



## Decadal Changes in Shoreline Patterns in Sundarbans, India

*Nilovna Chatterjee<sup>1</sup>, Ranadhir Mukhopadhyay<sup>2\*</sup>, Debashish Mitra<sup>3</sup>*

<sup>1</sup> Vellore Institute of Technology, Vellore, Tamil Nadu, 632 014, India

<sup>2</sup> CSIR- National Institute of Oceanography, Dona Paula, 403 004, Goa, India

<sup>3</sup> Indian Institute of Remote Sensing, Dehra Dun, 248 001, Uttarakhand, India

### ABSTRACT

Sundarbans is one of the most populated and largest deltas in the world and is located at the mouth of three major rivers- Ganges, Brahmaputra and Meghna that empty into the Bay of Bengal along the east coast of India. The landforms of Sundarbans are changing shape rapidly following impact of several forcing parameters, both natural (atmospheric, physical, chemical and geological) and anthropogenic (pollution, tourism, deforestation). We submit here an assessment of changes in shoreline pattern of 14 islands in Indian Sundarbans (ISD) since 1979. Using multi temporal satellite images of LANDSAT, we found that as many as four islands within ISD have lost area in excess of 30%. While the area loss for another three islands has been between 10 and 30%, five islands show minor loss of area (<10%). The shoreline variations in two other islands, however, are of extreme nature. While the Lohachar Island on the river Hoogly was completely submerged by the end of the last century, the neighboring Nayachar Island on the same river has gained more than 30 km<sup>2</sup> of land area. An interesting difference in nature of land loss is seen between western and eastern group of islands. Over the last 32 years, the total loss of area in six western islands (Ghoramara, Sagar, Jambudwip, Mousuni, Namkhana, Lothian) has been 23.64 km<sup>2</sup>, while another six islands from eastern Sundarbans (Surendranagar, Dhanchi, Bulchery, Chulkati, Dalhousie and Bhangaduan) have lost about 53.85 km<sup>2</sup> of land area. The role of various forcing parameters, such as long shore current, abnormal tidal heights, subsidence, tilting of crust and sub-surface geomorphology, in effecting changes in shoreline pattern in 14 Islands of the Indian Sundarbans are discussed.

### ARTICLE INFO

Received  
15 July 2015  
Accepted  
21 September 2015  
Available online  
17 October 2015

Keywords  
Sundarbans  
RS-GIS mapping  
Landsat imageries  
Changing shorelines  
Erosion-accretion  
Forcing parameters

\*Corresponding author. E-mail address: [ranadhir@nio.org](mailto:ranadhir@nio.org)

Phone: +91 8322450246

© 2015 – Journal of Coastal Sciences. All rights reserved

### 1. Introduction

Erosion and accretion processes are common phenomena across the shoreline that demarcates land and sea, and the rate of such change in shoreline is an indicator of coastal dynamics (NRC Report 1990). The Sundarbans, at the meeting place of two major Himalayan rivers Ganges and Brahmaputra with the Bay of Bengal, are dominated by the monsoon, tidal currents, and often battered by cyclonic winds, floods, storms and submergence (Fig. 1; Choudhury 1987; Goodbred and Kuel 2000; Ganguly et al. 2006; Gopal and Chauhan 2006; Kotal et al. 2009; Roy 2010). The river Ganges is represented by Hoogly, Padma, Muriganga, Saptamukhi, Thakuran, Matla and Gosaba and their tributaries, while Brahmaputra (also known as Meghna) is drained through several of her tributaries. While the vulnerability of the Sundarbans is yet to be studied comprehensively, scattered studies made earlier (Gopinath and Seralathan 2005; Jayappa et al. 2006; Datta 2010) have identified coastal geomorphology as an important variable to determine the coastal vulnerability.

This region is further exposed to extensive flooding and storm surge inundation (Woodroffe et al. 2006; Nicholls et al. 2007) and is considered as one of the most vulnerable deltaic ecosystem in the world. Rapid aggradation of sediment occurred from 11,000-7,000

years BP as the deltas are built seaward despite rapid rate of Post glacial sea level rise (Goodberd 2003).

The high rate of sediment supply results in rapid accretion in parts of Ganges estuary (Mikhailov and Dotsenko 2007). Comparing the 1792 Rennel Chart and 1840 survey reports of the Sundarbans coast, Admiralty Charts of 1904 and 1908 and a 1984 Landsat image show a net rate of accretion (Allison 1998). However other parts of the coast experienced erosion because of strong tidal current, vigorous wave action and other factors including the land-fall of tropical cyclone (Allison and Kepple 2001). Rapid subsidence, perhaps tectonic but accentuated by compaction and dewatering of sediments has been inferred for the Sundarbans coast (Hoque and Alam 1997).

In this background, the present study aims to understand intensity of coastal erosion in Sundarbans, changes in shoreline pattern at least over three decades and to identify the major forcing parameters affecting the Sundarbans ecosystem.

### 2. Study area

The Sundarbans delta spans approximately between longitude 88°E and 91.5°E and latitude 21°30N and 24°30N, and spreads over

the two neighboring countries, India and Bangladesh (Fig. 1). The entire Sundarbans delta formed by these two major rivers (Ganges and Brahmaputra) can be divided into four specific zones, from north to south- Inactive (Moribund) delta, mature delta, tidally active delta and Sub-aqueous delta (Fig.1). The Active part of the delta however occupies entirely by Bangladesh. However for the present study, sea facing fourteen southernmost islands from the tidally active delta of the Indian part of Sundarbans (ISD, 88°E to 89°E) has been selected (Fig. 1).

