

## RESEARCH ARTICLE

## DYNAMIC COASTAL LAND CHANGES AND PREDICTIVE MODELLING ASSESSMENT: FORMATION, DEFORMATION, AND FUTURE SCENARIOS IN THE COASTAL REGIONS OF BANGLADESH

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## ABSTRACT

The coastal regions of Bangladesh are highly dynamic and increasingly affected by both natural processes and human activities, leading to notable land formation and deformation. This study examines coastal land-use changes over the last three decades and predicts future trends using a Cellular Automata-Markov (CA-Markov) model. Focusing on Noakhali and Sandwip, the analysis shows a net land gain of 600.45 sq. km between 2000 and 2010, which declined to 297.10 sq. km during 2010–2020, alongside increased land deformation. Conversion from water to vegetation rose sharply from 27.97 sq. km to 109.62 sq. km over the same periods. Projections for 2030 indicate continued changes, with land area increasing to 1,934.22 sq. km and water area decreasing to 5,671.38 sq. km. The results highlight the influence of climate change, including sea-level rise and storm surges, and emphasize the value of predictive modeling for sustainable coastal management and planning.

## KEYWORDS

Coastal land, CA-Markov model, land formation, land deformation, predictive modelling

## 1. INTRODUCTION

The coastal areas of Bangladesh are dynamic and hence complex due to the constant interplay between the forces of nature and human activities. These areas are of prime importance because of their ecological values, economic worth, and livelihoods (Sarwar, 2005). Still, they are also most vulnerable to a variety of types of degradation, like erosion and sediment deposition, by changes in land use caused by natural and anthropogenic forces. Understanding their formation and deformation processes is essential to ensuring the sustainable management and planning of coastal lands (Rezaie, 2015).

Having an extended coastline along the Bay of Bengal, Bangladesh is easily affected by changes within the coastline. The vast network of rivers and their deltaic landform make coastal areas easily flooded, eroded, and sedimented (Ahmad, 2019). Through sea level rise, storm surges, and changing precipitation, climate change also increases these processes. As a result, the coastal lands of Bangladesh are continuously changing over time, hence affecting agriculture, settlements, and natural habitats (Billah et al., 2025; Sajeeb, 2021).

The coastal zone of Bangladesh comprises about 47,201 square kilometres, accounting for 32 percent of the total land area of the country. This zone hosts about 35 million people, which holds a massive portion of the population of the country. Geomorphologically, this coastal region

is distinctive, and mainly shaped by the Ganges-Brahmaputra-Meghna river system that is largely responsible for sediment deposition and land formation (Goswami et al., 2025; Sajeeb, 2021; Sarwar, 2005).

Processes within the coastal zone are largely controlled by the sediment that the major rivers, issuing from the Himalayas, carry (Billah, 2024). These sediments, in the amount of approximately one billion tons a year, are discharged into the northern part of the Bay of Bengal by the Brahmaputra Meghna, and Padma rivers and then settle down in the Bay, generally in the estuaries of the Meghna River (Masum and Rakib, 2023). This process makes dramatic changes in bay morphology and creates new land, referred to as "char" lands, most of which have their own dynamic characters with perpetual cases of flooding and erosion (Memarian et al., 2012; Rezaie, 2015).

The coastal zone of Bangladesh faces numerous environmental challenges, primarily driven by climate change and natural disasters (Billah and Ahmmed, 2025). Key issues include, Sea Level Rise, Projections indicate that sea levels could rise by up to 1 meter by the end of the century, threatening to inundate significant portions of the coastal area and displacing millions of people (Parvin et al., 2017). Changes in the level of the sea are likely to affect, first of all, coastal areas at very low elevations, particularly the densely populated or socially and economically important areas (Qu et al., 2023). Exposition therefore plays

