IUBAT Review—A Multidisciplinary Academic Journal, 8(1): 206-222
https://doi.org/10.3329/iubatr.v8i1.83666

Spatiotemporal Assessment of Erosion-Accretion Dynamics and Morphological Evolution of Sandwip Island, Bangladesh

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Keywords:

Coastal Erosion and Accretion; Morphological Change; Land Use and Land Cover (LULC). Sandwip Island; Shoreline Change;

Abstract

Sandwip, an offshore island, is highly dynamic due to its geographical location and is experiencing significant morphological changes. To evaluate the effects of shoreline changes brought on by accretion and erosion on communities, it is crucial to comprehend these changes. This study analyzes shoreline and land use dynamics of Sandwip Island from 1994 to 2024 using Landsat satellite imagery. For this purpose, Landsat images from 1994 to 2024 were analyzed in this study. Shoreline digitization and Normalized Difference Water Index (NDWI) analysis were conducted to accurately delineate the water-land interface and assess the rates of coastal erosion and accretion, and a supervised classification technique was used for Land Use and Land Cover (LULC) classification from 1994 to 2024. The findings revealed that accretion was the dominant process from 1994 to 2004, while erosion became dominant from 2004 to 2014 and continued through 2024. Over the past 30 years, erosion prevailed overall, with the southwestern side of the island particularly vulnerable to erosion and the northeastern side to accretion. The total land area of Sandwip steadily declined from 1994 to 2024 (approximately 33.266 sq. km). Land Use and Land Cover (LULC) analysis showed a significant conversion of barren land to water bodies between 1994 and 2024. The implications of this study are vital for coastal management, as it provides data to guide sustainable development.

1. Introduction

Coastal regions are extremely dynamic and ecologically important areas shaped by natural phenomena such as tsunamis, floods, cyclones, storm surges, wave action, and sea-level rise (Hansom, Switzer & Pile, 2015). Since the coastline is a moving border between land and ocean, these pressures cause erosion, sediment deposition, and other changes that make it extremely unpredictable throughout time (Inman & Brush, 1973). In addition to providing vital habitat for a variety of species, this area sustains commercial endeavors like fishing, tourism, and trading. Its breadth

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Article received: February 2025 Revised and accepted: June 2025 Published: June 2025

fluctuates according to environmental conditions and management plans meant to combat urbanization, habitat loss, and erosion (Weinstein & Reed, 2005). Sustainable management of these delicate areas is crucial for striking a balance between ecological preservation and growth as climate change and human activities increase (Biswas *et al.*, 2022).

This coastal area is often viewed as a zone of opportunity as well as vulnerabilities (Andres Payo, 2013; Brown, Naylor & Quinn, 2017). Despite having abundant natural resources and supporting important ecosystems, it is quite vulnerable to cyclones, storm surges, and coastal floods (Mullick, Tanim & Islam, 2019). Due to frequent coastal flooding, rising sea levels, and increasingly powerful tropical cyclones, the coastline of Bangladesh is known as a global hotspot for coastal hazards (Karim & Mimura, 2008; Minar, Hossain & Shamsuddin, 2013). These dangers increase the difficulties of sustainable development in the area by posing serious risks to infrastructure, livelihoods, and local populations (Khan *et al.*, 2000). Because of the interaction between erosion and accretion brought on by changes in river flow, sediment load, and wave action, the coastal zone of Bangladesh has a very dynamic and unstable morphology (Shibly & Takewaka, 2012). The shoreline is constantly changing as a result of these processes, as well as the vast system of sediment-filled rivers that start in the Himalayas (Ghosh & Mukhopadhyay, 2016; Owen, 2018). With sediment deposition and erosion propelling the construction and deterioration of islands around the bay, the coastal landscape is constantly changing (Emran, Rob & Kabir, 2018).