The islands are (from west to east): Nayachar, Lohachar, Ghoramara, Sagar, Jambudwip, Mousuni, Namkhana, Lothian, Surendranagar, Bulchery, Chulkati, Dhanchi, Dalhousie, and Bhangaduani. The islands are traversed by six major tributaries of mighty Ganga- Hoogly, Muriganga, Saptamukhi, Thakuran, Matla and Gosaba (from west to east) and numerous creeks. The studied 14 islands are a part of 5 to 14 km thick bird-foot type Bengal Basin deltaic and alluvial sediment deposited since the early Tertiary in Sundarbans and was formed by annual discharge of 1.06 billion tons of sediment by the Ganges-Brahmaputra River (GBR) system (Curry et al. 1982; Michels et al. 1998; Goodbred and Kuel 2000).

In fact, the Meghna-Brahmaputra-Ganga Basin has been one of the largest hydrological catchment areas in the world extending to about 1.75 million Km<sup>2</sup>. The catchment area of River Ganges has been 1.08 million Km<sup>2</sup>, and that of Brahmaputra, 0.577 million Km<sup>2</sup> and Meghna, 0.091 million Km<sup>2</sup> (Allison 1998). In addition, the suspended sediment (flux) discharge is estimated to be about 1.4 trillion tons (Milliman and Meade 1983).

About 21% of this sediment is estimated to have been used for construction of the delta front, while another 12.5% is sequestered in the upper forest area between 20 and 50 m water depth (Choudhury 1987; Allison 1998). The total area of Indian Sundarbans region is about 9630 Km<sup>2</sup>, out of which the Reserve Forest occupies nearly 4260 Km<sup>2</sup>. At present, out of 102 islands of the Sundarbans region, 54 are inhabited with a population of about 3.2 million (1991 census).

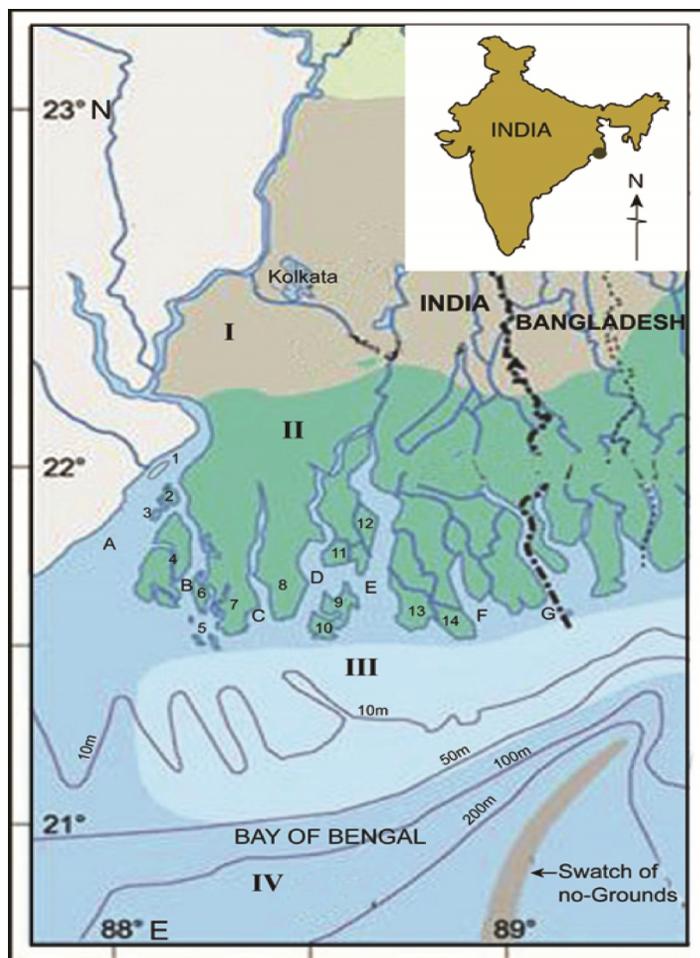
The region is spread over two administrative districts, namely South 24-Parganas (13 blocks) and North 24-Parganas (6 blocks). Out of the 102 islands in Sundarbans region, 48 islands in southernmost region are declared as Reserved Forest and are out of bounds for human settlement. The 3500 km long embankment protects the rest densely populated 54 islands from incursion of saline water during high tide. Though the deltaic inter-tidal region is very rich in biological resources, inhabitants of the area are very poor. Despite unfavourable physical environment, high salinity and crustal subsidence, the area can still generate high production of sustainable biological resources if properly managed (CSE Report 2012).

The reclaimed inter-tidal lands are single croplands for paddy and hence, people often have to depend on aquaculture, fishing, honey collection and wood cutting. As a result the native people here are much below the poverty level (CSE Report 2012). The only means of communication within the 4500 km<sup>2</sup> of inhabited areas is the less organized water ways.

There is accurate shortage of pucca/well maintained jetties. Due to obvious reason of inaccessibility, much of the inhabited areas are yet to avail of conventional electricity supply though there has been some perceptible breakthrough in the field of solar power supply to a few locations.

