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# Shoreline change analysis and sustainable coastal management for Kutubdia island: trends, vegetation impact, and future projections

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## Abstract

This paper explores the shoreline evolution of Kutubdia Island, situated in the southeast Bay of Bengal, over 36 years (1988-2024). This is mainly to determine long-term changes in the shoreline by using geospatial analysis, which is done by using Digital Shoreline Analysis System (DSAS) and Weighted Linear Regression (WLR) to establish a trend in the change of erosion and accretion. The paper also examines how shoreline movement correlates with vegetation health in order to determine how it helps stabilize the coastline in terms of the Normalized Difference Vegetation Index (NDVI). Findings show that a considerable amount of erosion occurred on the coastline, as 88.57 percent of the transects had evidence of shoreline erosion, resulting in a total loss of land of more than 4,990 meters. Regions that had reduced cover of vegetation were identified as prone to erosion, and this justifies the significance of restoring the vegetation in preventing further erosion. To add to this, the research makes projections on the shoreline location in 2034 and 2044, which demonstrate that there is still a loss of land, especially on the lower side of the island. On the basis of such findings, a sustainable coastal management plan has been advanced, which has an emphasis on ecological reinstatement, including the plantation of mangroves and community-customized strategies. The article identifies a pressing need to implement special measures to safeguard vulnerable areas and guarantee a sustainable future of sustaining the ecological resiliency in the coastal environments, serving as a reference to other exposed coastal geographies susceptible to environmental attrition.

**Keywords**: Shoreline change, geospatial analysis, vegetation impact, sustainable coastal management

## Introduction

The environment of the coastal area is changing to an unprecedented extent as a result of climate change, sea level rise, besides human-triggered activities (He and Silliman 2019). The groups most vulnerable include low-lying islands that experience constant deterioration of the shoreline, inundation, and degradation of habitat (Raimundo Lopes *et al.* 2022). There is a fact that Bangladesh is situated on the largest delta plain in the world, and it is very vulnerable to these changes (Hossain *et al.* 2020). Its coastal areas, which have dynamic geomorphology and high population density, are most prone to erosion, storm surge associated with cyclones, and tidal inundation (Murshed *et al.* 2022)integrating environmental hazards (EH. The landscape can also change a lot because of rapid urbanization and economic growth, which makes the environment and people more at risk (Hossain *et al.* 2025). The case of the island of Kutubdia, an elongated, narrow piece of land in the south-east Bay of Bengal, is one of the most representative examples of such vulnerability, as the land loss seems to be steady over the last several decades (Saddam *et al.* 2025).

The island is more extensive in terms of size, although it has continuously been affected by natural forces, causing the displacement of people and the reduction of areas with habitable and farmlands. Most of the major activities on the island are being threatened; fishing, salt farming, and subsistence agriculture are the major activities on the island (Rahman and Schmidlin 2019). The assessment of changes in the shoreline is an essential study because it is needed to determine the dynamics of the coast and the decision-making aspect of land use (Dewi and Bijker 2020). Of these, shoreline erosion in particular poses a threat to not just the landmass but also social stability, economic viability, and ecological balance. One special characteristic of this research is that it is integrative. Besides establishing the tendencies of the

coastal passing, it also examines the implications of this variation regarding the ecology. Plants not only serve as an expression of the vulnerability of coasts but also serve as a buffer to shoreline erosion and help cushion storm surges; in contrast to healthy vegetative cover, particularly mangroves that act as a dampener, degraded vegetative cover serves as a signal to ecological distress (Asari *et al.* 2021).

In view of these forecasts, the study puts forward an area-wise and sustainable plan of development. This study aims to bridge that gap by following a geospatial orientation to study erosion along the coastline in a 36-year span, between the years 1988 and 2024, by using Landsat satellite time series and the Digital Shoreline Analysis System (DSAS). The paper is organized into three objectives: (1) to assess long-term shoreline changes on Kutubdia Island (1988-2024) using DSAS and WLR for identifying erosion and accretion areas, (2) to analyze the relationship between shoreline movement and vegetation health (NDVI) and its impact on erosion and stability, (3) to predict future shoreline positions of Kutubdia Island for 2034 and 2044. Lastly, it recommends a sustainable coastal management plan focused on ecological restoration and community adaptation. This is done with a larger goal of being able to gain scientifically based, spatially explicit insights into Zone-wise coastal processes in Kutubdia Island, which is the type of information that can become essential to policymakers, planners, and local stakeholders.