Bangladesh is situated within a prograding delta, where the Ganges-Brahmaputra-Meghna (GBM) river system contributes to the advancement of the delta into the Bay of Bengal by sediment deposition (Islam, 2016). Two separate physiographic units make up the deltaic coastline of Bangladesh: the geologically active Meghna deltaic plain and the comparatively dormant or abandoned Ganges tidal plain (Hassan, Syed & Mamnun, 2017). An older, more stable section of the shoreline is represented by the Ganges tidal plain, which originated during the Eocene Epoch (56–34 million years ago) (Steckler *et al.,* 2021). On the other hand, the Meghna deltaic plain, which stretches from the Tentulia channel in the west to the Chattogram coast in the east, is geologically young and extremely dynamic (Chowdhury, 2005). Due to the complex interactions between various natural processes, such as erosion, sediment deposition, and tidal dynamics, this region experiences constant variations in its planform (Ali, Mynett, & Azam, 2007). The Meghna deltaic plain is distinguished by its fluctuating islands and channels, which are formed by the estuarine system's accretion and erosion processes (Sarker *et al.*, 2021). The susceptibility of the region to environmental changes and natural disasters is highlighted by the wealth of documentation on these dynamic changes. Incoming tidal waves from the Bay of Bengal have a significant impact on the tidal characteristics along the Bangladeshi coastline and other regions (Haque & Nahar, 2023). These waves interact with the hydrodynamics and geomorphology of the delta. In some areas, this interaction leads to tidal amplification, which affects sediment transport and contributes to the formation of tidal channels (Murshed *et al.*, 2022).

In recent years, various researchers have used Remote Sensing (RS) and Geographic Information System (GIS) methodologies to study shoreline change (Akhter, Hoque & Xu, 2024; Kabir *et al.*, 2020; Sarwar & Woodroffe, 2013). Geographic Information Systems (GIS) and Remote Sensing (RS) are commonly used for extracting and evaluating coastal changes and dynamics due to their synoptic and repeated coverage, high resolution, multispectral capability, and cost-effectiveness when compared to other approaches (Nabila, Israd, & Akhter, 2017; Nones, 2021; Shibly & Takewaka, 2012). Researches by (Emran *et al.*, 2018), (Dutta *et al.*, 2022), (Ghosh, Osmani & Hossain, 2015), (Kabir *et al.*, 2023) have significantly enhanced knowledge of the shoreline dynamics, hydrology, and morphology of particular islands in the Meghna estuary. All these studies have used GIS and RS techniques for detecting shoreline transformation. These studies could evaluate shoreline dynamics, landform changes, and the effects of man-made and natural influences on the stability and morphology of the islands by combining satellite imagery with GIS-based spatial analyses.

There are several benefits to use remote sensing and GIS techniques, especially when researching dynamic coastal areas like the Meghna estuary. Because high-resolution satellite data and open-source GIS platforms are becoming more widely available, these techniques are becoming more affordable and accessible (Kumar *et al.*, 2018; Nones, 2021; Radočaj *et al.*, 2020). Researchers may track changes over long time periods and over wide geographic areas with the help of remote sensing data, which offers important temporal and spatial insights into tidal impacts, erosion-accretion patterns, and coastal dynamics (De Lisle & Drapeau, 1993).

This study focuses on assessing the morphological changes and shoreline dynamics of Sandwip Island over a 30-year period (1994–2024) using high-resolution satellite imagery. Landsat satellite images from 1994, 2004, 2014, and 2024 have been used to track spatial and temporal variations in land cover. Sequential preprocessing techniques, including geometric correction, radiometric correction, are applied to ensure accuracy. Geospatial analysis is conducted to quantify erosion and accretion rates, identifying areas most affected by land loss or gain, providing valuable insights for coastal management, disaster risk reduction, and sustainable development planning in Sandwip.

2. Materials and methods

2.1 Study area

Sandwip is an island off the south-east coast of Bangladesh. At 22.490513°N and 91.421185°E, Sandwip is in the Chattogram district. It is located on the Bay of Bengal in the Meghna River estuary, and the Sandwip channel divides it from the Chattogram coast (Ciavola *et al.*, 2015). Numerous coastal islands are located in the Meghna estuary, which is undergoing significant morphological changes as a result of accretion, erosion, and freshwater discharges with a heavy sediment load (Brammer, 2014).

