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Shoreline Change and Vegetation Dynamics of Kuakata Sea Beach, Bangladesh (2008–2023): A DSAS and Remote Sensing-Based Assessment

Shabnom Momtaz

shabnom1095@gmail.com

University of Dhaka

Rony Hossain

University of Dhaka

Nusrat Jahan Shimu

University of Dhaka

Abu Hena Muhammad Yousuf

University of Dhaka

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Abstract

Kuakata Sea Beach, located along the dynamic coast of southern Bangladesh, has experienced substantial geomorphological and ecological changes over recent decades due to both natural processes and increasing human pressure. This study assesses shoreline change and vegetation dynamics along the Kuakata coast over a 15-year period (2008–2023) using multi-temporal Landsat imagery and GIS-based analysis. Shorelines were extracted from Landsat 5 TM and Landsat 8/9 OLI images and analyzed using the Digital Shoreline Analysis System (DSAS) to quantify erosion and accretion through End Point Rate (EPR) and Linear Regression Rate (LRR) statistics. Vegetation change was evaluated using the Normalized Difference Vegetation Index (NDVI). Results indicate pronounced spatial and temporal variability in shoreline behavior. The western segment of the coast experienced persistent erosion, while localized accretion dominated parts of the eastern and southeastern shoreline. Maximum shoreline advance reached approximately 37.5 m/year based on LRR analysis, whereas maximum retreat exceeded −32 m/year in erosion-prone zones. Area-based analysis shows that erosion has increasingly outweighed accretion since 2013, resulting in net land loss in recent years. NDVI analysis reveals a long-term decline in vegetation cover, closely associated with expanding built-up areas and coastal modification. DSAS-based forecasting suggests continued shoreline retreat over the coming decades, indicating heightened risk to coastal land, ecosystems, and human activities. The findings highlight the highly dynamic nature of the Kuakata coastline and emphasize the need for integrated, evidence-based coastal management strategies that balance development with ecosystem protection.

Keywords: Kuakata, shoreline change, coastal erosion, accretion, NDVI, DSAS.

Introduction

Shoreline change, which includes both erosion and accretion, is an important dynamic process along the land-water interface that is influenced by a variety of natural factors and human activities (Mohsen et al., 2023). The ever-changing nature of the coast also promotes the need for on-going monitoring and analytical techniques in coastal management and planning processes, particularly with respect to global climate change and sea-level rise (Das & Dhorde, 2022). Natural processes that induce such changes involve wave activity, tidal conditions, storm surge, sediment transport, and sea-level rise/fall. Relative sea-level rise, for example, can further intensify coastal erosion, but morphological processes along with the interaction of vertical land motion can buffer or reinforce such responses (Aschenneller et al., 2024; Deng & Wu, 2020). Sandy shorelines are imagined to recede with rising sea level through the Bruun effect, although such recurrence is far more complex involving sediment budgets and profile morphology (Deng & Wu, 2020). Events like glacial erosion, which shapes such glaciated landscapes and can affect sediment supply to coastal systems over much longer timescales, also leave their influence on coastal areas. Shoreline changes are aggravated by anthropogenic activities. This includes coastal development, land reclamation, coastal infrastructure structures, sand mining, and disruption of natural sediment fluxes (Gao et al., 2023; Karimi et al., 2021). For instance, in Shandong Peninsula, total shoreline