### 3. Methodology

In this study, the data and images of Sundarbans region from Landsat satellites were used and analyzed on a GIS platform to



**Fig. 1.** Digitized image of a part of Sundarbans deltaic region located at the tails of the rivers Ganges and Brahmaputra. The black north-south line of dash and dot represent political boundary between India and Bangladesh. I=Mature delta, II=Tidally active delta, III=Subaqueous delta, IV=Open sea. The rivers are designated as: A=Hooghly, B=Muriganga, C=Saptamukhi, D=Thakuran, E=Matla, F=Bhangaduani and G=Goasaba. The islands are: 1=Nayachar (*only accreting island in Sundarbans*), 2=Ghoramara, 3=Lohachar (*presently submerged*), 4=Sagar Island (*pilgrimage centre*), 5=Jambudwip, 6=Mousuni, 7=Namkhana (*tourism centre*), 8=Lothian, 9=Chulkati, 10=Bulchery, 11=Surendranagar, 12=Dhanchi, 13=Dalhousie, and 14=Bhangaduani. The islands 13, 14 and their northern areas encompass national park and sanctuaries. The areas coming under islands 8 to 12 and their northern extensions are covered by deep forest. Thin lines are bathymetry contours. "Swatch of no-ground" is a sharp, deep nearly north-south trending narrow gorge. Haldia Port is located on the western bank of river Hooghly.

determine shift in shoreline of the fourteen islands over a period of 32 years. The land area of these islands was measured from satellite images for the years 1979, 1989, 2001 and 2011 (Fig. 1). The details of the satellite imageries used in this study are given in Table 1. The archived LANDSAT images (when unavailable for chosen period of time) are ortho-rectified and geo-referenced. The USGS Global Visualization viewer provided the LANDSAT images for all the years. The details of the multi temporal imageries acquired are furnished for better appreciation. The Survey of India topographic sheets were geo-referenced using image processing software and used as base data. The desired time period for acquiring the satellite images is between October and March as it gives the right exposure of vegetation. The images obtained were all within this time frame.

Satellite/ Sensor	Date of Acquisition	Time	Spatial resolution	Path / Row
Landsat- 5 TM	15/11/2011	10:30 AM	30 m	149/45
IRS 1D LISS III	16/12/2001	10:30 AM	23 m	108/67
Landsat-7 ETM+	01/02/2001	10:45 AM	30 m	149/45
Landsat- 4 TM	19/01/1989	10:37 AM	30 m	149/45
Landsat-3 MSS	26/02/1979	10:38 AM	79 m	149/45

**Table 1.** Satellite data used for this study

For easy visual interpretation, the near-infrared (NIR), red and green bands were stacked to produce a standard False Color Composite image (FCC). Vegetation appears red due to high reflection in NIR by green leaves. A standard FCC was created from Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) data by stacking the bands 4, 3 and 2. A standard FCC was obtained from Multispectral Scanner (MSS) data by stacking the bands 7, 5 and 4 to help identify various different land features. Shapefiles were created for each of the 14 studied island and images were digitized on a 1:20,000 scale. Every land feature has a specific reflectance value that is captured by the satellite’s sensor. For example, vegetation appeared as shades of red, soil and sand as shades of white, while water appeared as shades of blue to black (Lillesand et al. 2008; Cornforth et al. 2013). Superimposition of digitized shorelines for all the four year’s images over FCC was made to demarcate the areas of erosion /accretion. The high tide lines were mapped using Survey of India topographic sheets as reference. The multi-temporal Landsat images were selected in such a way that all the images were of similar tidal conditions and tidal heights were almost same during image acquisition.

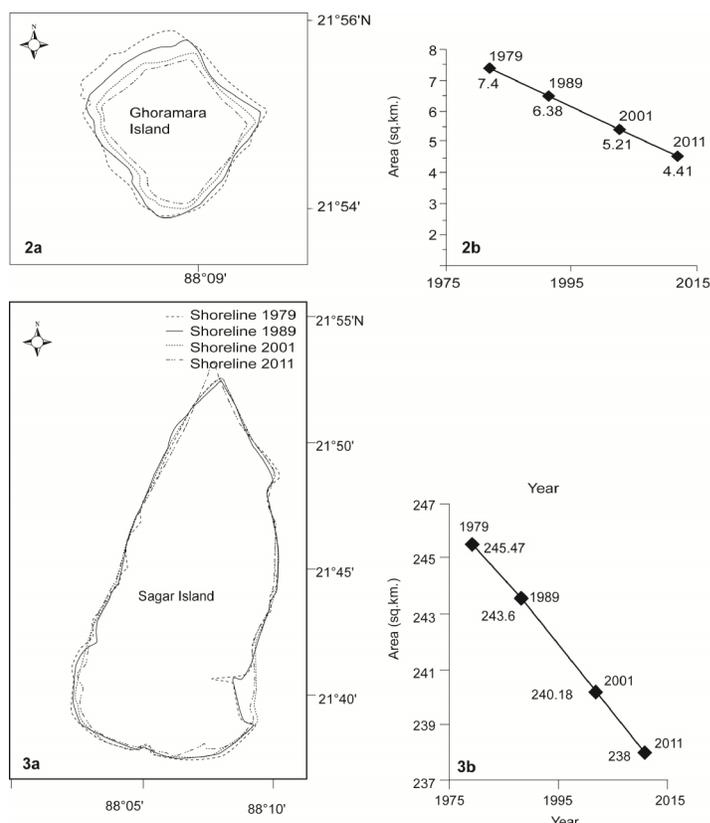
**4. Results and discussion**

The nature and trend in change of shoreline and an estimation of overall loss or gain of the land area of the fourteen southern islands of Sundarbans over a period of 32 years has been investigated and the results are placed below. In addition the pattern of shoreline change and the parameters that might have forced such changes are discussed.