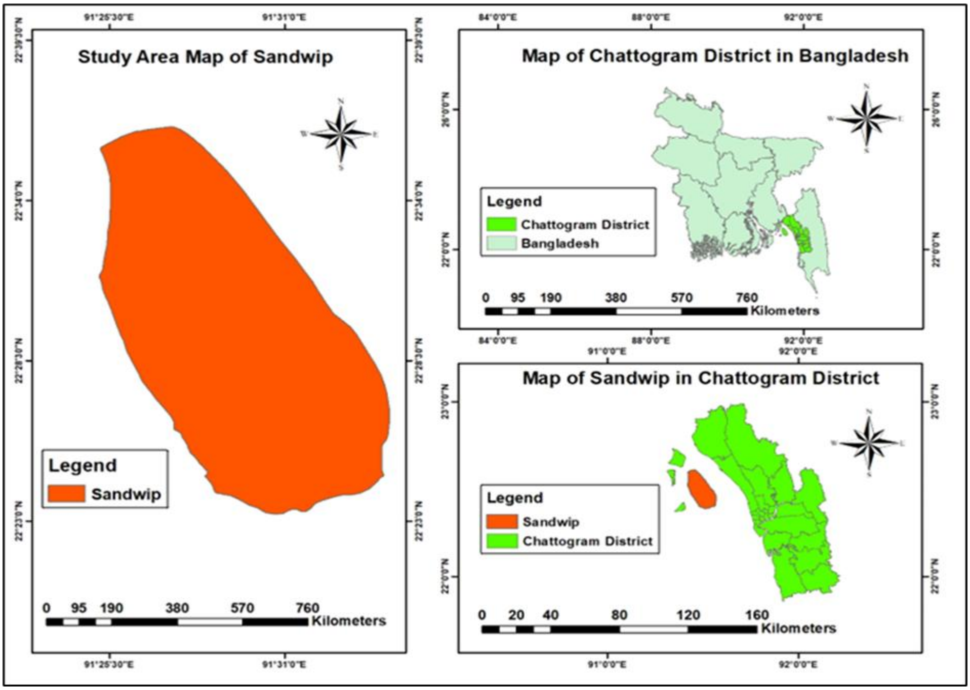

Figure 1: Study area map of Sandwip

Sandwip Island was chosen as the study area to examine the erosion/accretion pattern and temporal land boundary shifting in this research based on an examination of the geophysical, hazard, and demographic environment of Meghna estuarine islands. The island is geographically surrounded to the north by the Bamuni River, to the west by the Meghna River and Hatia Island, to the east by the Sandwip Channel, Sitakunda, and Mirsharai Upazila, and to the south by the Bay of Bengal (Emran *et al.*, 2018). The island is part of the young Meghna estuary floodplain, which receives an average of 2000–3600 mm of rainfall annually (Roy & Mahmood, 2016). Sediment distribution, salt intrusion, and water circulation are all impacted by the Meghna estuary's severe seasonality of freshwater intake close to the island (Ali *et al.*, 2007). Severe land erosion on this island is accelerated by the Ganges-Brahmaputra-Meghna (GBM) river system's high freshwater inflow into the estuary (Rahman *et al.*, 2018). Aside from the geophysical, meteorological, and threatening environment, the demography of the island differs significantly from that of the rest of the country. While the national population has steadily increased, the population of the island declined significantly between 1981 and 2011. Population declines are particularly noticeable in unions that are vulnerable to erosion (Roy & Mahmood, 2016).

2.2 Images used

To analyze coastal changes on Sandwip Island, satellite images from four distinct periods were used, classified at 10-year intervals. Landsat Thematic Mapper (TM) images with a 30m spatial resolution were acquired in February 1994, followed by Enhanced Thematic Mapper Plus (ETM+) images in February 2004, Operational Land Imager (OLI) images in February 2014, and finally, Operational Land Imager (OLI) images in February 2024. All images were Level-1 products obtained from the USGS Earth Explorer portal. Temporal comparisons were ideally conducted at the same tidal stage to enhance accuracy. However, due to limitations in data availability over such a long period and the fixed schedules of satellite overpasses, ensuring complete tidal consistency during image acquisition was not feasible. These factors introduced some level of uncertainty in shoreline change analysis. Image selection was informed by metadata analysis, which included cloud cover percentage, tidal cycle estimation, and acquisition time, in order to reduce tidal inconsistencies. To minimize tidal influence, dry-season images from December to February were prioritized, as tidal variations tended to be smaller during this period.

2.3 Image preprocessing

The images were pre-processed using established protocols for Landsat remote sensing data, which included radiometric corrections, atmospheric corrections, and image enhancement. Radiometric corrections involved converting Digital Numbers (DN) to Top of Atmosphere (TOA) reflectance using metadata files (MTL). To address atmospheric interference from clouds, dust, and smoke, the dark-object subtraction technique was applied as part of the radiometric correction process. This method is widely used in remote sensing to account for atmospheric scattering effects. It assumes that certain areas in an image, known as “dark objects,” have near-zero reflectance in specific spectral bands but appear brighter in satellite images due to atmospheric scattering. Radiometric corrections were further refined using sun azimuth and sun elevation data extracted from the image header files. All preprocessing steps were performed using ERDAS Imagine 2015 and ArcGIS 10.8, ensuring consistency in the spatial reference system (WGS 84/UTM Zone 46N).