length dropped and artificial shoreline sharply increased in 2007- 2020 as shoreline naturally decreased by 25.41% as a result of land reclamation (Gao et al., 2023). Likewise, Ghanas eastern coast is undergoing rapid coastline changes brought about by human-induced and natural factors (Baah Asare-Bediako et al., 2023). Due to these interacting factors, some areas in the north Suez Canal Zone are affected from erosion (Mohsen et al. 2023). In many parts of the world, growing population density and associated economic activities have transformed coastal foreshores that are important for maintaining stability into densely populated urban areas where erosion rates have increased (e.g., Songkhla Province, Thailand (Nipaporn Chusrinuan et al., 2009). The advent of remote sensing and Geographic Information Systems (GIS) has made these techniques irreplaceable for monitoring and analysis of shoreline change on different spatial and temporal scales. Multiple spectral datasets from satellite remote sensors, such as Landsat terrestrial missions, have been extensively utilized for long-term observation that enables the extraction of shoreline positions and the computation of erosion/accretion rates (Paul et al., 2024). The Digital Shoreline Analysis System (DSAS) a GIS-based software is often used for statistical computations of shoreline change rate, including End Point Rate (EPR), Linear Regression Rate (LRR), Weighted Linear Regression (WLR) and Net Shoreline Movement (NSM) (Santos et al., 2024; Abd-Elhamid et al., 2023) For instance, one study that employed DSAS alongside Landsat images over the Digha Coast, India from 1992 to 2022, displayed a mean longterm shoreline change rate of -0.54 m/year (Paul et al., 2024). Changes in the shoreline of the Nile Delta coast were also analyzed and predicted using DSAS and GIS (Abd-Elhamid et al., 2023). UAV photogrammetry is emerging as a new shoreline assessment method that provides high-level resolution data for detailed mapping capabilities. CoastSat open-source software that utilizes publicly available satellite imagery for shoreline change analysis and future shoreline recession prediction (Sadewa & Supriyadi, 2024) In addition, citizen science programs such as CoastSnap help to monitor coastal change with public contributions in the form of coastal photographs uploaded for analysis (Harley & Kinsela, 2022).

Bangladesh's coastline is a highly dynamic setting characterized by complex and coupled erosion-accretion processes driven by the Ganges-Brahmaputra-Meghna (GBM) river system, sea-level rise, and human activities (Sarwar & Woodroffe, 2013; Shamsuzzoha & Ahamed, 2023). The sylhet delta that shelters a vast and fast-growing population, is acknowledged as one of the most susceptible regions in the world to climate change and sea-level rise (Shamsuzzoha & Ahamed, 2023) Rapid land gain and massive erosion are widespread processes, mainly governed by huge inputs of heavy sediment through the Meghna estuary leading to highly dynamic changes along the shorelines of Bangladesh (Chowdhury & Sikder, 2023). However, in some parts of the coast the long-term balance between erosion and accretion is heavily skewed by abundant supply of sediment, producing accretion, whereas other segments erode severely. For example, significant positional changes were observed in response to both processes by an analysis of fifteen multi-temporal Landsat images with a thirty-year span (1989-2019) covering the entire coast of Bangladesh (Hasan & Matin, 2019). Climate change and sea-level rise impact coastal zones of Bangladesh deeply. As a result, the planetary climate is heating up, causing a fast 4.0 mm/year global sea level rise in the 21st century (Shariot-Ullah, 2024). Bangladesh, being located in the Ganges-Brahmaputra Delta, is a low lying country that experiences a 26.0 cm mean-sea level of shift through an average of 11.6 mm/year in the last 2.5 decades (Shariot-Ullah, 2024). Attributing the increase to mega geosynclinals, natural disasters, and subsidence of the ground, the relative sea-level rise in surface 4.0 to 7.8 mm/year, leads to the shoreline to hurry (Shariot-Ullah, 2024). Coastal people are particularly vulnerable as climate change causes shorelines to move further

inland faster. Remote sensing (RS) and Geographic Information System (GIS) technologies are being increasingly utilised in Bangladesh for coastal management practices for monitoring and analysing the shoreline changes (Bushra et al., 2021; Uddin et al., 2022). Such techniques enable digitization of shorelines obtained from multi-temporal satellite images and the computation of erosion and accretion rates with assistance of tools like Digital Shoreline Analysis System (DSAS) (Bushra et al., 2021; Fernández & Bértola, 2023). As an example, from 1978 to 2018 archived multi-temporal Landsat data were utilized to monitor shoreline changes in the Mahi River estuary (Patel et al., 2021) and along the Indian coast for similar assessments (Kankara et al., 2015).

The aim of this study is targeted towards the key dimensions of coastal dynamics in the Kuakata area. In particular, the objectives of the study are to assess spatio-temporal dynamics of vegetation cover through the Normalized Difference Vegetation Index (NDVI), measure coastal erosion-accretion rates along the Kuakata coast, and quantify the temporal changes of shoreline position assessing the followed retreats and advances. Additionally, using the Digital Shoreline Analysis System (DSAS), the study seeks to forecast possible future shoreline movement, to further enhance understanding of the area coastal environment changes over time.