**4.1. The Western Islands**

The variations in shoreline pattern of six western islands (Ghoramara, Sagar, Jambudwip, Mousuni, Namkhana and Lothian) during the last three decades are described here. The digitized temporal shoreline shift of Ghoramara Island (Fig. 2a) indicates maximum erosion on the north western and western banks, compared to southern banks. This was probably due to geographical positioning of Ghoramara Island, as it lies in a tide-shadow zone of Sagar Island and thus north-moving tidal currents from the sea during high tide could not impact vigorously the southern areas of Ghoramara (Fig. 1). In contrast the tidal flow of river Hoogly from the west could hit the north-western face of Ghoramara Island with full might causing extensive erosion. The island generally experiences stronger tides for shorter durations. In fact the total land area of the island has been reduced from 7.4 km<sup>2</sup> in 1979 to 4.41 km<sup>2</sup> in 2011, with a total shoreline length of 8.2 km (Table 2, Fig. 2b). Incidentally, two villages located on Ghoramara Island- Kashimara Char and

Lakshminarayanpur- has already been submerged. It is interesting to note that in spite of severe coastal erosion, the Ghoramara Island continues to maintain its rhombic shape. The Sagar Island is the largest island of the Indian Sundarbans and experienced extensive modifications in shoreline through erosive transgression (Purkrait, 2009; Fig. 3a) In fact, there has been a total loss of 7.37 km<sup>2</sup> during the last 32 years, as the area of 245.37 km<sup>2</sup> in 1979 was reduced to 238 km<sup>2</sup> in 2011 (Table 2, Fig. 3a, b).

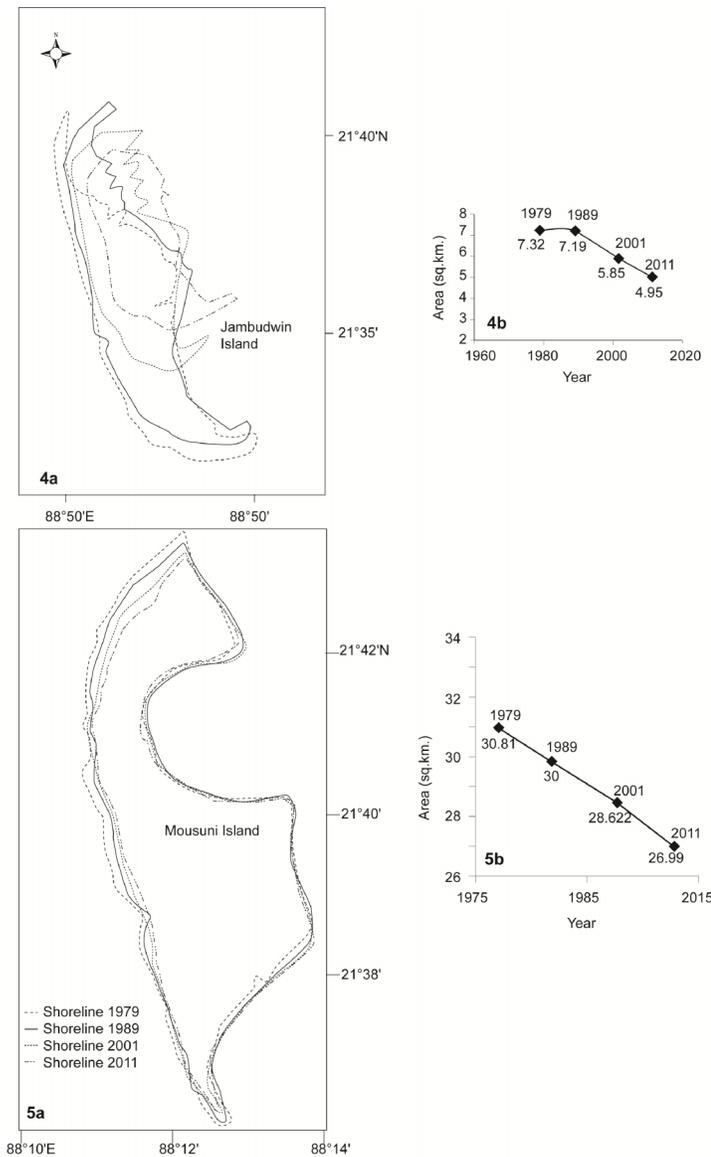


**Fig. 2 and Fig. 3.** Temporal changes in shoreline pattern and land loss of two western islands in Sundarbans: 2 a-b Ghoramara, 3 a-b Sagar

The southern and southwestern parts of the island recorded increased erosion, which has been evidenced by the northward shifting of the famous Kapil-Muni Temple by local authority several times in the past. The higher velocity of long shore currents (0.714 m/s) could be one of the factors responsible for increased erosion on the southern beaches of Sagar Island (Purkrait 2009). In a tide dominated island like Sundarbans, variations in tide height also alters erosion rates. During monsoon the average tide on the southwestern side of Sagar attains a height of 3.38 m and that on the southern side as 3.66m (Unnikrishnan and Shankar 2007; annual average 3.54m). Such variation also contributes to the erosion on the southern side. The satellite image showed some accretion on the northern most part of Sagar Island, in addition to its southeastern side (Fig. 3a). It is possible that the eroded material from the southern areas might have been transported by ocean currents for deposition in the tide-shadow areas in the northern part (Bhattacharya 2008).