2.4 Identification of coastline

Two distinct methodologies were employed to identify the coastline and analyze shoreline changes on Sandwip Island. The first method used the Normalized Difference Water Index (NDWI) to detect the land–water interface, ensuring accurate shoreline extraction by enhancing the spectral contrast between water bodies and land surfaces. The second method involved on-screen digitization, where shorelines were manually traced from satellite images acquired in 1994, 2004, 2014, and 2024 at 10-year intervals. Each selected water index was applied to the pre-processed datasets to enhance the distinction between land and water, minimizing errors in shoreline extraction. The combination of automated analysis and manual digitization provided a comprehensive and accurate assessment of erosion and accretion patterns, enabling a detailed evaluation of long-term coastal changes on Sandwip Island.

2.5 Change detection

Change detection focused on identifying and quantifying shifts in erosion and accretion patterns along the coastline of Sandwip Island over the 30-year period (1994–2024). By comparing the shorelines extracted from the satellite images at 10-year intervals, changes in the extent of erosion and accretion were tracked. The automated water index algorithm and manual digitization of the coastline were used to accurately map land-water boundaries, allowing for precise delineation of the shoreline in each image. The analysis then focused on detecting areas of shoreline erosion or accretion by comparing the position of the coastlines across the different time points.

2.6 Land use/ land cover preparation and accuracy assessment

A supervised classification technique using the Maximum Likelihood Classifier (MLC) was applied to categorize land cover into four major classes: Vegetation (including agricultural land and mangroves), Water Bodies (such as rivers, canals, and tidal flats), Built-up Areas (including settlements and infrastructure), and Others (barren land). The MLC method, which calculates the probability of a pixel belonging to a particular class based on the statistical distribution of training data, was applied to classify the entire study area. The accuracy of the classification results was quantitatively assessed by generating confusion matrices, calculating overall accuracy, user's and producer's accuracies, and the Kappa coefficient, which measures the agreement between the classified image and ground truth data beyond chance level.

3. RESULT

3.1 Erosion accretion pattern

To analyze the temporal areal changes due to erosion and accretion on the island, GIS-based vector differencing methods were used. Figure 2 depicts the spatial dynamics of erosion and accretion in Sandwip from 1994 to 2024, highlighting significant coastal changes over three decades. Erosion is most pronounced along the southern and southwestern coasts, indicating persistent land loss due to tidal forces, river dynamics, and coastal currents. Accretion is mainly observed in the northern and northeastern regions, where sediment deposition has contributed to land formation. Over time, erosion has remained dominant, with varying levels of accretion in different periods. The maps of (a) 1994–2004 show relatively balanced erosion and accretion, but in (b) 2004-2014 and (c) 2014–2024, erosion appears more extensive, particularly along the southern coast. The cumulative change (d) from 1994 to 2024 reveals that despite some land gain in the northern and north eastern side, net land loss has occurred due to the persistent dominance of erosion over accretion.

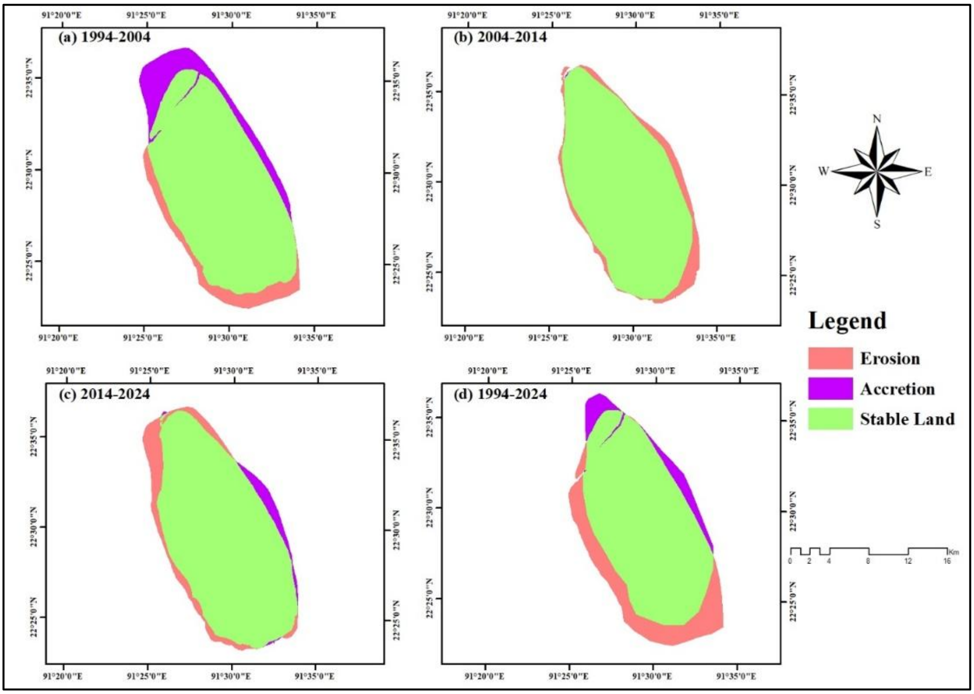

Figure 2: Erosion and accretion on Sandwip Island during the last 30 years (1994-2024)