Study Area

Kuakata Sea Beach is in Kalapara Upazila, Patuakhali District, Barishal Division, Bangladesh (approx. 21.8182° N, 90.1398° E). It lies along the western Meghna estuary, where sediments from the Padma, Meghna, and Brahmaputra shape the coastline (Uddin et al., 2022).

The site has a long, gently sloping sandy shore with mangrove patches. A nearby mud ridge helps protect the area from tidal surges (Rahman et al., 2013). Sand particles average 0.177–0.207 mm, influencing local erosion and sedimentation (Rahman et al., 2013).

Soil properties such as bulk density, porosity, moisture, pH, and electrical conductivity support both agriculture and coastal management (Ferdouse Zaman Tanu, 2017).

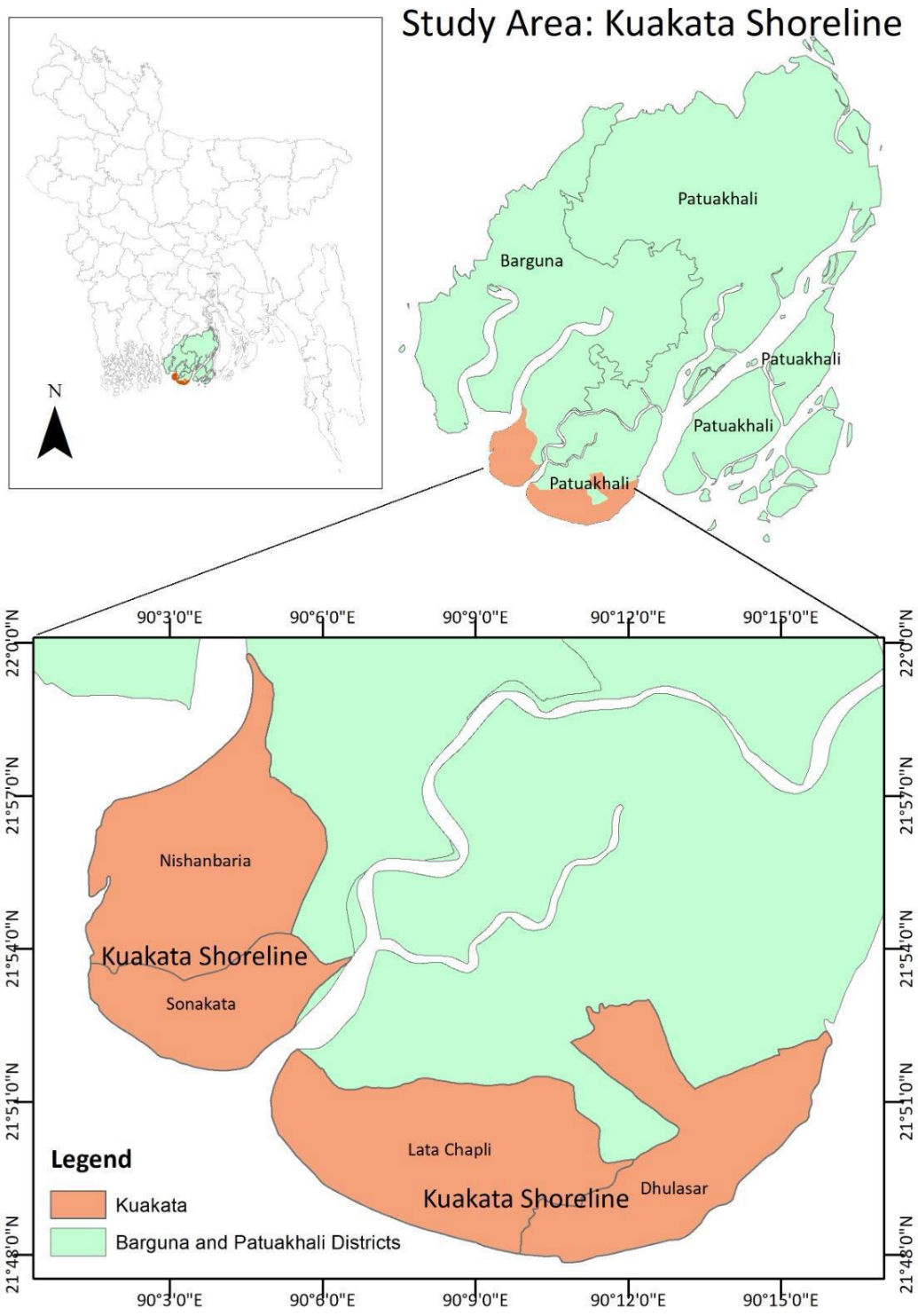


Fig: Study Area Kuakata

Materials and methods

3.1 Data Sources and Image Selection

This study employs multi-temporal satellite imagery to examine shoreline and vegetation changes along Kuakata Sea Beach from 2008 to 2023. Landsat 5 Thematic Mapper (TM) imagery for 2008 and Landsat 8/9 Operational Land Imager (OLI) imagery for 2013, 2018, and 2023 were obtained from the USGS EarthExplorer archive. All images have a spatial resolution of 30 m and were selected from the dry season to reduce cloud cover and seasonal effects. The datasets were supplied in GeoTIFF format and projected to a common coordinate system to ensure spatial consistency across all analyses.

3.2 Image Preprocessing

Basic preprocessing steps were applied to all images prior to analysis. These included layer stacking, radiometric consistency checks, and clipping to the study area boundary. Images affected by excessive cloud cover or haze were excluded. The use of consistent spatial resolution and acquisition season ensured comparability between different years and sensors.

3.3 Methodology

Shoreline Extraction

Shorelines were extracted through manual digitization using the visible land–water boundary as the shoreline proxy. This method was chosen to maintain consistency across sensors and to reduce classification errors associated with automated techniques in turbid coastal waters. Each shoreline was visually inspected and refined to minimize inaccuracies caused by tidal conditions, sediment plumes, and mixed pixels. A baseline was generated landward of all shoreline positions to support subsequent shoreline change analysis.