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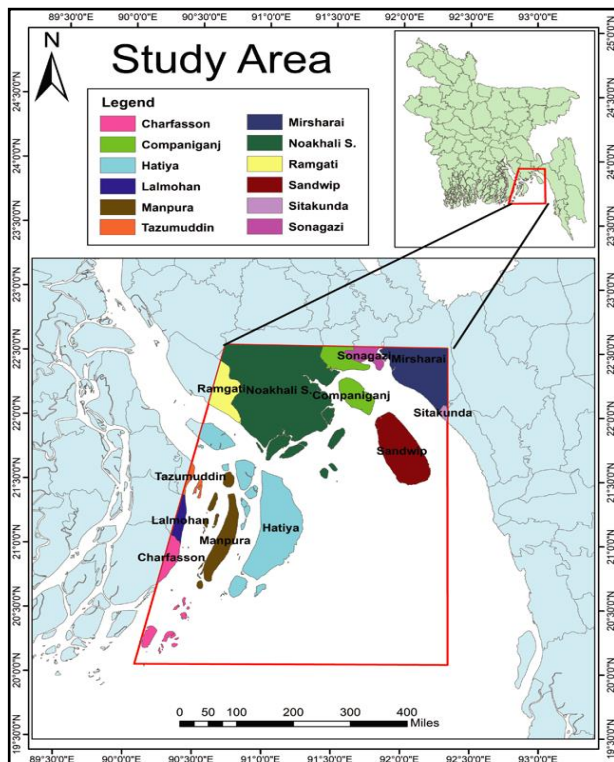
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an additional role in enhancing vulnerability in the case of urban coastal centres. Coastal protected zones and deltas are of importance because they help in sustaining the specificity of natural environments (Han et al., 2022; Rodríguez et al., 2017). In a report by the Intergovernmental Panel on Climate Change, it is projected to affect protected natural areas and agriculture through land submergence, soil, and freshwater salinization, and loss of land from coastal erosion. These are changes that will have far-reaching implications for food security and production (Elias et al., 2020). Cyclones and Storm Surges, the region is prone to cyclones, which can cause devastating impacts, including loss of life and property. For instance, the cyclone in 1991 resulted in approximately 2.5 million fatalities in the Chittagong region (Aziz and Paul, 2015). Coastal Erosion, the dynamic nature of the coastal environment, coupled with anthropogenic pressures, contributes to significant land erosion, particularly in the exposed coastal areas (Billah, 2023). All those are the major issues to deforming the coastal lands (Ahmad, 2019).

The CA-Markov model excels in simulating land use changes across multiple categories by integrating the Cellular Automata (CA) and Markov chain methodologies. While Markov analysis alone does not consider the causes of land use changes and lacks spatial sensitivity, the CA-Markov approach mitigates these limitations (Surabuddin et al., 2019). The approach based on CA Markov modelling has been widely applied to predict land use changes. The CA Markov model uses spatial and temporal data to simulate the future scenario of land use, which is based on historical trends (Memarian et al., 2012; Taloor et al., 2024). The CA Markov model will apply to aid in land use pattern prediction of 2030 compared to changes observed in 2020 for the coastal region of Bangladesh. Predictive modelling is highly important in the management and planning of the coastal area that permits anticipation and reduction of the effect of LULC change on ecosystem and community (Surabuddin Mondal et al., 2019). Therefore, the main objectives of the study are: (i) to detect the coastal land area change in the last three decades, (ii) to predict future coastal land in 2030 by the CA Markov Model, (iii) to make a comparison of formation and deformation of land in 2020 & 2030.

**2. STUDY AREA PROFILE**

The study area is located in the southern coastal areas of Bangladesh. The area is situated between 21°40'N to 22°50'N and 90°40'E to 91°40'E. This study consists the area of Charfasson, Companiganj, Hatiya, Lalmohan, Manpura, Tazumuddin, Mirsharai, Noakhali, Ramgati, Sandwip & Sonagazi upazila of Bangladesh. Here the land area is about 3243 sq.km and the water area consists 6012 sq.km area (in 2010).



**Figure 1: Study Area Mapping**

**3. MATERIALS AND METHODS**

**3.1 Data collection**

Landsat satellite images for 2000, 2010, and 2020 were collected from the United States Geological Survey (USGS) Earth Explorer platform. The images were selected based on cloud cover (<10%) to ensure high-quality data for analysis. Landsat images provide multispectral data which are crucial for LULC classification due to their high spatial and temporal resolution (Wulder et al., 2019).

Table 1: Data collection			
Information	Image 2000	Image 2010	Image 2020
Satellite	Landsat 5 TM	Landsat 5 TM	Landsat 8 OLI
WRS Path	136	136	136
WRS Row	044, 045	044, 045	044, 045
Date	28.01.2000	08.02.2010	20.02.2020
Cloud Cover	0%	0%	0%
Datum	WGS 1984	WGS 1985	WGS 1986
UTM Zone	46N	46N	46N

**3.2 Supervised classification of collected Landsat images**

The collected Landsat images were pre-processed to correct atmospheric distortions using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) algorithm. This was followed by image enhancement techniques such as histogram equalization to improve the visual quality of the images.