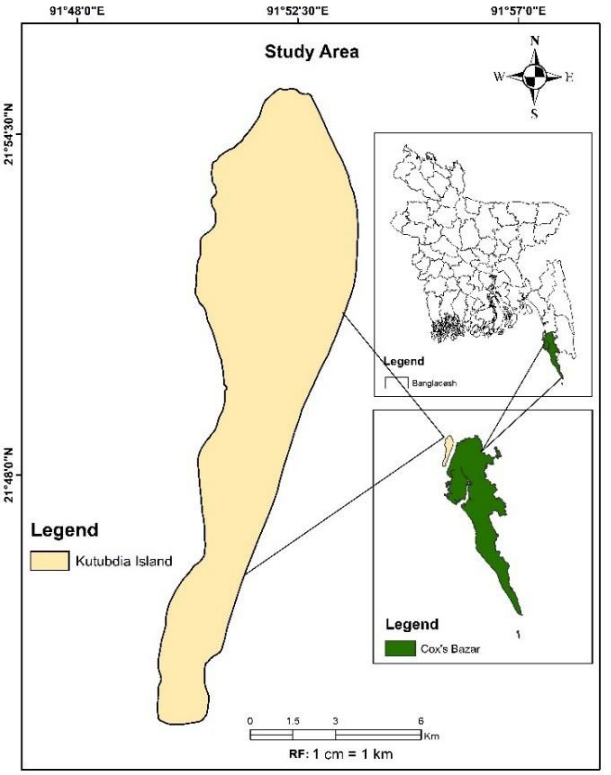



**Figure 1:** Location map of Kutubdia Island in the southeastern coastal region of Bangladesh. The figure shows the geographic position of Kutubdia Island's location within the national and regional context. (Source: Authors, 2025)

## Materials and methods

**Study area:** Kutubdia is an island of Bangladesh's southeast coastal region in the Bay of Bengal, adjacent to Cox's Bazar district (Figure 1). It lies between 21°44′30″ N to 21°55′30″ N latitude and 91°50′0″E to 91°53′ 30″ E longitude (Islam *et al.* 2023).

Kutubdia Island is vulnerable due to its dynamic and active coastline. Portions of the island have been washed away over the years, and there are fears that they will be uninhabited due to their inaccessibility, rendering them not even economically viable (Islam *et al.* 2016) 1976, 1980, 1989, 1999, 2004, 2009, 2011 and 2014 covering a long term of 42 years period. Rates of shoreline changes were estimated by four statistical methods namely, end point rate (EPR. The island now has a large population that practices mostly agriculture, salt farming, and fishing, although cyclones are one of the most significant natural threats faced due to the thinning of the land by tidal surges and rising sea levels.

The study is multi-temporal, geospatial in character, in the way it can be applied to finding out changes of the shoreline, ecological test, and even something on the lines of predicting what the situation would be as far as the shoreline is concerned in the future in Kutubdia Island by way of remote sensing technology and geospatial investigation techniques. The offered methodology can be displayed in five major stages (Figure 2).