Vegetation Analysis Using NDVI

Vegetation dynamics were assessed using the Normalized Difference Vegetation Index (NDVI), calculated as:

$$NDVI = (NIR - RED) / (NIR + RED)$$

where NIR and RED represent the near-infrared and red spectral bands (Landsat 5: Band 4 and Band 3; Landsat 8/9: Band 5 and Band 4). NDVI values were classified into three categories: water bodies (−1 to 0), built-up or barren land (0 to 0.15), and vegetation (>0.15). Water bodies were excluded from further land-based analysis to focus on terrestrial vegetation change.

Erosion and Accretion Area Estimation

Erosion and accretion were quantified by overlaying shoreline polygons from consecutive years within a GIS environment. For each time interval (2008–2013, 2013–2018, and 2018–2023), erosion was identified where the newer shoreline retreated landward relative to the earlier shoreline, while accretion was identified where shoreline advance occurred seaward. Area changes were calculated in square kilometers using consistent spatial units across all periods.

Shoreline Change Rate Analysis Using DSAS

Shoreline change rates were computed using the Digital Shoreline Analysis System (DSAS v5.0) extension in ArcGIS 10.8. Transects were generated perpendicular to the baseline at regular intervals along the coastline. Two statistical indicators were applied: End Point Rate (EPR), which calculates shoreline change based on the distance between the oldest and most recent shoreline positions divided by the time interval, and Linear Regression Rate (LRR), which estimates long-term shoreline trends using all available shoreline positions. These metrics quantify both the magnitude and direction of shoreline movement.

Shoreline Forecasting

Future shoreline positions were projected using the DSAS Kalman filter approach, which integrates observed shoreline positions with modeled trends derived from LRR values. Forecasts were generated to assess potential shoreline movement over future decades. These projections provide an indication of likely trends but are interpreted cautiously due to uncertainties related to image resolution, shoreline proxy selection, and natural coastal variability.