The Jambudwip is an uninhabited island and is covered with dense mangrove forests and Casuarinas (Fig. 1). The ocean currents impact the western and southern banks of Jambudwip causing rapid erosion (Fig. 4a). In fact, the shoreline has drastically changed over

the past 32 years, as its western and southern banks are getting eroded rapidly (Fig. 4a). The Jambudwip has lost more than 32% of its area since 1979. The area is reduced presently to 4.95 km<sup>2</sup> (2011) from an area of 7.32 km<sup>2</sup> three decades ago (Table 2, Fig. 4b).

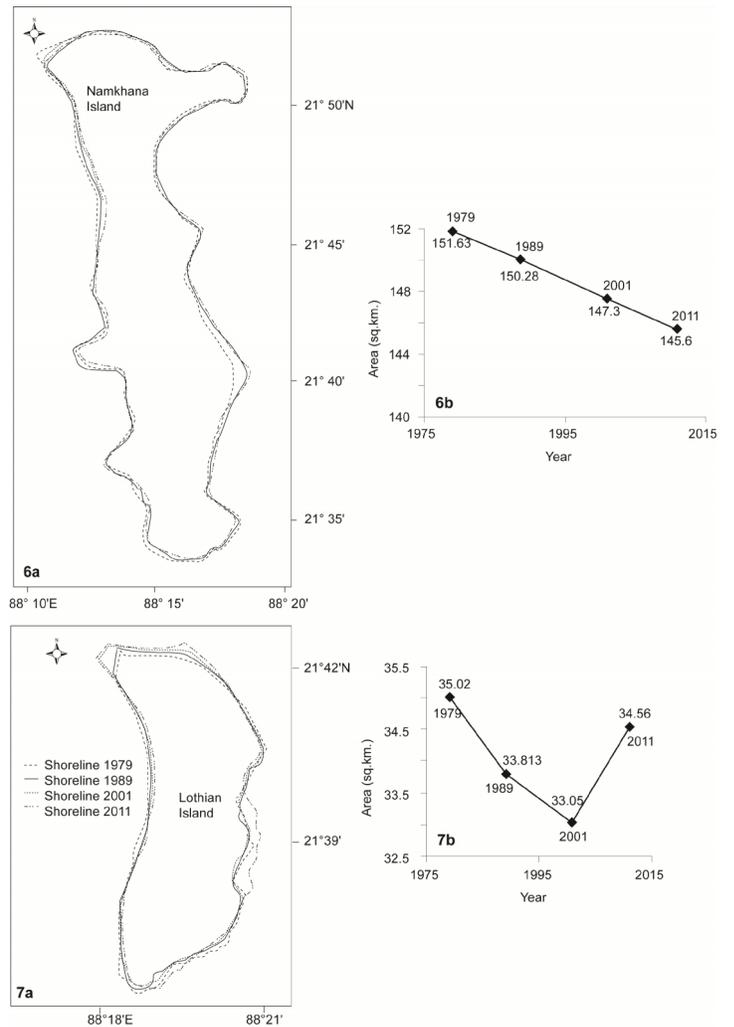


**Fig. 4 and Fig 5.** Temporal changes in shoreline pattern and land loss of two western islands in Sundarbans: 4 a-b Jambudwip, 5 a-b Mousuni

The Jambudwip appears moving slowly towards northeast due to tectonic movements (Purkrait 2009). This is coupled with depositional condition, as the eroded silt from the southern and western areas are carried away by the long-shore currents and got deposited on the north. However the rate of erosion is much larger than the rate of accretion here.

The Mousuni Island shows heavy erosion on the western and northwestern banks (Fig. 5a). Several embankments along this long bank were breached due to increased storm surges and tidal heights. The land area of this island has reduced from 30.81 km<sup>2</sup> in 1979 to 26.99 km<sup>2</sup> in 2011 (Table 2, Fig. 5b). In addition, the very high

density of population (813 persons/km<sup>2</sup>) in Mousuni Island seems to be impacting the environment adversely (Danda 2007). The Survey of India topo-sheets showed the presence of dense forest in the Kakramari area around the year 1968. Even, satellite imageries acquired in 1979 also indicated the presence of dense forest in this region. However the Kakramari region has now developed into a den of several aquaculture farms. Dilapidation of forest and degradation of Hental mangrove species can be the possible reasons for erosion in this area.



**Fig. 6 and Fig 7.** Temporal changes in shoreline pattern and land loss of two western islands in Sundarbans: 6 a-b Namkhana, and 7 a-b Lothian

Almost all the major tourist-frequented areas (e.g., Kakkdwip, Bakkhali, Frazerganj) located on the Namkhana Island (Fig. 1) show significant erosion (Fig. 6a). Bakkhali and Frazerganj are twin beaches with plantations like casuarinas and coconut lining all along. Beaches in Bakkhali area are of mud mixed sand, which makes the area unstable and more prone to erosion. The long shore current hits Frazerganj and Bakkhali tangentially and erodes the area. Photographic evidences reveal that the older dunes on Bakkhali beach are getting eroded and the older mudflats lying in inter tidal beaches are getting exposed indicating rapid erosion (GSI 2004). Not much erosion is however observed in the other areas on the western bank as they partially lie on the tide sheltered area of Mousuni Island. The

temporal shoreline shift of Namkhana Island shows area loss from 151.63 km<sup>2</sup> in 1979 to 145.6 km<sup>2</sup> in 2011 (Table 2, Fig. 6b).