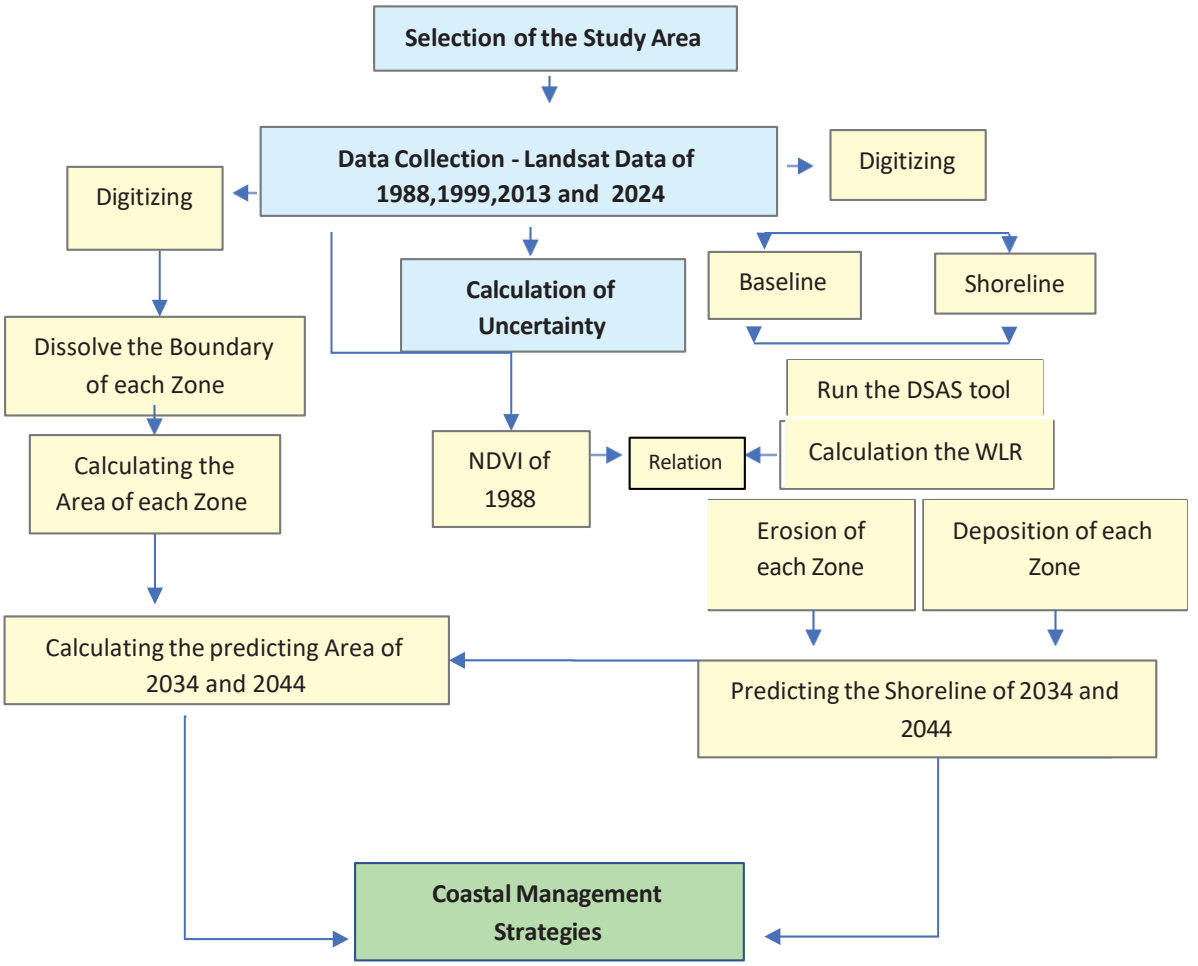



**Figure 2:** Methodological framework for shoreline change analysis and coastal planning on Kutubdia Island. The figure presents a stepwise geospatial workflow incorporating Landsat data (1988–2024), shoreline digitization, NDVI analysis, and WLR-based erosion assessment to predict shoreline positions for 2034 and 2044. The process culminates in the development of coastal management strategies for Kutubdia Island. (Source: Authors, 2025)

Satellite data acquisition: Satellite images belonging to Landsat had been taken in four years, including the years 1988, 1999, 2013, and 2024. The pictures used were taken with clear skies, with little cloud cover, and tides, so that the pictures give accurate information about the shorelines (Table 1). They have been acquired under conditions of tidal range and season (November-December) that are very similar, and will minimize seasonal bias in the location of the shoreline (Wicaksono et al., 2018).

**Image pre-processing, shoreline digitization, and accuracy assessment:** ArcGIS was used to pre-process images to rectify, improve, and orthorectify the images and geo-reference them to UTM Zone 46N/WGS84. Visual interpretation was conducted by manually digitizing the high-water lines and assisted with band composites and NDWI. Cleaning, topologically correcting, and merging shorelines were performed through the Dissolve tool. Accuracy was carried out in accordance with the USGS and DSAS recommendations, and digitizing error (Ed) has been determined as 15 and 30 m caused by operator variation and mapping resolution (Den Boer *et al.* 2018). The value of geo-referencing error (Er) was assigned 0 m, and seasonal variation was not taken into account (Table 2). The tide table was used to determine the average tidal height, which was used to calculate the shoreline positional error, or Esp, in total (Xia *et al.* 2021).

**Table 1. Details of the Landsat satellite imagery used in the shoreline change. The table summarizes the satellite scenes used for shoreline extraction and NDVI analysis of Kutubdia Island, ensuring consistent spatial resolution (30 m) and low cloud cover across all datasets.**

| Year | Landsat | Sensor | Acquisition Date | Path/Row | Cloud Cover | Resolution |
|---|---|---|---|---|---|---|
| 1988 | Landsat 5 | TM | 10.11.1988 | 136/45 | 3.28% | 30m x 30m |
| 1999 | Landsat 7 | ETM+ | 19.12.1999 | 136/45 | 6.23% | 30m x 30m |
| 2013 | Landsat 8 | OLI | 01.12.2013 | 136/45 | 2.75% | 30m x 30m |
| 2024 | Landsat 9 | OLI-2 | 27.11.2024 | 136/45 | 5.12% | 30m x 30m |

**Table 2. Estimation of shoreline positional error from Landsat satellite data (1988–2024). The table outlines the positional uncertainty associated with shoreline extraction for each Landsat scene used in the study. Errors include digitizing error, tidal variation, and spatial resolution effects, with a total shoreline positional error**

| Scene ID | Acquired date/time | Satellite | Seasonal error | Spatial resolution | Pixel Error | Mean tide Level (m) (Etd) | Tide Condition | Rectification Error (Er) | Digitization Error | Uncertainty |
|---|---|---|---|---|---|---|---|---|---|---|
| | 11/1/1988 | landsat 5 | 0 | 30 | 0 | 6.998 | Slack/ Rising/NA | 0 | 15 | 30.8053892 |
| | 12/19/1999 | landsat 7 | 0 | 30 | 0 | 7.143 | Slack/ Rising/NA | 0 | 15 | 30.83865187 |
| | 12/01/2013 | landsat 8 | 0 | 30 | 0 | 7.043 | | | 15 | 30.81564293 |
| | 12/01/2014 | landsat 9 | 0 | 30 | 0 | 7.069 | | | 15 | 30.82159569 |

| Positional Error (m) | 1988 | 1999 | 2013 | 2024 | Remarks |
|---|---|---|---|---|---|
| Seasonal error ($E_s$) | NA | NA | NA | NA | All datasets were acquired in the same season |
| Tidal fluctuation ($E_{td}$) | 6.998 | 7.143 | 7.043 | 7.069 | As per Tidal Data |
| Shoreline proxy offset ($E_o$) | NA | NA | NA | NA | |
| Measurement errors (m) | 0 | 0 | 0 | 0 | |
| Geo-referencing/ Rectification error (Er) | 0 | 0 | 0 | 0 | All data are orthorectified |
| Digitizing error ($E_d$) | 15 | 15 | 15 | 15 | As per the spatial Resolution |
| Toposheet survey offset (Et) | NA | NA | NA | NA | Na |
| Pixel Error (Ep) | 0 | 0 | 0 | 0 | All datasets have uniform spatial resolution |
| Total Shoreline position error (Esp) m | 22.00 | 22.14 | 22.04 | 22.07 | |

| | Year | 1988-1999 | 1999-2013 | 2013-2024 | 1988-2024 |
|---|---|---|---|---|---|
| | Uncertainty | 0.60 | 0.47 | 0.66 | 0.27 |