Table 1 highlights a clear shift in coastal dynamics from 1994 to 2024, with a transition from net accretion to significant erosion over the 30-year period.

Table 1: Trends in erosion and accretion rates from 1994 to 2024

Year	Erosion (km^2)	Accretion (km^2)	Net Erosion/ Accretion (km^2)	Rate of net erosion/ accretion (km^2 y^{-1})	Dominant Process
1994-2004	24.407	34.027	9.62	0.962	Accretion
2004-2014	27.21	9.081	-18.129	-1.8129	Erosion
2014-2024	24.838	0.081	-24.757	-2.4757	Erosion

Year	Erosion (km^2)	Accretion (km^2)	Net Erosion/ Accretion (km^2)	Rate of net erosion/ accretion ($km^2\ y^{-1}$)	Dominant Process
1994-2024	49.818	16.552	-33.266	-3.3266	Erosion

The table shows that between 1994 and 2004, the region experienced a net accretion of 9.62 km², at a rate of 0.962 km² per year, suggesting stable coastal conditions with sediment deposition outpacing erosion. However, this trend reversed during the 2004-2014 period, when net erosion of 18.13 km² occurred, with a rate of -1.8129 km² per year. This shift was likely driven by reduced sediment deposition, changing sediment transport dynamics, and the impact of storm surges, tidal bores, and other natural forces. The erosion continued to intensify in the following decade (2014-2024), with a substantial net loss of 24.76 km² and a rate of -2.4757 km² per year. The increased erosion during this period can be attributed to factors such as heightened storm activity, reduced sediment supply, and possibly human interventions like river channelization or embankment construction. Over the full 1994-2024 period, the total net erosion amounted to 33.27 km², with an average rate of -3.3266 km² per year, indicating that, over time, erosion became the dominant process in the region.

Figure 3 indicates a significant shift from accretion to erosion in Sandwip over the past three decades.

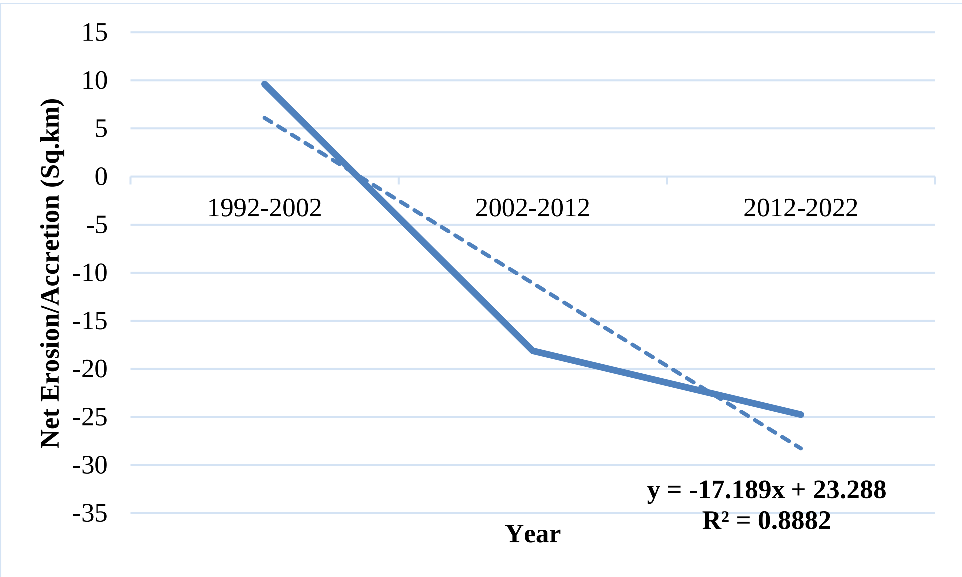

Figure 3: Trend of erosion and accretion in Sandwip

From 1992–2002, the region experienced net accretion, but this trend reversed sharply in the following decades, with increasing land loss due to erosion. The equation y=−17.189x+23.288 and a high R^2 value (0.8882) suggest a strong negative trend, meaning erosion has progressively intensified.