The Lothian Island lies on the river Saptamukhi, and located approximately 20 km south of Namkhana Island (Fig. 1). This island has a National park, a mangrove botanical garden, and the Bhagavatpur crocodile breeding ground. Lothian is a well conserved island and houses a rich variety of flora and fauna. The crocodiles bred here are finally let out into their natural habitat. The highly scientific shrimp breeding project is being operated from this island. This well conserved island has been an ecological reference point of our study and recorded very little erosion over the last 32 years (Fig. 7a, b).

4.2. The Eastern Islands

The shoreline pattern of another six islands spread over eastern Sundarbans over the last little more than three decades is discussed below. The Surendranagar Island under Patharprotima Block is located southeast of Namkhana (Fig. 1). This almost lenticular shaped island faced rapid erosion along its southern boundary with the sea (Fig. 8a). The total land area of the island has been reduced from 47.3 km<sup>2</sup> in 1979 to a little more than 40 km<sup>2</sup> in 2011, ensuring a loss of almost 7 km<sup>2</sup> of land due to erosion (Table 2, Fig. 8b). It is observed that the south and southeastern banks of the island faced maximum burnt of erosion.

The Dhanchi Island is a mangrove reserve forest and located north of Surendranagar Island (Fig. 1). The island is conserved on all sides except the southern part. Almost 3 km<sup>2</sup> of land got eroded from the southern tip of this island (Fig. 9a). A small patch of accretion however could be seen in the north. The change in shoreline of Dhanchi Island and the areal loss of land in Dhanchi between 1979 and 2011 is estimated to be 3.12 km<sup>2</sup> (Fig. 9b, Table 2).

The Bulchery and Chulkati Islands lie under the reserve forest area of Indian Sundarbans, southeast of Surendranagar Island (Fig. 1). The Southern areas of both these islands are getting eroded at an alarming rate. Presence of long shore currents, tidal height, and storm surges are considered responsible for such erosion (Ganguly et al., 2006; Fig. 10a, 11a). There has been a steady decrease in land area in both these islands. Bulchery Island showed greater degree of erosion, reducing to 21.23 km<sup>2</sup> from about 30 km<sup>2</sup> in 1979 (loss of about 29%; Fig. 10b), whereas the Chulkati showed a relatively moderate erosion (13%, from 44 km<sup>2</sup> to 38.3 km<sup>2</sup> in 32 years; Table 2, Fig. 11b). The Dalhousie and Bhangaduani Islands are a part of Sundarbans National Park, a world heritage site declared by the UNESCO (Fig. 1). These islands are uninhabited and densely forested. Yet, the southern banks of these islands are getting eroded, with no signs of accretion on any other sides (Figs. 12a, 13a). The area of Dalhousie Island has been reduced from 76.51 km<sup>2</sup> in 1979 to 60.32 km<sup>2</sup> (loss of 21%; Fig. 12b) and that in Bhangaduani Island the land has been eroded from 40 km<sup>2</sup> in 1979 to 25 km<sup>2</sup> in 2011 (loss by 37%; Table 2, Fig. 13b).

4.3. Two Extreme Islands

Two islands, Lohachar and Nayachar have shown unique deviation in shoreline pattern from the other twelve islands discussed above. For example, the Lohachar Island, located northwest of Sagar Island, which was visible in satellite images of 1979 and 1991, has permanently sunk after 1995 (Fig. 1; 14a). It appears subsidence might have been responsible for this tiny island to submerge completely. Human interventions along with geomorphologic changes are also responsible for sinking of this island.

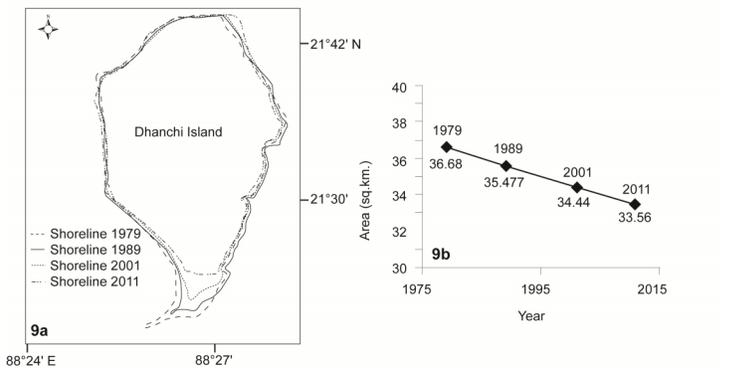
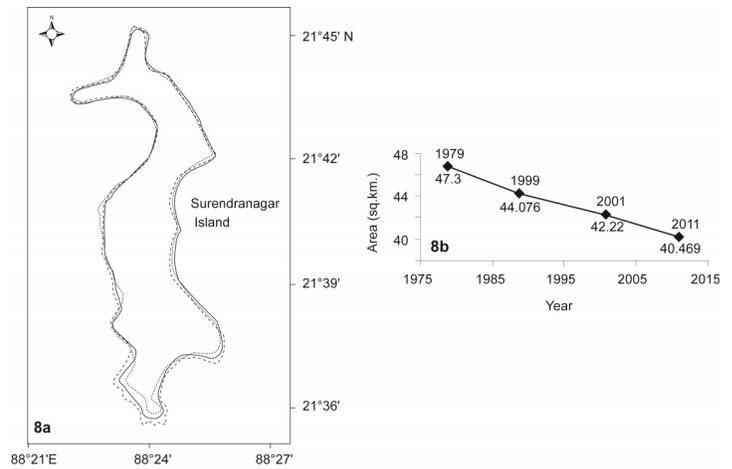