**Shoreline change analysis using DSAS:** The quantity of the change in shorelines over time was quantified using a digital shoreline analysis system (DSAS 5.1), which is an ArcGIS extension developed by the USGS (Zorlu and Kusak 2025). A common line was established on shore to a greater extent so as to command all preceding coastlines, and at 50-meter intervals, transects were drifted out to sea. It has computed rates of shoreline change, including WLR, which integrates the weighting in time with the uncertainty of the position of each shoreline (Hossen and Sultana 2023). This classified the transect zoning into either erosional, accretional, or stable according to administrative areas.

**NDVI and vegetation analysis:** To determine the ecological impact of the alterations of the shoreline, the NDVI values of the red and the near-infrared bands were calculated using each of the Landsat scenes (Fokeng and Fogwe 2022). This index is utilized in the assessment of the coastal zones of vegetative health and density.

$$NDVI = - \frac{NIR\text{-}RED}{NIR+RED} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

**Shoreline prediction and sustainable planning:** The projections of the position of the shoreline in 2034 and 2044 were carried out with the help of the temporal WLR trends and area loss data, and the linear extrapolation method was used with the DSAS results. Such projections were used in a sustainable development framework. The goal of the restoration proposals is to improve resilience on the coast and to have a climate-based approach based on ecosystem management (Simonson *et al.* 2021).

## Results

**Shoreline change analysis on Kutubdia Island:** The shoreline changes map of Kutubdia Island between the years 1988 and 2024 reports that the erosion trend is continuing and is thus extensive, as the accretion forms occur in minor and opportunistic pockets. Such evaluation on a temporal scale based on geospatial data analysis using Digital Shoreline Analysis System (DSAS) and Weighted linear Regression (WLR) deriving data based on 1,032 transection found (Figure 3) that 88.57 per cent of the

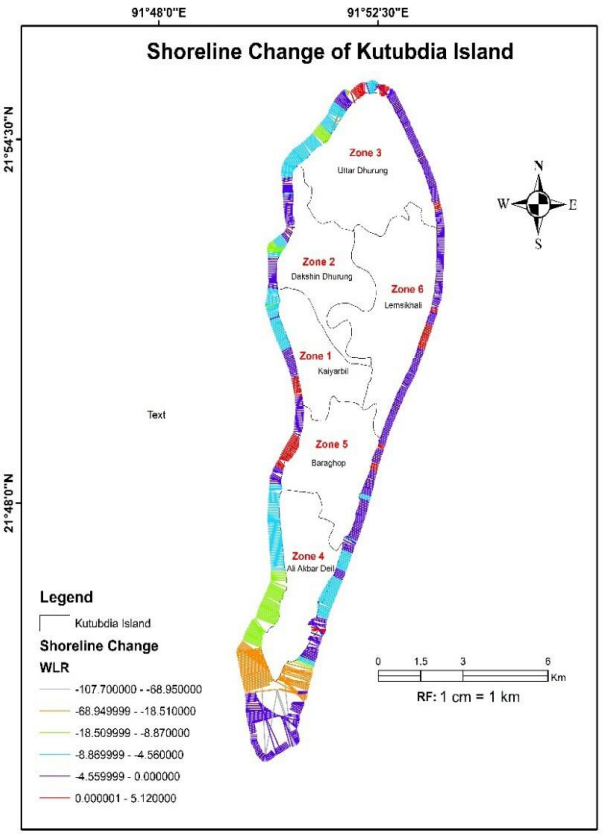



**Figure 3.** Spatial distribution of shoreline change on Kutubdia Island (1988–2024) based on Weighted Linear Regression (WLR). The map illustrates the magnitude and spatial variation of shoreline change on Kutubdia Island over a 36-year period using WLR analysis. Zones 1 to 6 show differing erosion and accretion trends. (Source: Authors 2025)

transects experienced the activities of erosion, 11.43 per cent of the transections indicated accretion and none of the transection experienced neither erosion nor accretion within the thirty six year assessment period.

The mean value of shoreline recession was estimated to be -5.32 meters with maximum erosion of -107.7 meters and maximum accretion of 5.12 meters. These totals indicate a significant shoreline asymmetry with losses of over 4,990.82 meters being far more than the relatively insignificant 129 meters that were gained instead (Table 3).

Spatial disaggregation along the coast with respect to zones reveals strong spatial heterogeneity in the behavior of the shoreline. A total of 83.95 per cent of the transects