Figure 4 represents the land area changes in Sandwip, highlighting the effects of erosion and accretion between 1994 and 2024. The decline from 233.402 sq. km in 1994 to 200.136 sq. km in 2024 indicates significant land loss, likely due to coastal erosion caused by tidal action, river dynamics, and climate change impacts.

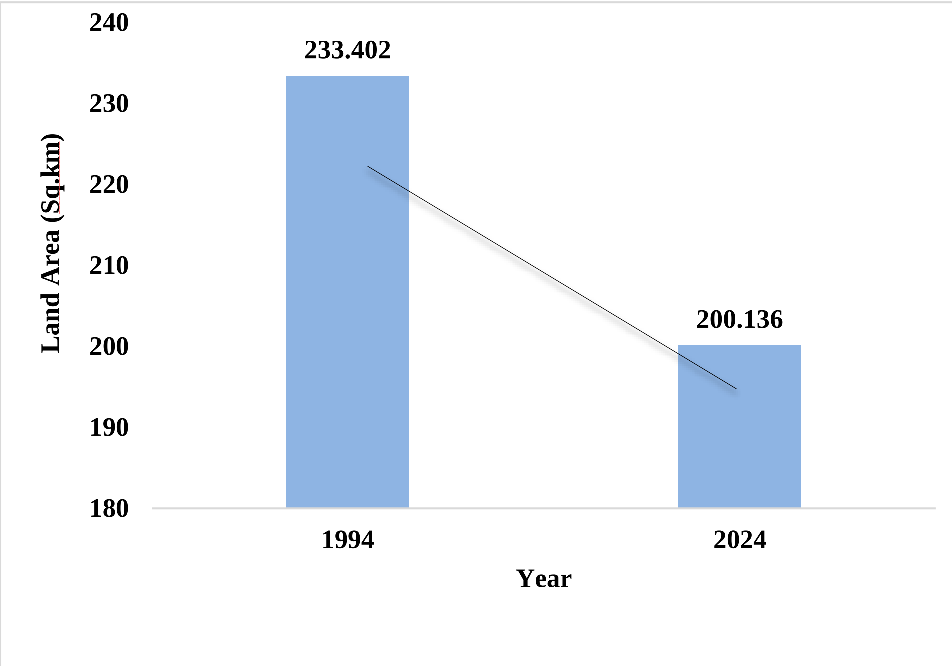

Figure 4: Change in total land area (sq km) from 1994 to 2024

While accretion have contributed to some land formation, the overall trend suggests that erosion has outpaced accretion, leading to a net reduction in land area of Sandwip over the 30-year period.

3.2 Morphological change

The morphological changes in Sandwip from 1994 to 2024 indicate significant coastal erosion, expansion of built-up area, and land-use shifts. The southern and southwestern coasts of the island experienced progressive erosion. Over the three decades significant portion of barren land has been converted to water bodies. In contrast, areas of accretion on the northern and northeastern side are relatively narrow and unstable. The accuracy of the supervised classifications for the years 1994 and 2024 was found to be 98%, with corresponding Kappa coefficients of 0.96 and 0.95, respectively. These high values indicate a very strong agreement between the classified images and the reference data, validating the effectiveness of the classification method and confirming the reliability of the result.