Supervised classification was conducted using the maximum likelihood classification (MLC) algorithm, a popular method for LULC classification due to its high accuracy (Lu, and Weng, 2007). Training samples were selected based on prior knowledge of the study area and visual interpretation of the images. The classification scheme included categories such as urban, agricultural land, forest, water bodies, and barren land.

LULC map development for 2000, 2010, and 2020 Post-classification, the accuracy of the LULC maps was assessed using the confusion matrix approach. Overall accuracy and Kappa statistics were calculated to ensure reliability of the classification results. The LULC maps for 2000, 2010, and 2020 were developed to visualize spatial distribution patterns and changes over time (Foody and G.M, 2002).

**3.3 Accuracy assessment**

The accuracy evaluation phase of the image categorization process is the last one. A procedure to evaluate the categorization with actual data or other sources of information is called accuracy evaluation. It enables assessing a file of categorized images. To ground truth each and every pixel of the categorized image is unusual. So, a few reference pixels are produced. On the categorized image are locations called reference pixels. Each reference pixel in the picture corresponds to a particular geographic coordinate. These reference pixels were chosen at random. Two sets of class are present at the randomly chosen positions in the categorized image list. The actual kind of land cover is represented by the first set of class values. The second class, sometimes referred to as reference values. The researcher enters these reference values, which are based on the ground truth data (Dewan and Yamaguchi, 2009).

The map is validated using the Kappa coefficient (K). K is determined by applying the equation.

$$k = \frac{N \sum_{i=1}^r x_{ii} - \sum_{i=1}^r (x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^r (x_{i+} \times x_{+i})} \tag{1}$$

Where,

N = Number or quantity of pixels.

r = number of rows in matrix.

Xii = number of observations in row land column i.

xi+ and x+i are the marginal totals for row and column i, respectively.

### 3.4 Land use change detection

Change detection analysis was performed to identify the transformations in LULC between 2000 and 2010, and between 2010 and 2020. The post-classification comparison method was utilized to detect changes, which involves comparing classified images of different times to identify transitions between LULC categories (Singh, 1989). This analysis helped in quantifying the extent of land conversion processes such as urban expansion, deforestation, and agricultural intensification.

### 3.5 Transition potential modelling and CA-Markov model for 2030 simulation

To predict future LULC patterns for the year 2030, the CA-Markov model was employed. The model combines cellular automata (CA) and Markov chain analysis to simulate LULC dynamics by considering spatial and temporal dependencies (Memarian et al., 2012; Taloor et al., 2024). Transition probability matrices were derived from historical LULC data, which describe the likelihood of change from one class to another. Spatial variables including Digital Elevation Model (DEM), slope, and aspect were incorporated into the model to account for topographical influences on land use changes. The Multi-Criteria Evaluation (MCE) technique was used to derive suitability maps for each LULC category based on these spatial variables.

### 3.6 Prediction of 2030 LULC map and analysis of formation and deformation

The CA-Markov model output provided a simulated LULC map for the year 2030. The predicted map was analyzed to identify potential areas of land formation (e.g., urban development) and deformation (e.g., deforestation). The analysis was conducted by comparing the 2020 and 2030 LULC maps to detect significant changes and trends. This step helps in understanding future land use dynamics and assists in sustainable planning and management (Pontius and Malanson, 2005).