**Table 3. Descriptive Statistics of Kutubdia Island**

| Descriptive Statistics | |
|---|---|
| Total Transects | 1032 |
| Total Erosional Transects | 914 |
| Total Accretional Transects | 118 |
| Total Stable Transects | 0 |
| Erosional Transects (%) | 88.56589147 |
| Accretional Transects (%) | 11.43410853 |
| Stable Transects (%) | 0 |
| Mean Shoreline Change (m) | -5.319277899 |
| Max Shoreline Change(m) | 5.12 |
| Min Shoreline Change(m) | -107.7 |
| Mean Erosion(m) | -4.836065891 |
| SD Erosion(m) | 8.124953017 |
| Total Erosional (m) | -4990.82 |
| Mean Deposition(m) | 0.125 |
| SD Deposition(m) | 0.627461129 |
| Total Deposition (m) | 129 |

in Zone 1 were showing evidence of erosion, whereby the average shoreline retreat of -3.62 meters and maximum retrospective erosion of -8.93 meters, respectively, are some of the highlights of the period of erosion in a total of 299.64 meters of erosion loss (Figure 5). Zone 2 was found to be the most prone zone to erosion, and as 97.87 percent of these transects were found to be erosional and the mean shoreline change of -4.44 meters contributed to erosion of -417.76 meters, and the greatest limit of retreat was -12.35 meters, thus indicating the intensity of erosive processes. On the same note, Zone 3 also showed a large range of shoreline changes, with the lowest scores falling to -37.85 meters, the mean erosible rate being -3.50 meters, giving an overall figure of -735.28 meters loss of land mass.

The worst shoreline retreat was observed in the southern part of the island, especially Zone 4, which indicated average shoreline change of -8.46 meters as against the highest profile of all the zones and its total erosion -3,141.61 meters (Table 4), the southern part of the island as the most threatened area in the island and it is the most destressed ecologically (Figure 4).

The lower average rates of shoreline retreat, as recoded in Zones 5 and 6, with -0.75 representing the retreat rate recorded in the two zones, indicated much lower rates of shoreline retreat, erosional activity that was, however, present in the two zones (Figure 5). The only transects that showed a slight but measurable trend in accretion were the same zones and constituted, in terms of percentage, 13.42 of the transects in both scenarios.

**Shoreline movement and vegetation health relationship:** The second aim of this study was to explore the potential ecological consequences of shoreline dynamics in comparing vegetation health, as a proxy measured by the Normalized Difference Vegetation Index (NDVI), with shoreline movement as determined

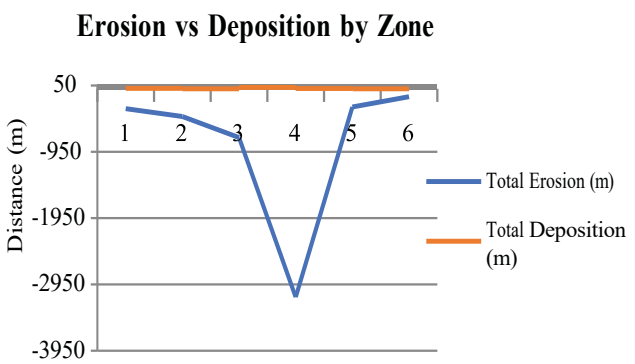



**Figure 4.** Shoreline erosion and deposition by zone on Kutubdia Island (1988–2024). The chart compares total shoreline erosion and deposition across six zones of Kutubdia Island.

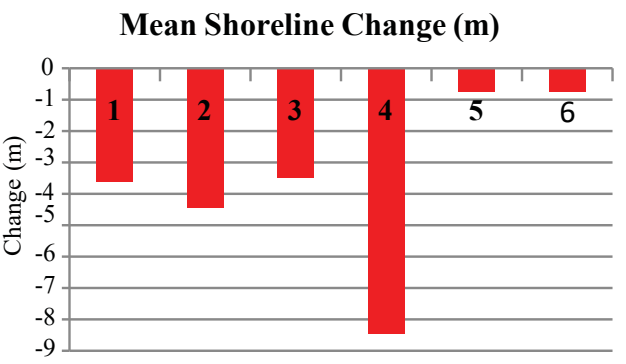



**Figure 5.** Mean shoreline change by zone on Kutubdia Island (1988–2024). The figure illustrates average shoreline change across the six coastal zones of Kutubdia Island.

**Table 4. Spatial summary of erosion and deposition across six coastal zones of Kutubdia Island (1988–2024). Zone 4 exhibited the highest shoreline retreat both in mean value and total loss, while Zones 5 and 6 had the lowest erosion rates.**

| Descriptive Statistics | Zone 1 (Kaiyarbil) | Zone 2 (Dakshin Dhurung) | Zone 3(Uttar Dhurung) | Zone 4 (Ali Akbar Deil) | Zone 5 (Baraghop) | Zone 6 (Lemsikhali) |
|---|---|---|---|---|---|---|
| Total Transects | 81 | 94 | 204 | 371 | 149 | 149 |
| Total Erosional Transects | 68 | 92 | 175 | 252 | 127 | 127 |
| Total Accretional Transects | 13 | 1 | 27 | 3 | 20 | 20 |
| Total Stable Transects | 0 | 1 | 2 | 116 | 2 | 2 |
| Erosional Transects (%) | 83.95 | 97.87 | 85.78 | 67.92 | 85.23 | 85.23 |
| Accretional Transects (%) | 16.05 | 1.07 | 13.23 | 0.80 | 13.42 | 13.42 |
| Stable Transects (%) | 0 | 1.06 | 0.98 | 31.26 | 1.34 | 1.34 |
| Mean Shoreline Change(m) | -3.62 | -4.44 | -3.50 | -8.45 | -0.75 | -0.75 |
| Max Shoreline Change(m) | 0.73 | 0.35 | 2.86 | 1.86 | 0.49 | 0.49 |
| Min Shoreline Change(m) | -8.93 | -12.35 | -37.85 | -107.7 | -1.96 | -1.96 |
| Mean Erosion(m) | -3.69 | -4.44 | -3.60 | -8.46 | -0.79 | -0.79 |
| Standard Deviation Erosion(m) | 2.65 | 2.76 | 4.53 | 12.01 | 0.56 | 0.56 |
| Total Erosional (m) | -299.64 | -417.76 | -735.28 | -3141.61 | -273.99 | -118.78 |
| Mean Deposition(m) | 0.078 | 0.003 | 0.10 | 0.01 | 0.04 | 0.04 |
| Standard Deviation Deposition(m) | 0.20 | 0.03 | 0.43 | 0.13 | 0.11 | 0.11 |
| Total Deposition (m) | 6.35 | 0 | 20.95 | 4.32 | 0 | 6.36 |