Result and Discussion

4.1Vegetation Dynamics Based on NDVI

The NDVI analysis reveals marked temporal variation in vegetation cover along Kuakata Sea Beach between 2008 and 2023 (Figure 4.1). In 2008, vegetation cover was relatively extensive, indicating a comparatively stable coastal environment with limited built-up expansion. A notable decline in NDVI values was observed between 2008 and 2013, coinciding with increased construction activity and land conversion in the coastal zone. This period reflects growing anthropogenic pressure driven by tourism infrastructure and settlement expansion.Vegetation cover showed partial recovery in 2018, which may be attributed to reduced disturbance in certain areas, natural regeneration, or localized plantation initiatives. However, by 2023, NDVI values declined sharply again, indicating significant vegetation loss and expansion of built-up or barren land. This long-term downward trend suggests a gradual weakening of the natural buffer capacity of the coast, increasing vulnerability to erosion and storm impacts. Similar NDVI-based vegetation decline has been reported for other parts of the Bangladesh coast, highlighting a broader pattern of development-driven coastal transformation.

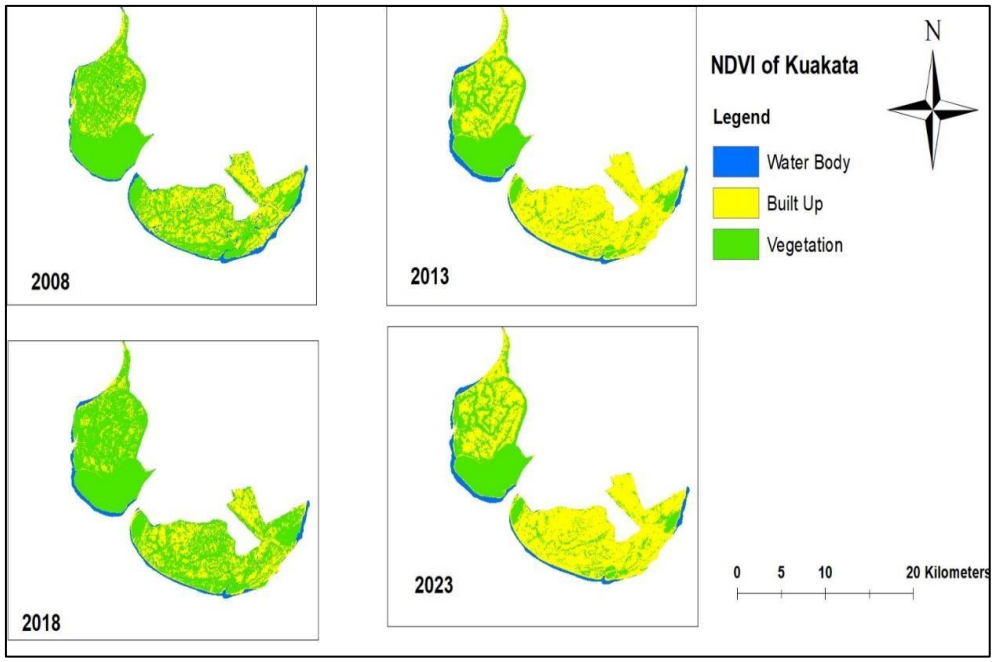


Figure 4.1 NDVI rate of Kuakata from 2008-2023

4.2 Spatial and Temporal Patterns of Erosion

Erosion analysis indicates that Kuakata has experienced substantial and spatially heterogeneous land loss over the study period (Figure 4.2a–c). Between 2008 and 2013, erosion was primarily concentrated along the western and northwestern sections of the coastline, while other segments remained relatively stable (Figure 4.2a). This pattern suggests differential exposure to wave energy and sediment transport processes.

The most severe erosion occurred during the 2013–2018 period (Figure 4.2b), when large portions of the southern and western shoreline retreated significantly. This phase corresponds with increased cyclonic activity and storm surges affecting the region, including Cyclone Mora in 2017. Such extreme events are known to accelerate shoreline retreat by redistributing sediments and destabilizing unconsolidated coastal materials.

From 2018 to 2023, erosion persisted but showed localized stabilization in parts of the southeastern shoreline (Figure 4.2c). Despite this partial stabilization, the overall erosion trend remained dominant, particularly along the western coast, indicating long-term geomorphological instability rather than short-term fluctuation.