Fig. 8 and Fig 9. Temporal changes in shoreline pattern and land loss of two eastern islands in Sundarbans: 8 a-b Surendranagar, and 9 a-b Dhanchi

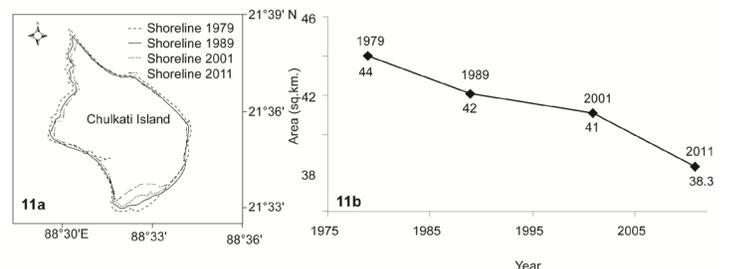
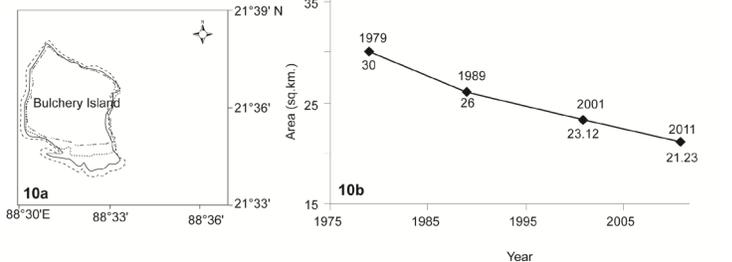
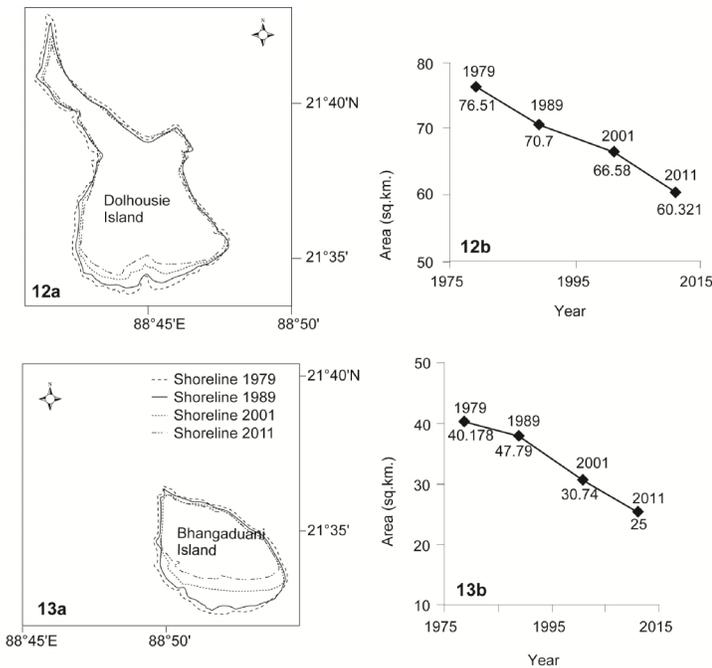


Fig. 10 and Fig 11. Temporal changes in shoreline pattern and land loss of two eastern islands in Sundarbans: 10 a-b Bulchery, and 11 a-b Chulkati

Lohachar Island was visibly present in the satellite images during the year 1979, which changed to a small eroding chunk in the image of 1989 (Fig. 14a). In fact the land area of this island reduced from 3.25 km<sup>2</sup> in 1979 to simply zero in 2001 (Table 2, Fig. 14b). However, recent studies revealed that Lohachar Island may have

started reappearing once again. The island seems to be even visible under very high resolution satellite imageries. Field studies showed appearance of this island during low tide, indicating a possible reactivation of the subsurface structure (Ghosh et al. 2003).

