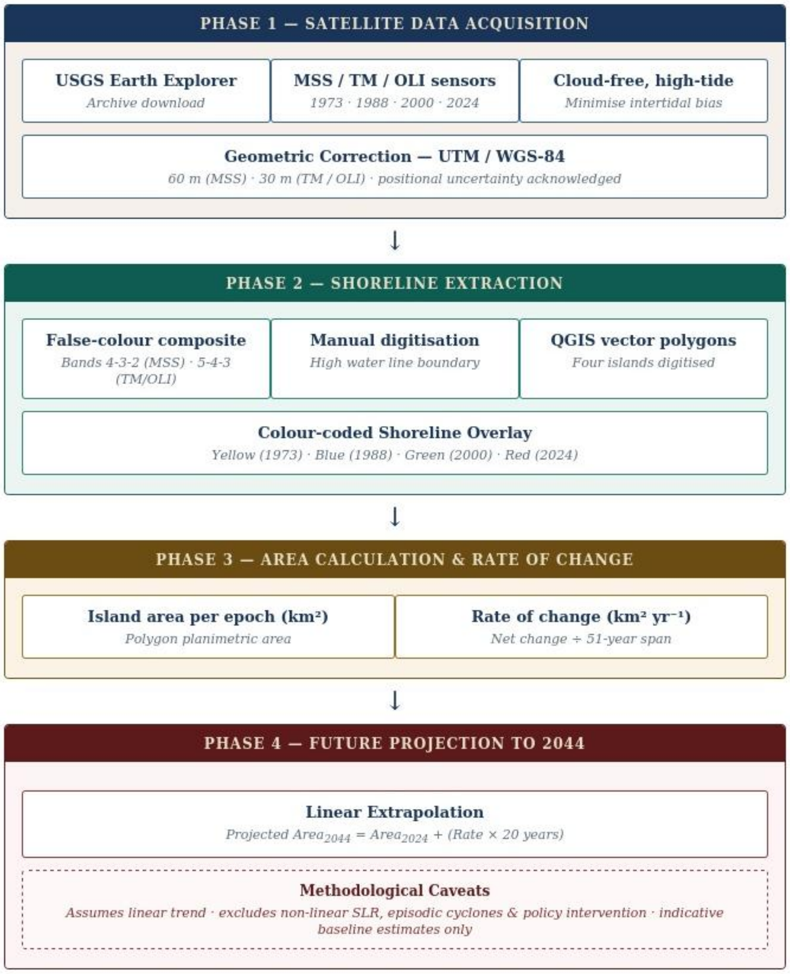

Figure 2: Flowchart of Methodology

Results and Discussion

A. Multi-Temporal Area Change Analysis Using Overlay Technique

In the Hugli Estuary, Nayachar Island recorded progressive areal expansion throughout the study period, growing from 27.39 km^2 in 1973 to 56.66 km^2 by 2024 a net gain of 29.27 km^2, which is equivalent to an accretion rate of 0.57 $km^2\ yr^{-1}$ (Tables 2 and 3). Overlay mapping reveals that eastern shoreline experienced localised retreat, while the western margins showed pronounced outward advance, consistent with the island's location within a sediment-rich depositional zone where the combined influence of fluvial discharge and tidal dynamics fosters land building (Paul et al., 2023).

Ghoramara Island, by contrast, shrank from 8.18 km^2 in 1973 to just 3.33 km^2 by 2024, representing a loss of approximately 60% of its total area (4.85 km^2; Tables 2 and 3) at a mean erosion rate of 0.09 $km^2\ yr^{-1}$. Shoreline retreat was evident from all directions, reflecting the island's position within a high-energy erosional environment where channel migration, relative sea-level rise, wave attack, heightened storm activity, and lateral sediment redistribution collectively sustain persistent land loss (Karapurkar et al., 2025).