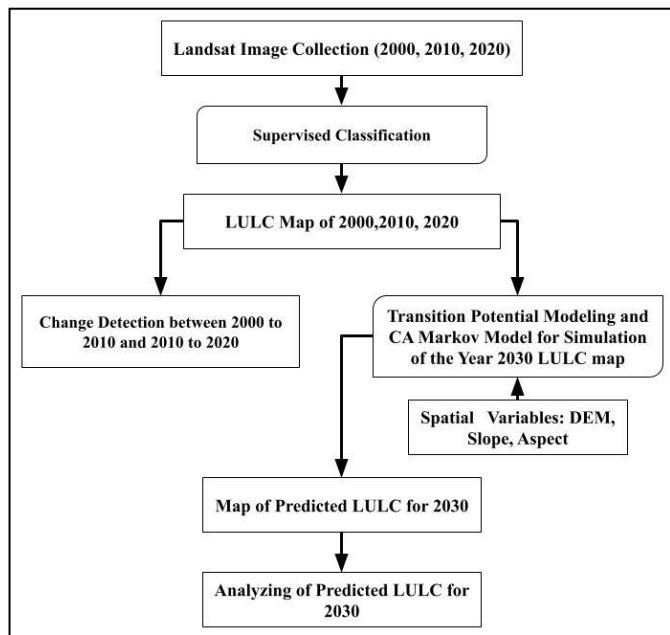


Figure 2: Flowchart of Methodology

## 4. RESULT

### 4.1 Detecting coastal land area change in last three decades

#### 4.1.1 Land-use classification in different year

In this analysis, three types of land cover were considered: vegetation, land, and water. The water area mainly consists of the Bay of Bengal. Figure 2 shows the land use of the coastal region for the years 2000, 2010, and 2020. It is evident that from 2000 to 2020, new land is forming mostly near the Sandwip region, while significant land deformation is occurring along the coastline in the Noakhali region. To validate the image classification, Google Earth images were used, and the validation was

conducted using the overall accuracy and kappa coefficient methods.

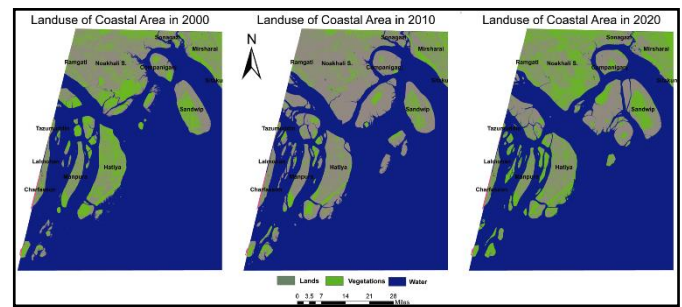


Figure 3: Landuse of coastal area in different years

The overall accuracy results were 86.13% for 2000, 88.32% for 2010, and 91.22% for 2020. The kappa coefficients for 2010 and 2020 were good, with values of 0.83 and 0.81, respectively, while the year 2000 had a slightly lower efficiency with a value of 0.78 (see Table 2).

Table 2: Accuracy check			
Accuracy	2000	2010	2020
Overall Accuracy	86.13%	88.32%	91.22%
Kappa	0.78	0.83	0.81

#### 4.1.2 Change detection

Figure 3 illustrates the changing pattern from 2000 to 2020. This is divided into 2 segment landuse change from 2000 to 2010 and 2010 to 2020. In first decade, the changing pattern is huge, a great number of water area about 600.45 sq.km had change to land as well a significant amount of vice versa shown in blue mark (land to water), about 148.32 sq.km land area deformed into water (see in table 3). But in next decade the situation was opposite, the number of formed lands from water is lesser than deformed land into water area, which is about 297.10 sq.km and 364.67 sq.km simultaneously. Conversely, the conversion of water to vegetation increased significantly from 27.97 sq. km in the first decade to 109.62 sq. km in the second decade. The change from land to water more than doubled, going from 148.32 sq. km in the first decade to 364.67 sq. km in the second decade, while the conversion from land to vegetation also saw a significant increase from 13.32 sq. km to 65.12 sq. km. On the other hand, the transition from vegetation to water decreased from 69.98 sq. km to 29.06 sq. km in the second decade, as did the conversion of vegetation to land, which decreased significantly from 71.12 sq. km to 11.25 sq. km (table 3). These changes reflect dynamic shifts in land cover types, influenced by various environmental factors and possibly human interventions in the coastal region.