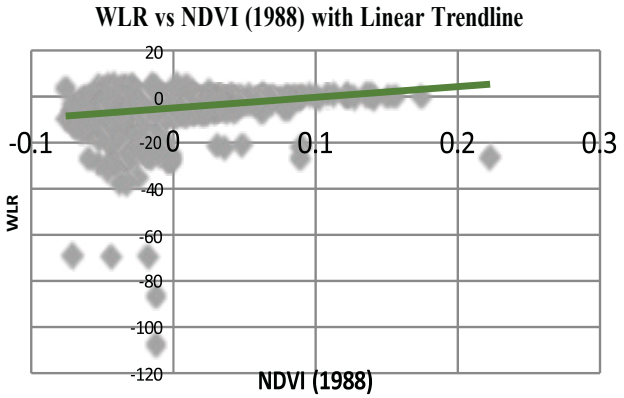



**Figure 6.** Relationship between NDVI (1988) and Weighted Linear Regression (WLR) of shoreline change with linear trendline on Kutubdia Island

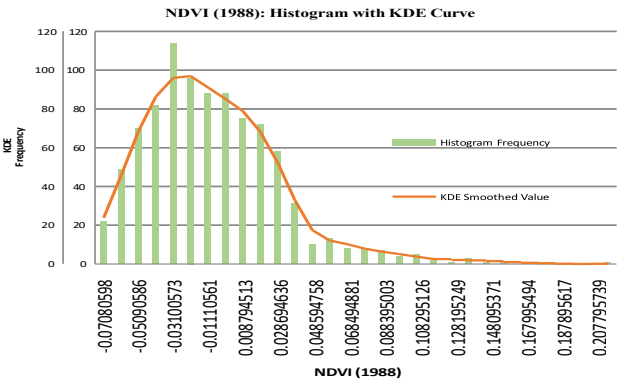



**Figure 7.** NDVI (1988) distribution on Kutubdia Island: Histogram with KDE smoothing curve

**Table 5. Area change (1988–2024) and projected shoreline loss (2024–2044) for different unions of Kutubdia Island (in hectares). The table displays land area values (in hectares) for each union from 1988 to 2024, along with shoreline change projections**

| Union | 1988 | 1999 | 2013 | 2024 | 2034 | 2044 | Change 1988–2024 | Predicted Loss 2024–2044 |
|---|---|---|---|---|---|---|---|---|
| Ali Akbar Deil | 1615.40 | 1330.69 | 1016.96 | 937.13 | 807.54 | 722.05 | -678.27 | -215.08 |
| Baraghop | 1005.95 | 1000.43 | 976.65 | 981.92 | 963.06 | 949.73 | -24.03 | -32.19 |
| Dakshin Dhurung | 993.44 | 977.06 | 947.51 | 943.97 | 925.86 | 913.61 | -49.47 | -30.36 |
| Kaiyarbil | 731.69 | 722.85 | 691.36 | 691.19 | 672.16 | 659.53 | -40.50 | -31.66 |
| Lemsikhali | 1461.03 | 1458.86 | 1445.70 | 1448.70 | 1439.74 | 1432.98 | -12.33 | -15.72 |
| Uttar Dhurung | 1528.17 | 1479.57 | 1458.03 | 1429.72 | 1399.93 | 1376.19 | -98.44 | -53.53 |

by the Weighted Linear Regression (WLR) rate. NDVI is effective in grasping vegetative cover, and WLR is used to show whether the shoreline is changing direction towards, or away, and negative values represent erosion and positive values represent accretion. The derivation of a scatter plot using the 1988 NDVI tracked a weak positive linear connection with WLR, which was an indication that denser vegetation may face less erosion (Figure 6). Though the association is weak, it is in line with the ecological knowledge that vegetation, especially mangroves and coastal vegetation, contributes immensely to stabilizing the shores and reducing shoreline erosion.