Table 2: Island area changes (km²) of the Hugli Estuary from 1973–2024

Estuary	Action	Island	1973	1988	2000	2024
Hugli Estuary	Accretion	Nayachar	27.39	40.61	49.42	56.66
Hugli Estuary	Erosion	Ghoramara	8.18	5.73	5.18	3.33

Table 3: Net Island area change of the Hugli Estuary, 1973–2024

Island	Area 1973 (km²)	Area 2024 (km²)	Accretion (km²)	Erosion (km²)	Rate (km² yr⁻¹)
Nayachar	27.39	56.66	29.27	–	+0.57
Ghoramara	8.18	3.33	–	4.85	−0.09

In the Meghna Estuary, comparable but larger-magnitude contrasts were recorded. Hatia Island underwent an initial expansion from 396.17 km² in 1973 to 408.96 km² in 1988, before reversing to 367.77 km² in 2000 and declining further to 318.38 km² by 2024 a net reduction of 77.79 km² over the period (Tables 4 and 5). Overlay analysis identifies northward shoreline retreat as the dominant spatial pattern, attributable to prevailing river flow direction, tidal exchange dynamics, recurring cyclonic events, evolving hydrodynamic conditions, and ongoing relative sea-level which are identified as the primary drivers of this long-term land loss (Sorna et al., 2025; Zhang et al., 2025).

Nijhum Island demonstrated the most pronounced accretionary trend among the four study sites, expanding from 11.65 km² in 1973 to 31.50 km² in 1988 and maintaining near-stable growth to reach 32.47 km² in 2024 a total increase of 20.82 km² (Tables 4 and 5). Sediment accumulation was most active along the northern margins, consistent with Nijhum's sheltered position within the depositional sector of the Meghna Estuary.

Table 4: Island area changes (km²) of the Meghna Estuary from 1973–2024

Estuary	Action	Island	1973	1988	2000	2024
Meghna Estuary	Erosion	Hatia	396.17	408.96	367.77	318.38
Meghna Estuary	Accretion	Nijhum	11.65	31.50	31.43	32.47

Table 5: Net Island area change of the Meghna Estuary, 1973–2024

Island	Area 1973 (km²)	Area 2024 (km²)	Accretion (km²)	Erosion (km²)	Rate (km² yr⁻¹)
Hatia	396.17	318.38	–	77.79	−1.52
Nijhum	11.65	32.47	20.82	–	+0.41