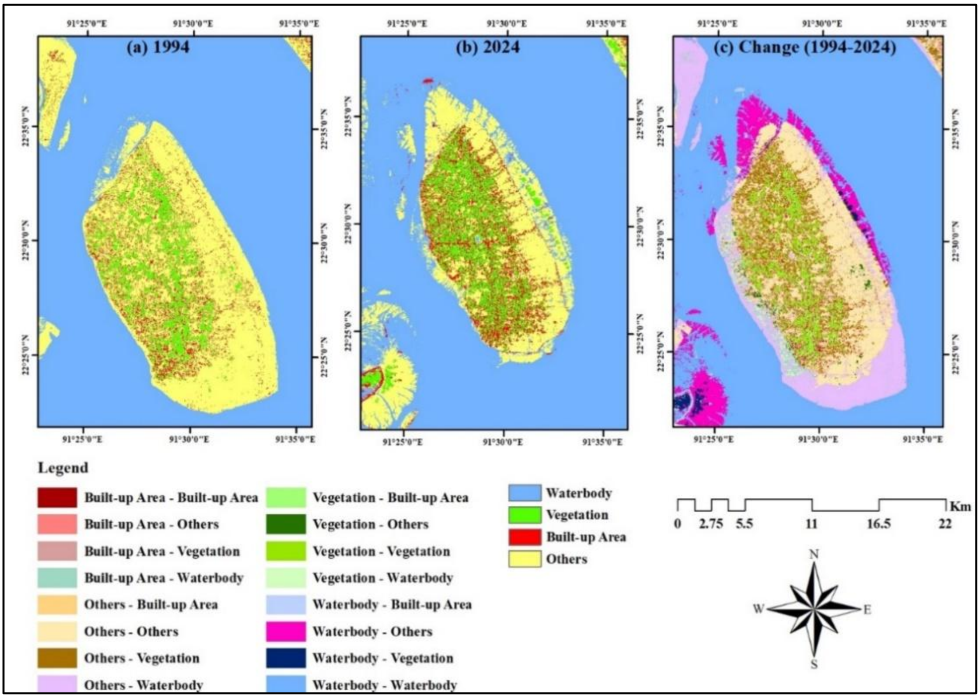

Figure 5: Morphological change in Sandwip from 1994 to 2024

Table 2 illustrates significant land use changes in Sandwip from 1994 to 2024, revealing a pronounced shift due to coastal erosion and accretion dynamics. The most striking change is the increase in water bodies from 537.19 sq. km in 1994 to 565.11 sq. km in 2024, which strongly indicates land submersion caused by tidal forces, river currents, and long-term erosion.

In contrast, built-up areas have increased from 3.09% (24.78 sq. km) to 5.02% (40.25 sq.km), reflecting growing settlements and infrastructure development, despite the overall shrinking landmass. There has been a significant change in barren land to vegetated areas from 1994 to 2024. The “Others” category, which includes barren lands, sandbanks, and mixed-use areas, has changed significantly, demonstrating landform instability due to both erosion and accretion processes. It has declined from 25.55% (205.07 sq.km) in 1994 to 17.11% (137.33 sq. km) in 2024.

These findings align with previous maps and bar charts, confirming that Sandwip is experiencing significant land loss due to persistent erosion, with accretion occurring but not at a rate sufficient to offset the disappearing land. As a result, rising water levels, shrinking vegetation, and shifting built-up areas underscore the ongoing environmental and socio-economic challenges in Sandwip.

Table 2: Contingency table of morphological change

		2024					
	Land Uses (Sq.km)	**Water (Sq.km)**	**Vegetation (Sq.km)**	**Built-up Area (Sq.km)**	**Others (Sq.km)**	**Total Area (Sq.km)**	**% of Total Area**
1994	**Water**	490.73	3.74	2.83	39.90	537.19	66.94
	Vegetation	3.99	19.93	7.42	4.13	35.47	4.42
	Built-up	5.04	6.79	5.08	7.89	24.78	3.09
	Others	65.36	29.37	24.93	85.41	205.07	25.55
	Total Area (Sq.km)	565.11	59.81	40.25	137.33	802.51	100
	% of Total Area	70.42	7.45	5.02	17.11	802.51	100

4. Discussion

The result of the study of coastline changes from 1994 to 2024 found a net land loss of around 33.266 square kilometers, with erosion dominating the southwestern part of Sandwip Island and accretion occurring primarily in the northeast. Between 1994 and 2004, accretion was the most common process, according to the temporal pattern; however, after 2004, erosion took over as the primary process, and this trend persisted until 2024. The impact of coastal erosion on land resources was highlighted by a Land Use and Land Cover (LULC) analysis that showed a discernible change, particularly the transformation of arid land into aquatic bodies. These results support the increasing susceptibility of the southwest region of Sandwip Island to coastal retreat, which would result in the loss of agricultural land and the displacement of communities.

Coastal areas exhibit unique and dynamic characteristics, constantly reshaped by natural forces such as tides, waves, and sediment transport (Prieto & Javier, 2022; Rizzo & Anfuso, 2020). Newly accreted landmass is often seen as a blessing for coastal inhabitants, providing opportunities for agriculture, settlement, and economic activities. In the case of Sandwip Island, accretion has contributed to its expansion, particularly in the eastern part, where continuous sediment deposition has added new landmass (Nabila *et al.*, 2017). Conversely, erosion in the southwestern region has become a severe challenge, displacing communities and leading to the loss of ancestral lands (Sarker *et al.*, 2015).