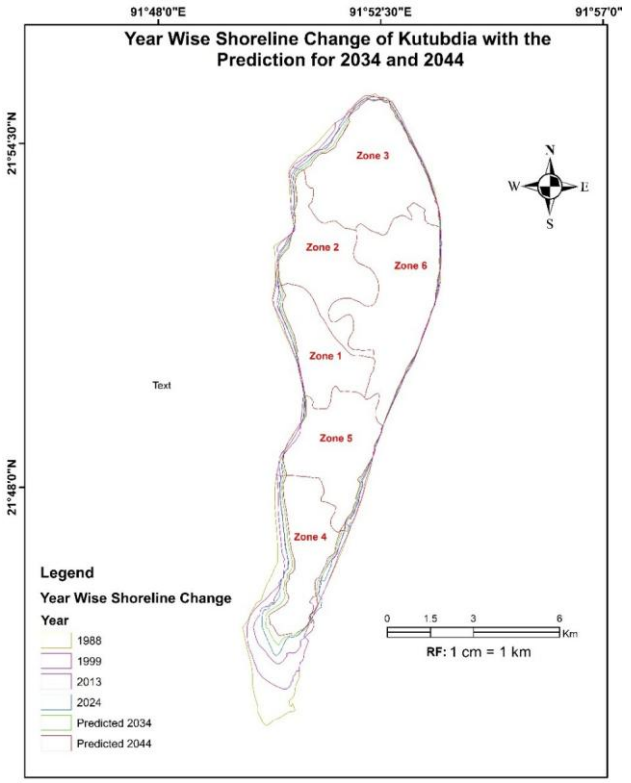



**Figure 8.** Temporal shoreline change of Kutubdia Island with future projections for 2034 and 2044. The map shows the shoreline positions of Kutubdia Island for the years 1988, 1999, 2013, and 2024, along with projected positions for 2034 and 2044. (Source: Authors, 2025)

This interconnection confirms why it is essential to incorporate ecological indicators of shoreline management, since the vegetated terrains, although neither free of erosion processes, display an overall comparatively less dynamic coastal behavior compared with that of the unvegetated ones. Greenspaces enhance environmental comfort by reducing temperature levels sufficiently to mitigate the adverse impacts of the Urban Heat Island (UHI) effect (Tahia *et al.* 2025).

**Shoreline shift forecasts:** With the help of multi-temporal shoreline data in 1988, 1999, 2013, and 2024, the positions of the years 2034 and 2044 were calculated with the help of linear extrapolation of the historical trends of shoreline movement patterns (Table 5).

With the spatial overlaying of the year-by-year location of the shoreline, the seaward shifting is evident, and even the most intense loss in land area has occurred in Ali Akbar Deil, where a strong and consistent land loss has been recorded. On the same note of things, the other zones like Uttar Dhurung, Dakshin Dhurung, and Kaiyarbil are also areas connected to the decline of areas, not as serious as Ali Akbar Deil though. Baraghop and Lemsikhali, on the contrary, show comparatively less area loss and a less variable shoreline situation (Figure 8).

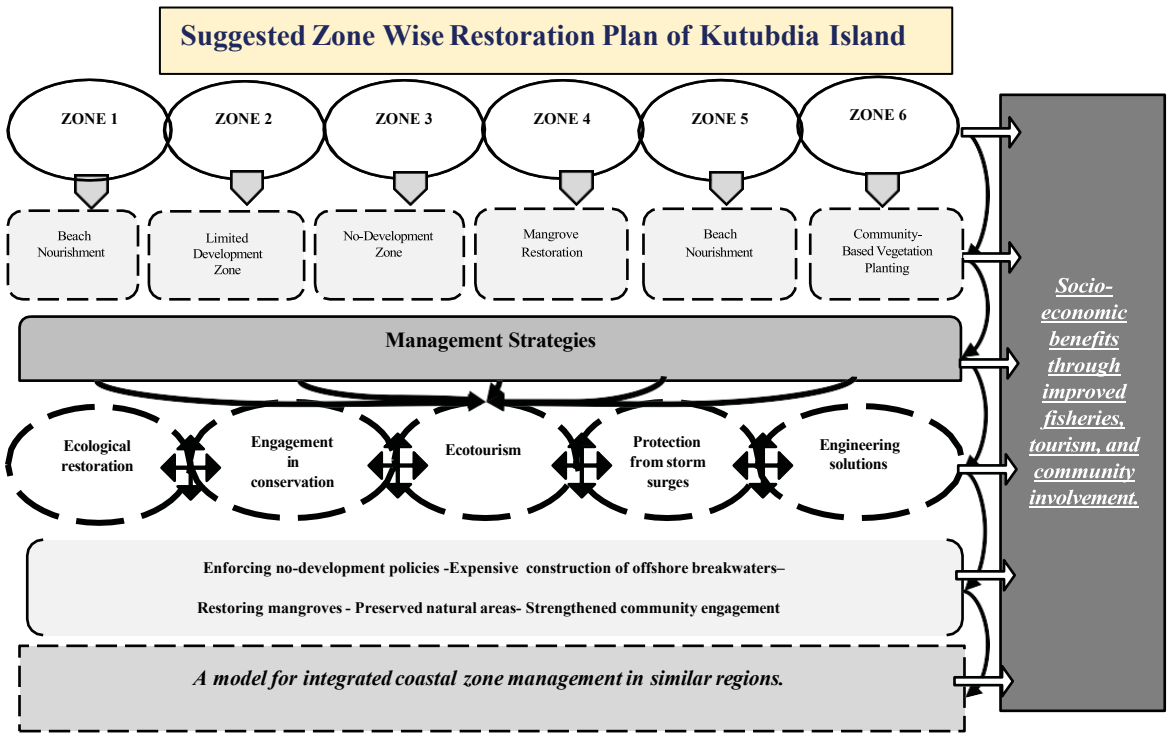



**Figure 9.** Integrated zone-specific restoration strategy for sustainable coastal management of Kutubdia Island. The diagram presents tailored restoration strategies based on erosion severity across different zones of Kutubdia Island. (Source: Authors 2025)

This degrading path is well illustrated on the area change graph, where the most susceptible areas have been subjected to sharp decreases and the more stable areas to insignificant variations. This kind of spatial-based perception of the risk zones out in the future allows prioritizing interfacing areas. The results are all in support of the integrated management measures, in which the strategies rely on the particular resilience of the zones.