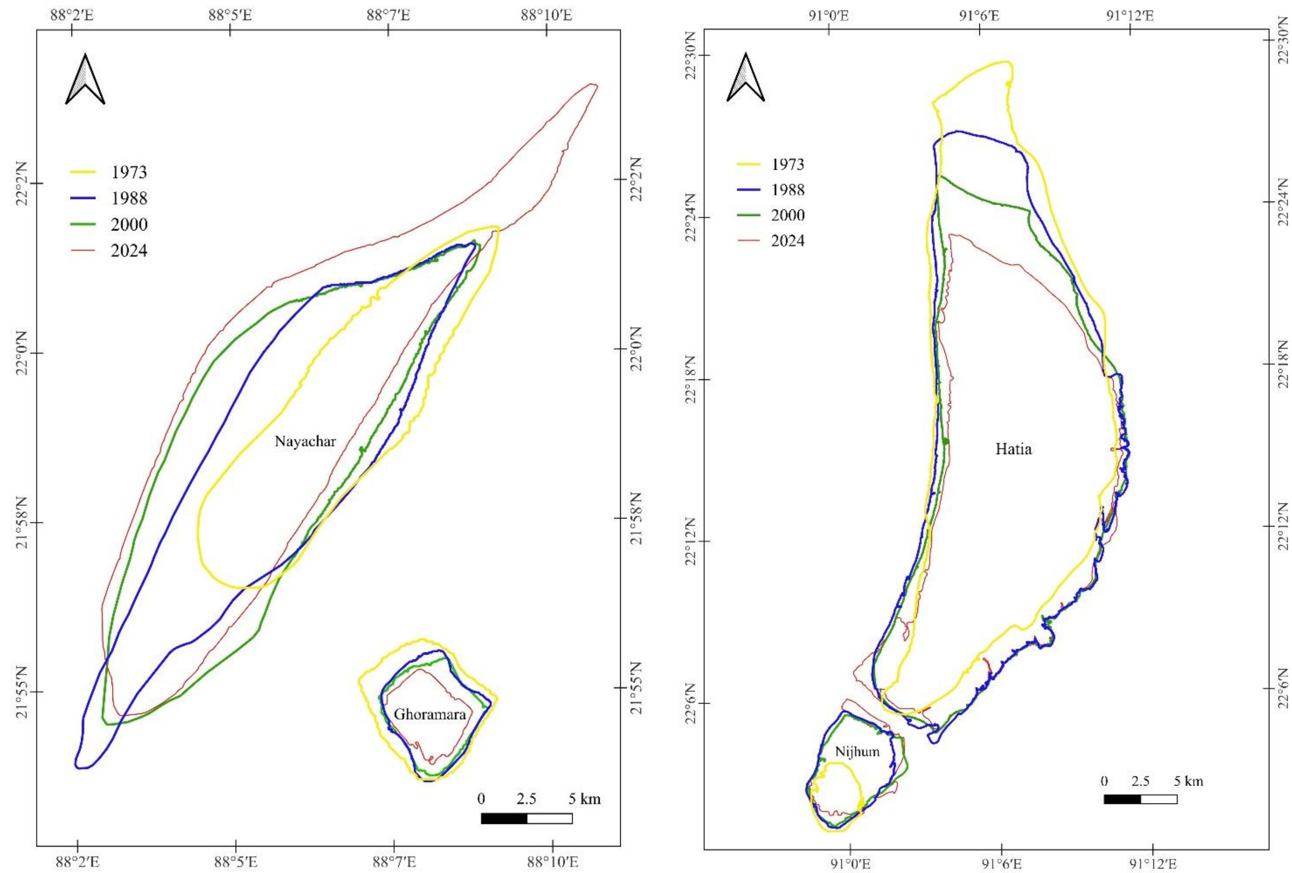

Figure 3: Island vector overlay of Hugli and Meghna estuaries from 1973 to 2024

B. Long-Term Change and Future Trends Under Sea Level Rise

In the Hugli Estuary, Nayachar shows steady growth from 27.39 km² (1973) to 56.66 km² (2024), with a projected area of 67.40 km² by 2044, reflecting continued sediment deposition. Ghoramara, conversely, declined from 8.18 km² to 3.33 km² over the same period and is projected to shrink further to just 1.53 km² by 2044 along with a projected sea-level rise of 0.20–0.40 m by mid-century (IPCC AR6), raising serious concerns of accelerated inundation and potential submergence.

In the Meghna Estuary, Hatia recorded a brief area gain to 408.96 km² in 1988 before declining to 318.38 km² by 2024, with a projected area of 287.98 km² by 2044. Nijhum expanded rapidly from 11.65 km² (1973) to 32.47 km² (2024) and is projected to reach 40.67 km² by 2044, though Cyclone Amphan introduced a temporary disruption to this growth trend (Biswas & Rajak, 2022; Mishra et al., 2022). Across both estuaries, future sea-level rise will increasingly threaten even accreting islands through heightened flood. frequency, saltwater intrusion, and episodic erosion.