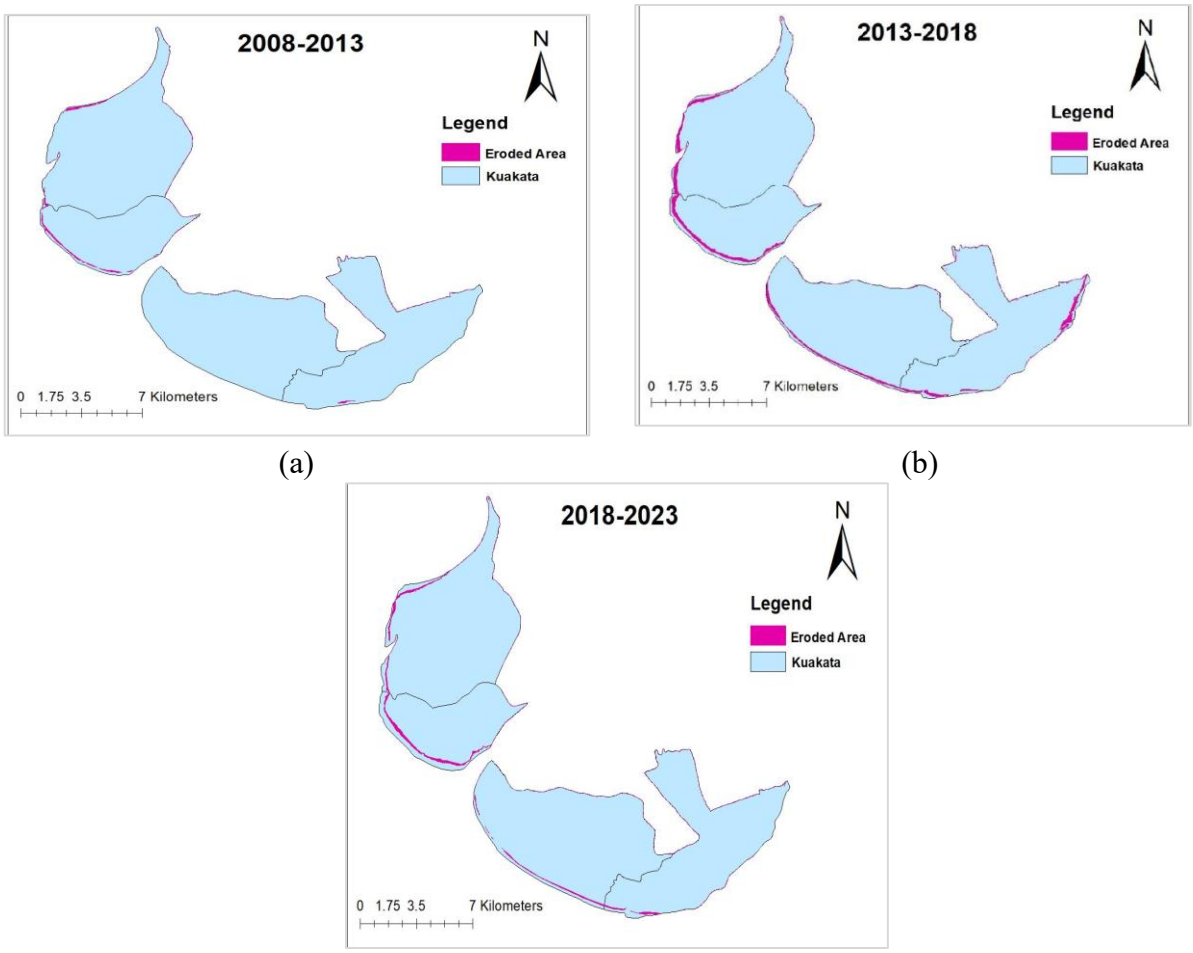


Figure 4.2 (a) Erosion of Kuakata from 2008-2013; 4.2 (b) Erosion of Kuakata from 2013-2018; 4.2 (c) Erosion of Kuakata from 2018-2023

4.3 Accretion Patterns Along the Kuakata Coast

Accretion was also observed along the Kuakata coastline, though its spatial extent and magnitude varied considerably over time (Figure 4.3a–c). During the 2008–2013 period, significant accretion occurred mainly in the southern and southeastern segments of the coast (Figure 4.3a). This land gain is likely associated with high sediment supply from the Ganges–Brahmaputra–Meghna river system, particularly during the monsoon season.