The process of land formation and degradation in this region is closely tied to historical sediment deposition patterns. After the 1950 Assam earthquake, large amounts of silt and clay were transported into the Meghna estuary, leading to rapid land accretion in the following years (Hassan *et al.*, 2017). This sudden influx of fine sediments contributed to the formation of new coastal areas, benefiting the region with additional land for habitation and cultivation (Gazi *et al.*, 2021; M. Sarker *et al.*, 2021). However, in the mid-1970s, a different phase of sediment dynamics began with the arrival of sand waves—large-scale, migrating sand deposits (Al Mahmud & Sultana, 2023). These sand waves influenced incremental accretion over the following decades, but also altered coastal hydrodynamics (Bruun, 2011).

Erosion in Sandwip Island has become more prominent after 2000, particularly in the southwestern region, due to several interconnected factors (Emran *et al.*, 2018). Increased tidal forces and changing hydrodynamics have intensified coastal retreat, gradually washing away land (Bruun, 2011). Additionally, a reduction in sediment supply from upstream rivers, influenced by dam construction and embankments, has disrupted the natural balance of accretion and erosion (Langat *et al.*, 2024). The impact of major cyclones and storm surges has further worsened the situation, as extreme weather events accelerate land loss. Climate change and rising sea levels have also played a crucial role, making low-lying areas more vulnerable to submersion. Furthermore, human interventions, such as unplanned coastal infrastructure and deforestation, have disturbed the sediment balance, leading to rapid erosion (Rahimova, 2024). While Sandwip once experienced significant land accretion, particularly in the eastern region, the post-2000 period has marked a shift towards severe erosion, causing substantial land loss and displacement of coastal communities.

Coastal erosion, coupled with rising sea levels and global warming, poses a significant threat to the coastal population of Bangladesh, with millions at risk of displacement in the 21st century (CDMP-II, 2014). However, adopting effective management strategies based on accurate information on erosion-accretion rates and coastal morphology can significantly reduce the risk of displacement. Recognizing these challenges, the Government of Bangladesh (GoB) introduced the National Coastal Zone Policy (CZP) in 2005 to ensure sustainable coastal management while preserving the natural environment (GoB, 2005). The policy acknowledges the threats of erosion and climate-induced vulnerabilities and emphasizes the need to protect coastal ecosystems and infrastructure. The coastal communities of Bangladesh have generations of experience in adapting to land erosion and accretion, developing local strategies to cope with environmental changes. Similarly, the government has long been engaged in managing coastal transformations through disaster preparedness, embankments, and land management policies. However, post-2000 trends indicate more severe erosion, particularly in areas like southwestern Sandwip, where land loss has intensified due to tidal forces, sediment depletion, and climate change impacts.

While completely preventing coastal erosion may be unrealistic, Bangladesh must not be left to face this challenge alone. Integrated coastal zone management, sustainable infrastructure development, and climate adaptation measures are essential to mitigate erosion, protect livelihoods, and enhance coastal resilience for the future.

5. Conclusion

Sandwip is a highly dynamic island located in the coastal region of Bangladesh, shaped and continuously reshaped by intense fluvial and tidal processes. As part of the Meghna Estuary, it is heavily influenced by the combined effects of riverine sediment deposition, tidal currents, wave action, and monsoonal flooding. The analysis of morphological changes of Sandwip Island from 1994 to 2024 has revealed important patterns in coastal dynamics, marked by a predominant trend of erosion along the southern and southwestern shores. This erosion is likely influenced by a combination of factors, including rising sea levels, tidal forces, river sediment load, and deforestation. Despite pockets of accretion in the northern and northeastern regions of the island, the overall outcome is a noticeable loss of land area, particularly in areas vulnerable to wave action and tidal erosion. The study underscores the dynamic and fragile nature of the coastal ecosystem of the island, with the southern and southwestern edges, particularly at risk. The considerable land loss highlights the urgent need for integrated coastal zone management strategies to address erosion and safeguard the livelihoods of communities that depend on these coastal resources. Adaptive approaches, such as the use of artificial reefs, embankments, or reforestation, could be explored to mitigate the adverse impacts of erosion, while policies on sustainable development and land use could minimize further degradation. Moreover, the findings emphasize the need for comprehensive monitoring programs to track and predict future morphological changes on the island. These could include the use of remote sensing technologies, GIS, and hydrodynamic models to improve the accuracy of predictions and guide policy responses. As the threat of climate change continues to escalate, prioritizing sustainable coastal management and adaptive measures will be essential for ensuring the long-term environmental stability and resilience of Sandwip Island.

Conflict of interest

The author declares no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and/or submission, and redundancy have been completely witnessed by the author.

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