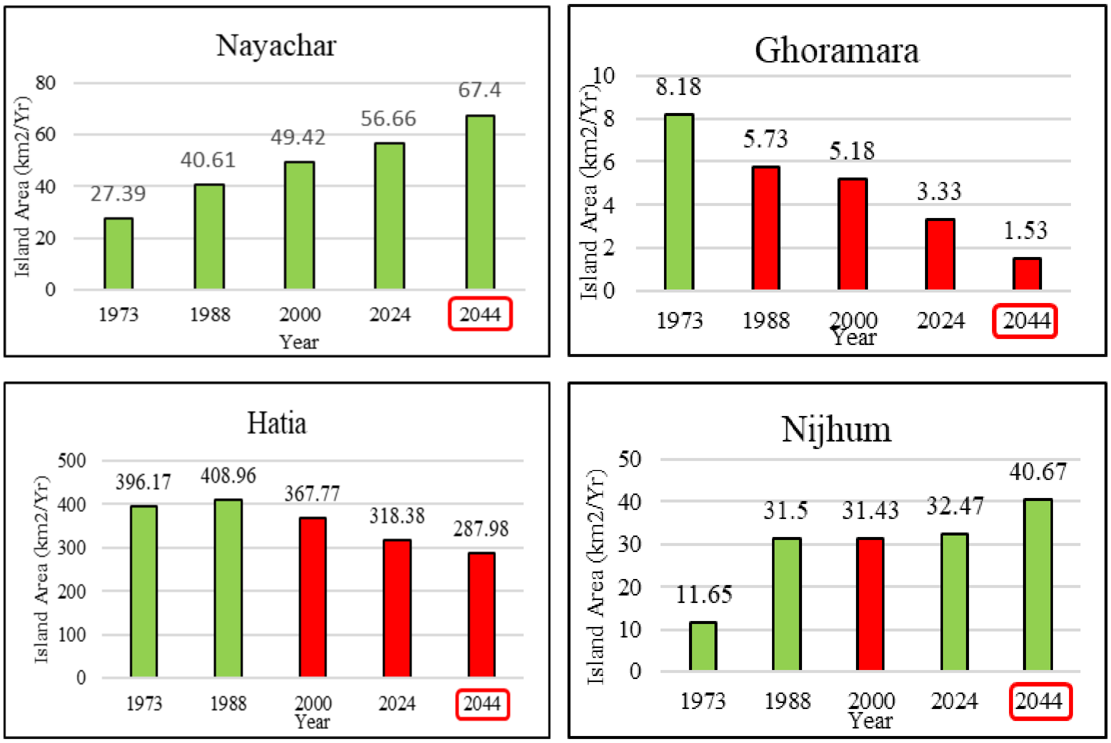

Figure 4: Statistical analysis of island area change with future projection

Discussion

The study across the four islands reflects the heterogeneous nature of sediment dynamics in the GBD. The Meghna estuary reportedly shows comparatively larger morphological adjustments than the Hugli estuary. A greater sediment load and river discharge was observed over the Meghna Estuary. Within each estuary, the distinction between accretion- and erosion-dominated islands reflects microscale variations in sediment supply, tidal hydrodynamics, susceptibility to channel migration, and wave exposure.

Ghoramara Island witnesses sediment migration due to the channel migration of the Hugli River along with progressive relative sea level rise. Nayachar, due to its sheltered estuarine location, along with the proximity of active sediment gain, has augmented the island-building process along its eastern margin.

Meghna Estuary encounters a more complex pattern where Hatia has gone through periods of island area gain and loss, especially between 1973 and 1988. The island has observed an elevated period of sediment deposition followed by island area erosion due to channel migration, tidal surges, cyclonic events and relative sea level rise. Nijhum has gone through a rapid early growth between 1973 and 1988, reflecting the development of sandbar colonised with vegetation and sediment trapping. The temporary disruption introduced by Cyclone Amphan (2020) confirms the findings of Biswas and Rajak (2022) and Mishra et al. (2022) that intense cyclones have the potential for rapid but partially recoverable geomorphic change, specifically on sandy deltaic islands.