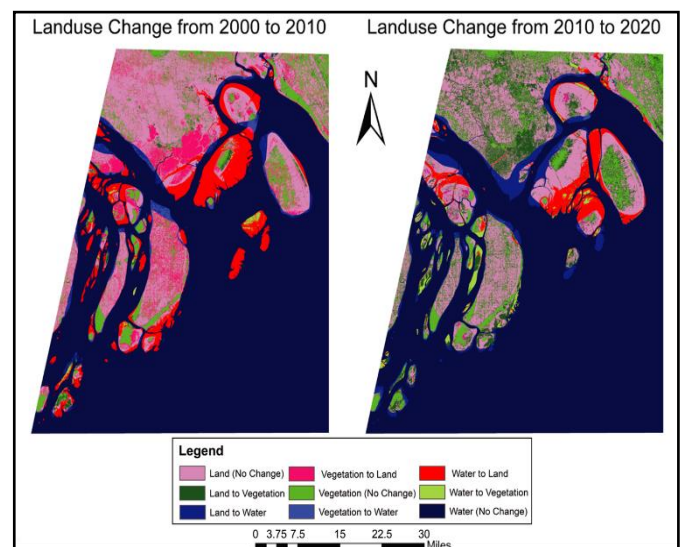


Figure 4: Change detection from 2000 to 2020

Table 3: Types of landuse changes		
Change	2000 to 2010	2010 to 2020
Water to Land	600.45	297.10
Water to Vegetation	27.97	109.62
Land to Water	148.32	364.67
Land to Vegetation	13.32	65.12
Vegetation to Water	69.98	29.06
Vegetation to Land	71.12	11.25

4.1.3 Future Land Cover Prediction in Coastal Area

Finally, figure 4 shows the predicted landform for the year 2030. The figure 5 titled "Landuse Change from 2000 to 2030 (sq. km)" illustrates the changes in three types of land cover—lands, vegetation, and water, in the coastal region from the year 2000 to the projected year 2030, measured in square kilometers (sq. km). For lands, the area increased from 1,673.3 sq. km in 2000 to 2,611.74 sq. km in 2010, followed by a decrease to 1,857.97 sq. km in 2020, with a slight increase projected to 1,934.22 sq. km by 2030.

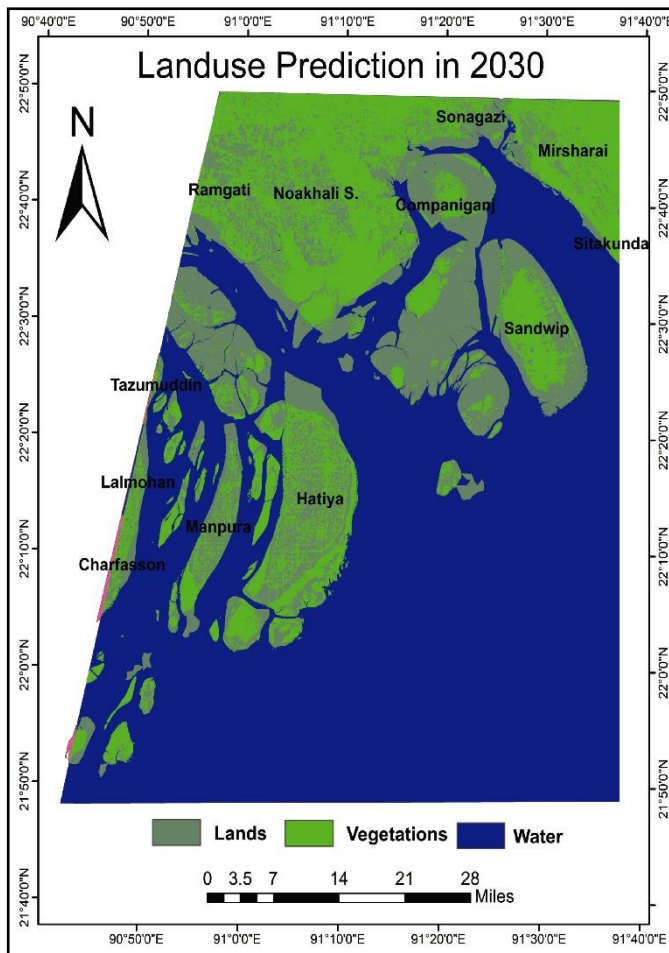


Figure 5: Predicted Coastal Land in 2030

Vegetation area decreased significantly from 1,159.34 sq. km in 2000 to 631.02 sq. km in 2010, then increased to 1,397.78 sq. km by 2020 and is projected to continue increasing to 1,648.94 sq. km by 2030. The water area showed a gradual decrease from 6,422.39 sq. km in 2000 to 6,012.27 sq. km in 2010, further declining to 5,999.28 sq. km by 2020, with a projected decrease to 5,671.38 sq. km by 2030. The data highlights dynamic changes in land use in the coastal region, with fluctuations in land area, significant recovery in vegetation, and a consistent decrease in water area, emphasizing ongoing transformations and future predictions for 2030.