Accretion rates declined sharply between 2013 and 2018 (Figure 4.3b), with only minor sediment deposition observed in limited areas. This reduction coincided with intensified erosional processes, suggesting a temporary imbalance between sediment supply and wave-driven sediment removal.

Between 2018 and 2023, accretion showed a slight increase but remained insufficient to offset concurrent erosion (Figure 4.3c).

These findings demonstrate that while accretion remains an active process at Kuakata, it is spatially restricted and episodic, and does not consistently compensate for land loss caused by erosion.

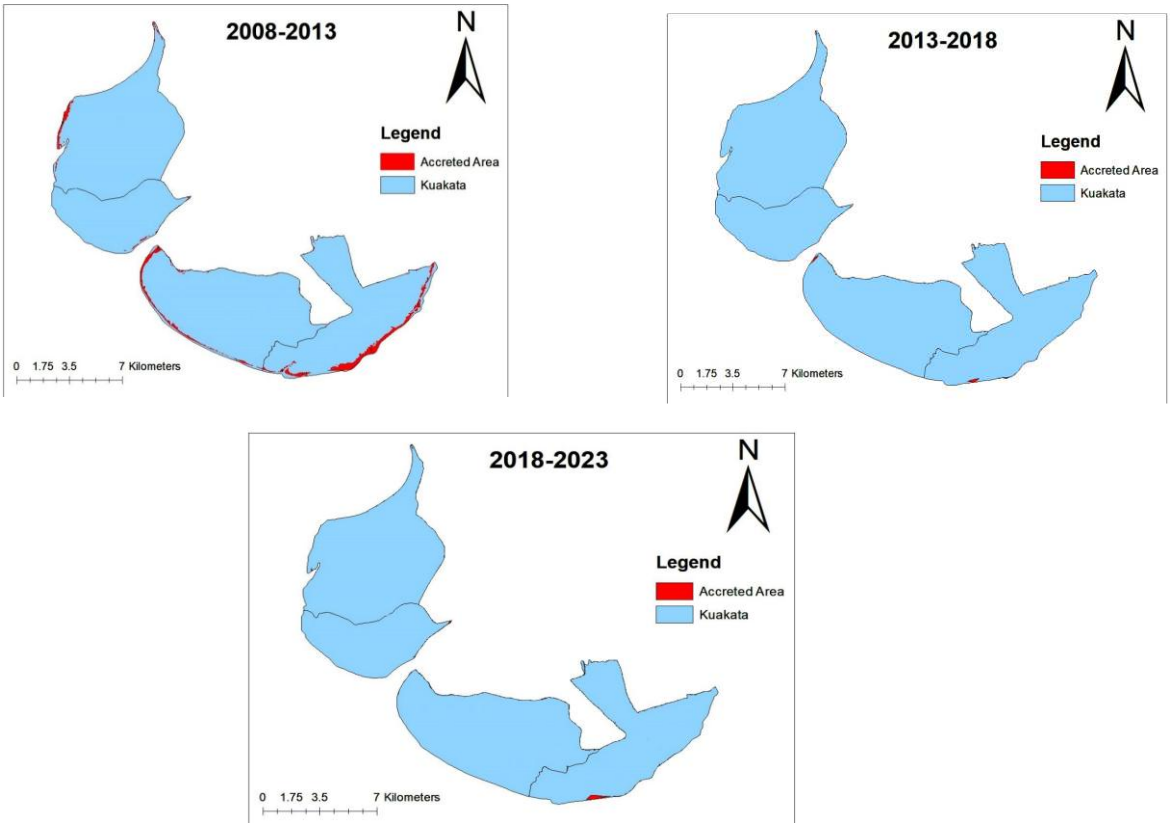


Figure 4.2 (a) Accretion of Kuakata from 2008-2013; 4.2 (b) Accretion of Kuakata from 2013-2018; 4.2 (c) Accretion of Kuakata from 2018-2023

4.4 Erosion–Accretion Balance and Net Shoreline Change

The combined analysis of erosion and accretion highlights the highly dynamic nature of the Kuakata coastal system (Figure 4.4a–b). Between 2008 and 2013, accretion exceeded erosion, resulting in a net land gain. However, this balance reversed during the 2013–2018 period, when accelerated erosion produced a net land loss. A slight stabilization was observed from 2018 to 2023, though erosion continued to marginally exceed accretion.