## Discussion

The long-term shoreline movements in Kutubdia Island between the years 1988 and 2024 show a strong signal of coastal erosion with some isolated areas that have accreted. This net erosion, which far exceeds accretion, is a pointer to the fact that there is yet to be an end to the land loss on the island. The net recession in the shoreline of 4,990.82 meters is further evident by the high percentage of erosional transects (88.57%) against the minimal accretion (11.43%), which shows that the erosion on the island is comprehensive and persistent even to date. Most intense erosion was observed in the southern part of the island, according to Zone 4. Conversely, Zones 5 and 6 showed lower values of erosion, which implies that such regions may not be severely prone to erosion.

The results also indicate that coastline stability and vegetation health (NDVI) are positively correlated. Although there was little relationship between shoreline alteration and the 1988 NDVI, overall erosion was lower in places with more vegetation cover. This helps to emphasize the need to preserve or improve on coastal plant cover, particularly mangroves, in anchoring or stabilizing the coastline and countering the erosion powers (Benazir et al., 2024). The green areas can positively influence physical health and emotional well-being, as well as stimulate recreational activities (Tahia et al., 2025)Dhaka, Bangladesh, following the visionary goal of SDG 11.7 on safe, accessible, and inclusive public spaces. The study hypothesizes a link between frequent park visits and a healthier Body Mass Index (BMI. Further, the shoreline time series analysis enabled the prediction of subsequent shoreline positions in 2034 and 2044 to realize the land loss experienced to date on the island. The loss of more

than 215 hectares in Ali Akbar Deil, which is expected by 2044, is an eye-opener on how intervention is needed. Although other sites, such as Baraghop and Lemsikhali, are comparatively more stable, the overall shoreline recession is already posing a compelling issue to the long-term sustainability of the island.

Coastal management strategies for Kutubdia Island: This proposal concentrates on the significance of making ecological interventions in line with the levels of degradation witnessed in various zones (Figure 9). For sites with low soil erosion levels, Zones 6, low-cost participation approaches are proposed, such as community vegetation planting, an inexpensive ecologically impacted method that builds a community capacity of stewardship and increases the ecological resistance (Adu-Boahen 2024). The ability of vegetated habitats to lower temperatures by several degrees emphasizes their importance in regulating the climate and stabilizing surrounding areas. When the erosion worsens, especially in Zones 1 and 5, then nourishing the beach becomes important, as the long-term deposition of sediments on the eroding beaches is done artificially in order to retain the buffer capacity and minimize land loss (Tiede *et al.* 2025) particularly in the face of rising sea levels and increasingly variable storm climates. This study examines the development of a large-scale sand nourishment (600,000 $m^3$. Moderately degraded zones, such as Zone 2, are recommended to have a limited development zone in a bid to limit the uncontrolled encroachment of human beings into these areas and lessen the load on the vulnerable coastal systems. It is a policy-based approach that would enable phased land use that would not compound degradation; hence, limited economic activity can be carried out.

Zone 3, which is potentially subject to more intense disturbance or repeated disturbance, is a no-development zone, thereby ensuring a severe prohibition of the use of the land. The most pronounced erosion, as in Zone 4, calls for the most coherent intervention, like the mangrove restoration, which acts as a wholesome ecological protective network. Mangrove reforestation not only stabilizes sediments and lowers energy levels of the waves but also improves biodiversity, carbon sequestration, and long-term resistance against storm surges and climate change (van Hespen *et al*. 2023).

This zone-specific concept promotes a cascading management system, allowing for more complicated actions as environmental degradation increases. It also emphasizes economic co-benefits, such as better fisheries, tourism potential, and community participation, which promote resilient and inclusive coastal governance (Viana *et al.* 2024).

## Conclusion

This research seizes upon the concerning nature of the shoreline incursion and environmental degradation that has taken place in the last 36 years on Kutubdia Island. Through the use of geospatial applications, including the Digital Shoreline Analysis System (DSAS) and Weighted Linear Regression (WLR), it was discovered that in the 1032 transects examined, 88.57 percent showed erosional trends, and thus had a total resulting land loss of almost 5,000 meters. Spatially, the southern regions, such as Ali Akbar Deil, were discovered to be so affected, and in the regions such as Baraghop and Lemsikhali, a lowered rate of erosion was realized. The correlation of erosion with vegetation health showed that healthier vegetation corresponded to lower rates of erosion. This confirmed the protective effect of coastal vegetation, and more specifically, the mangrove. The vulnerability of the island is even highlighted further by future shoreline projections. The results emphasize the need to consider future and zone-oriented management approaches rendered by the combination of ecological restoration, local adaptation, and infrastructural planning. On the one hand, it presents a policy-relevant coastal management framework that is climate resilient. Its combination strategy, which considers shoreline change, ecological health, and development in progress, can be scaled up to other points at risk on the frontier of climate change and human projects.

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