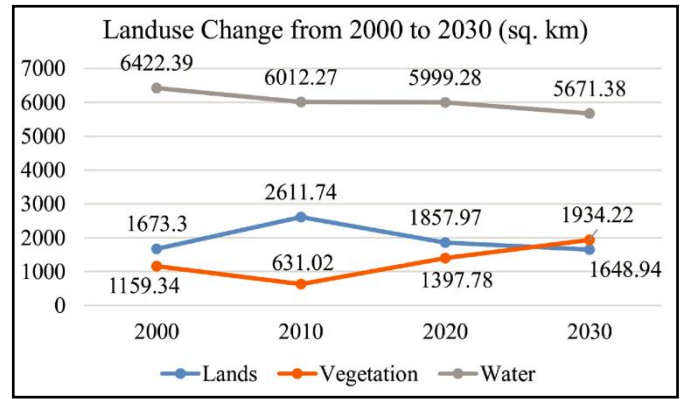


Figure 6: Area in sq.km for different landuse in different years

4.1.4 Comparison of Formation and Deformation of Land in 2020 & 2030

The figure 6 and 7 illustrate the spatial dynamics of land formation and deformation in the coastal regions of Bangladesh over different time periods. The first image, a map titled "Land Formed or Deformed in 2020 & 2030," highlights the regions where land has been newly formed and where deformation has occurred. Green areas represent new land formation in 2020 and projections for 2030, while red areas indicate land deformation in 2020. The second image, a bar chart titled "Formation or Deformation of Lands (sq. km)," quantifies the changes in land area over three decades: 2000-2010, 2010-2020, and 2020-2030. It shows that from 2000 to 2010, there was a significant net gain in land area, with 628.4 sq. km of land formed against 218.3 sq. km deformed. The period from 2010 to 2020 saw a reduced net gain, with 406.7 sq. km of land formed and 227.7 sq. km deformed. Projections for 2020 to 2030 indicate a continued trend of land formation, with 337.1 sq. km expected to form, although the extent of deformation is not specified in the provided figures. Overall, these visualizations highlight the dynamic nature of coastal land areas, influenced by both natural processes and human activities, which can significantly impact regional planning and disaster risk reduction efforts.