Under IPCC AR6 projections, regional sea-level rise of 0.43–0.84 m by 2100 under SSP2-4.5 to SSP5-8.5 scenarios will augment ongoing erosion trends. The accretion islands, such as Nayachar and Nijhum island, have an accretion rate that presently exceeds projected sea-level rise rates, suggesting the potential of these islands to maintain positive sediment budget under moderate SLR scenarios. However, sediment-risk mapping should be taken into consideration to ensure the future vulnerability of the islands. Ghoramara is at risk of complete submergence within the second half of the century. The island requires embankment assessment along with managed retreat planning, including supported reallocation of remaining residents. Hatia requires mangrove restoration along eroding northern margins, shoreline protection zoning, and early-warning systems for storm surge-driven inundation.

Limitations

The study contains methodological limitations when interpreting the results of the study. First, the mixed use of 60 m resolution MSS data (1973) along with 30 m resolution TM and OLI data (1988, 2000, 2024) creates resolution-related positional uncertainty that is significant for the 1973 baseline epoch. While this is a pervasive constraint commonly observed in long-term Landsat-based shoreline studies, it necessitates attention while interpreting very small area changes, especially for Ghoramara, where the island perimeter-to-area ratio is high.

Second, though tidal-stage correction has been done by poetising high-tide imagery, it requires calibration with tide data to ensure the ambiguity of tidal influence in shoreline offset.

Third, the linear extrapolation method used for the 2044 island area projection does not incorporate non-linear feedback such as relative sea level rise, effects of future tropical cyclones or threshold-triggered erosion. These projections should not be treated as probabilistic forecasts and should only be treated as indicative baseline scenarios. Future incorporation of DEM-based inundation analysis and hydrodynamic simulations will improve projection reliability.

Fourth, the study does not incorporate field validation, sediment budget analysis or bathymetric surveys. Future research should incorporate such data to strengthen the research results.

Conclusion

This study has documented and analysed the long-term geomorphic evolution of four deltaic islands, Nayachar, Ghoramara, Hatia, and Nijhum, using a half-century of data from Landsat imagery and digitisation-based overlay techniques. The findings confirm that accretion and erosion can coexist within the same estuarine system, a hallmark of the Ganga–Brahmaputra Delta's inherently dynamic sediment regime (Rudra, 2018). The Meghna Estuary records larger-magnitude morphological adjustments than the Hugli Estuary, a difference attributable to the greater river discharge and sediment load entering the former (Anwar & Rahman, 2021).

Under IPCC AR6 projections of 0.20–0.40 m of relative sea-level rise by mid-century, the compounding effects of rising waters, more intense cyclones, amplified storm surges, and ongoing land subsidence across the Bay of Bengal will further hasten shoreline retreat. The situation is particularly acute for Ghoramara, which faces potential disappearance within the coming decades absent urgent intervention. Sustained long-term monitoring and the development of integrated, estuary-wide management strategies such as managed retreat planning for Ghoramara, sustained long-term monitoring, shoreline protection zoning for Hatia, mangrove restoration, and integrated estuary-wide management are essential to reduce the growing geophysical and human vulnerability of these deltaic island communities under accelerating climate change pressures

Future Scope

Future research should address the methodological limitations of the study. High-resolution satellite imagery and SAR data should be used to analyse the shoreline changes to overcome the tidal-stage ambiguity. To enable positional accuracy assessment, UAV-based photogrammetric mapping should be incorporated.

Bathymetric survey of tidal zones will enable improved sediment-budget analysis, linking sediment storage and transport pathways of the estuarine system. Tidal-gauge records, along with GNSS-based subsidence measurements of the deltaic region, should be integrated to compute local relative sea-level rise rates to improve the realism of future-projection scenarios.

Application of the DSAS technique should be considered to produce EPR, LRR, and SCE statistics and strengthen the argument of shoreline area change. Land-use change analysis, socio-economic vulnerability assessment, livelihood surveys, including population exposure mapping and adaptation feasibility studies, should be undertaken for Ghoramara and Hatia in particular, to develop integrated coastal management planning by relevant national and local authorities in India and Bangladesh.

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