Spatially, erosion was consistently dominant along the western coastline, whereas accretion was more pronounced in the southern and southeastern areas. This contrast reflects the combined influence of wave approach direction, longshore sediment transport, and localized sediment deposition. The shifting balance between erosion and accretion underscores the sensitivity of the Kuakata shoreline to both climatic forcing and human modification.

Erosion–Accretion Balance and Net Shoreline Change

The combined analysis of erosion and accretion highlights the highly dynamic nature of the Kuakata coastal system (Figure 4.4a–b). Between 2008 and 2013, accretion exceeded erosion, resulting in a net land gain. However, this balance reversed during the 2013–2018 period, when accelerated erosion produced a net land loss. A slight stabilization was observed from 2018 to 2023, though erosion continued to marginally exceed accretion.

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4.5 Shoreline Change Rates Derived from DSAS

DSAS-based analysis further quantified shoreline dynamics using Linear Regression Rate (LRR) and End Point Rate (EPR) statistics. LRR results indicate strong spatial variability in shoreline behavior, with maximum shoreline advance reaching approximately 37.5 m/year in accretion-dominated zones. In contrast, erosion-prone areas exhibited retreat rates exceeding −25 m/year, particularly along the western coastline.

EPR analysis confirmed these trends, showing high rates of both erosion and accretion over shorter time intervals. Although some transects displayed rapid shoreline advance, erosion rates were more spatially extensive, suggesting that long-term coastal retreat remains the dominant process. The agreement between LRR and EPR results strengthens confidence in the observed shoreline change patterns.

4.7 Implications for Coastal Management

The observed shoreline and vegetation changes have important implications for coastal management and local livelihoods. Continued erosion threatens tourism infrastructure, settlements, and agricultural land, while vegetation loss reduces natural protection against storm surges. Although accretion creates temporary land gains, the instability of these areas limits their long-term usability.

The results highlight the need for integrated coastal zone management approaches that combine structural measures with ecosystem-based solutions, such as vegetation restoration and controlled development. Evidence-based planning informed by long-term monitoring, as demonstrated in this study, is essential to enhance resilience and ensure sustainable use of the Kuakata coastal zone.

Conclusion

This study provides a comprehensive assessment of shoreline change and vegetation dynamics along Kuakata Sea Beach, Bangladesh, over the period 2008–2023 using multi-temporal Landsat imagery and DSAS-based analysis. The results demonstrate that the Kuakata coastline is highly dynamic, with pronounced spatial and temporal variability driven by both natural coastal processes and increasing anthropogenic pressure. Persistent erosion, particularly along the western shoreline,

has increasingly outweighed localized accretion in recent years, leading to measurable net land loss.

NDVI analysis indicates a long-term decline in vegetation cover, closely associated with coastal development and land-use change. The reduction of vegetated areas weakens the natural resilience of the coast and increases susceptibility to erosion and storm impacts. DSAS-derived shoreline change rates and forecasting results further suggest that erosional trends are likely to continue in the coming decades, posing growing risks to coastal land, ecosystems, tourism infrastructure, and local livelihoods.

Although the study is constrained by the spatial resolution of Landsat imagery and uncertainties related to shoreline proxy selection and tidal variation, the consistent application of remote sensing, GIS, and statistical shoreline analysis provides a robust framework for long-term coastal monitoring. The findings highlight the urgent need for integrated coastal zone management strategies that balance development with ecosystem protection, including controlled infrastructure expansion and restoration of coastal vegetation. Such evidence-based interventions are essential to enhance resilience and support sustainable management of the Kuakata coastal zone.

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