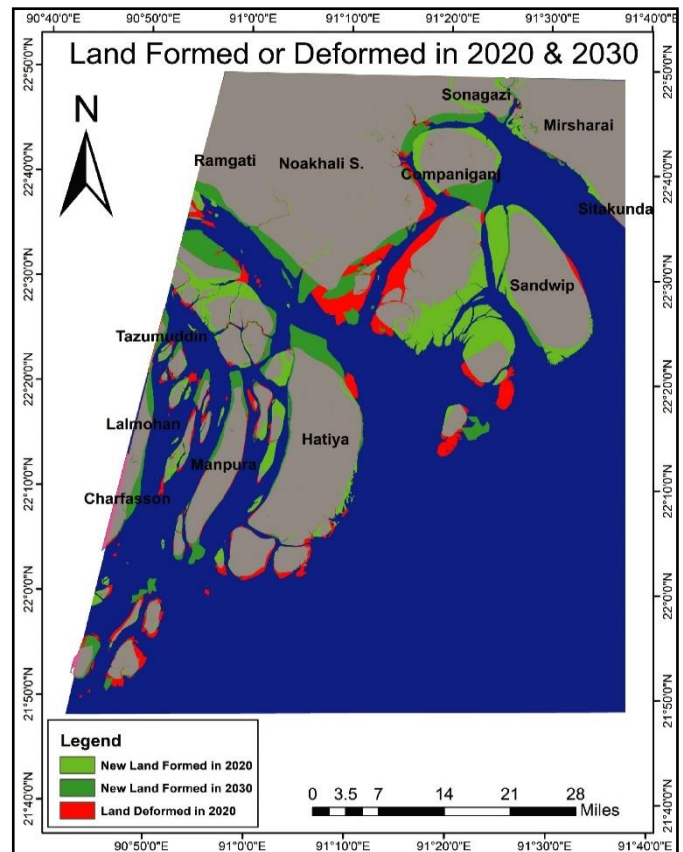


Figure 7: Formation and Deformation of Land in 2020 & 2030

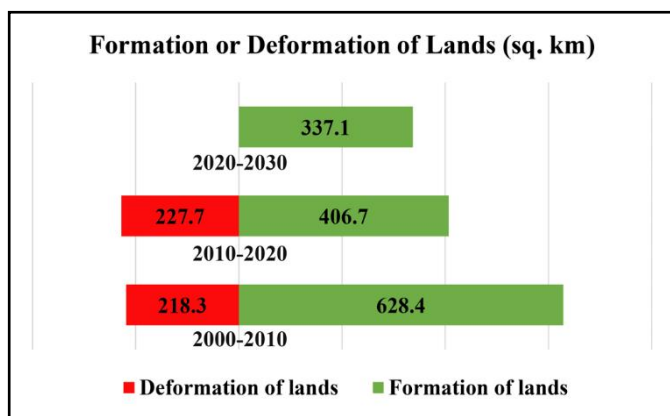


Figure 8: Area of formation and deformation of lands in different years

## 5. DISCUSSIONS

The study on the formation and deformation of coastal lands in Bangladesh presents a dynamic view of the coastal region's landscape changes over recent decades and offers predictions for the future. The findings underscore the significant role of natural processes, such as sediment deposition from major rivers like the Brahmaputra, Meghna, and Padma, in shaping the coastal morphology. However, the increasing influence of anthropogenic activities and climate change on these natural processes is evident. The use of the CA-Markov model effectively highlights the shifting patterns of land use, particularly the reduction in newly formed lands and the increase in deformed lands between 2000 and 2020. This trend suggests an accelerating vulnerability of the coastal region, largely attributed to sea-level rise and increased storm activities, which have been projected to continue affecting the coastal landscape into 2030 (Rezaie, 2015; Parvin et al., 2017).

Furthermore, the study's findings indicate that while there has been some recovery in vegetation cover, the overall decrease in land area and consistent increase in water area point towards a net loss in habitable and arable land. These shifts have profound implications for the local population, particularly concerning food security, settlement sustainability, and disaster risk reduction. The research highlights the importance of integrating predictive modeling tools like the CA-Markov model in coastal management strategies to anticipate and mitigate the adverse effects of land use and cover changes (Memarian et al., 2012; Taloor et al., 2024). Additionally, the study draws attention to the need for more robust and adaptive policy frameworks that can address the dual challenges of natural and human-induced land transformations in Bangladesh's coastal areas (Sarwar, 2005; Ahmad, 2019).

## 6. CONCLUSION

The analysis of coastal land formation and deformation in Bangladesh, as conducted in this study, reveals significant geomorphological shifts over the past two decades, driven by both natural and anthropogenic factors. Utilizing the CA-Markov model, the study quantified the dynamic land cover changes, showing a net gain of 600.45 sq. km of land between 2000 and 2010, which decreased to 297.10 sq. km in the subsequent decade. Simultaneously, land deformation increased substantially from 148.32 sq. km to 364.67 sq. km, indicating an accelerated erosion process and highlighting the region's growing susceptibility to environmental stressors.

The predictive modeling projects further land cover transformations by 2030, with an anticipated increase in terrestrial area to 1,934.22 sq. km, contrasted by a projected reduction in aquatic zones to 5,671.38 sq. km. These projections are critical for understanding the long-term implications of sediment dynamics, sea-level rise, and increased cyclonic activity on coastal morphology. The application of the CA-Markov model in this context not only validates its efficacy in simulating future land use scenarios but also underscores the importance of incorporating spatial and temporal data to enhance the precision of predictive models.

The findings of this study underscore the necessity for implementing robust coastal management strategies that integrate predictive analytics to mitigate the adverse effects of land use and cover changes. The observed trends in land deformation, particularly the significant increase in land-to-water transitions, necessitate urgent interventions aimed at reinforcing coastal defenses and managing sediment flux. The integration

of climate resilience measures into regional planning is essential to counteract the effects of projected sea-level rise and other climate-related hazards.

This study provides a critical foundation for understanding the geomorphological evolution of Bangladesh's coastal regions. The continued application and refinement of predictive modeling techniques like CA-Markov are imperative for developing adaptive management frameworks that address the multifaceted challenges posed by climate change and human activities. The insights gained from this research are instrumental for policymakers, enabling data-driven decision-making that ensures the long-term sustainability of these vulnerable coastal landscapes.

## CONFLICT OF INTEREST

The authors have no conflict of interest

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