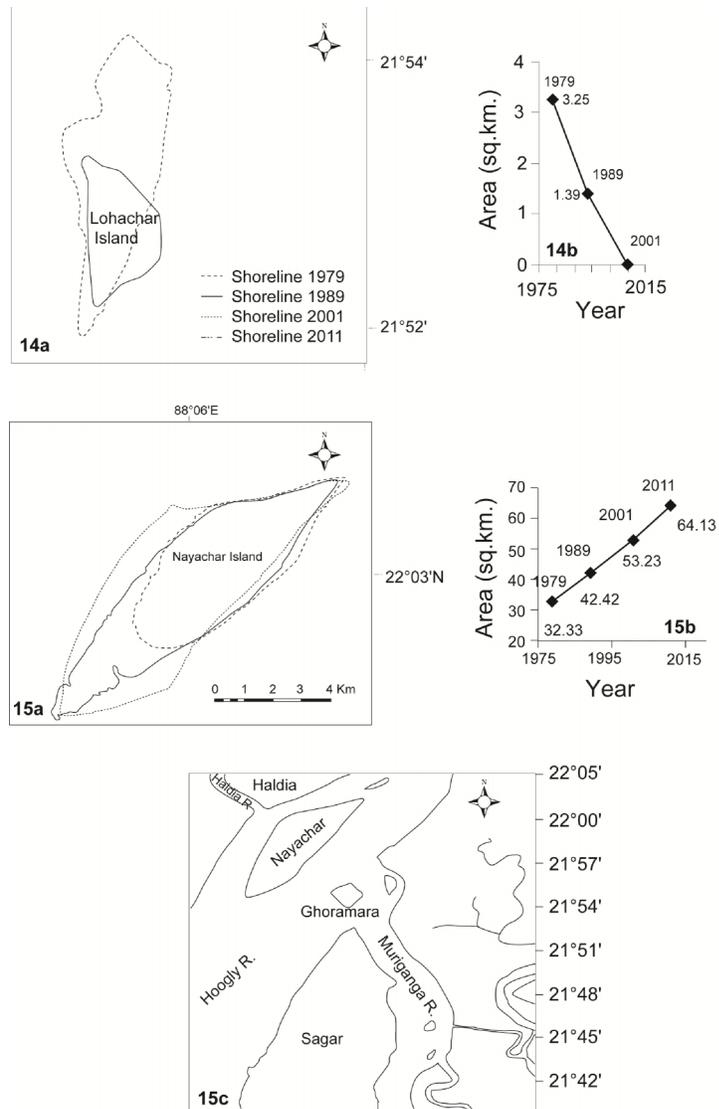


**Fig. 12 and Fig 13.** Temporal changes in shoreline pattern and land loss of two eastern islands in Sundarbans: 12 a-b Dalhousie, and 13 a-b Bhangaduani

Unlike most of the islands in Sundarbans, the Nayachar Island showed a continuous accretion pattern over the past 32 years (Fig. 15a). This island has grown in area from 32.33 km<sup>2</sup> in 1979 to 64.13 km<sup>2</sup> in 2011 (Table 2, Fig. 15b). Subsurface tilt of this area towards east, and less aggressive tidal impact might have played important role for Nayachar Island to grow (Fig. 15c, Ghosh et al. 2003). Satellite images showed emergence of another close-by island called Balari Bar in the river Hoogly.

**4.4. Pattern of Shoreline Modification**

The shorelines of Sundarbans islands have been under constant threat from erosion and environmental degradation. Ganguly et al. (2006) reported that the total area of Sundarbans has dwindled by about 57% within a period of last 200 years. Another earlier data set encompassing a period between 1840 and 1980 (span of 140 years) reported accretion of shoreline by about 2-5 km<sup>2</sup>/yr in eastern Sundarbans (parts under Bangladesh, BSD), while the western part (Indian Sundarbans, ISD, i.e. area west of latitude 89°E) recorded erosion by 1.9 km<sup>2</sup>/yr (Allison 1998; Jayappa et al. 2006). Few other studies suggest that the western part of the ISD has lost about 250 km<sup>2</sup> of land during the last 80 years (Bhattacharya 2008; CSE Report 2012). We found a variation in land loss even within the ISD. For example, it suggests that six western islands of ISD (after excluding Lohachar and Nayachar) have lost about 5.01% (equivalent to 23.73 km<sup>2</sup>) of the original land area during the last 32 years. In comparison, six eastern islands within the ISD lost 20.28% (equivalent to 53.85 km<sup>2</sup>) of the original land area since 1979 (Table 2). From the present study it is also quite discernible that over the past 32 years a total of 80.91 km<sup>2</sup> of land has been eroded from the thirteen southern islands of the ISD, as erosion played a dominant role in shaping these islands.



**Fig. 14 and Fig. 15.** Temporal changes in shoreline pattern of two unique islands: Completely submerged Lohachar (14 a-b) and Accreting Nayachar Island (15 a-b-c).

This is in sharp contrast to the Nayachar Island, where a land area of 31.81 km<sup>2</sup> has been added. We have categorized the islands based on the percentage of losing land area during the last three decades (Table 2), (a) Extreme loss (complete loss of the island), (b) Major loss (where land loss is > 30%), (c) Moderate loss (land loss between 10 and 30%), and (d) Minor loss (land loss < 10%). Under this categorization, Lohachar Island, which went submerged completely before 2001, falls under extreme loss category. The four other islands (e.g., Ghoramara, Bhangaduani, Bulchery and Jambudwip) fall under major loss of area category. The three islands (e.g., Dalhousie, Chulkati and Mousuni) with area loss between 10 and 30% are clubbed under Moderate loss category, while five islands (e.g., Dhanchi, Surendranagar, Namkhana, Sagar and Lothian) showed least loss of land (<10%). An interesting relation emerges between the geographical location of the island and their loss of land through erosion (Table 2).

Islands	1979	1989	2001	2011	Loss %	Land loss	Erosion direction	Accretion direction
<b>Extreme Loss</b>								
Lohachar	3.42	1.47	0	0	100	3.42	N, S	SE
<b>Major Area Loss</b>								
Ghoramara	7.40	6.38	5.21	4.41	40.40	2.99	NW,SW,NE,SE	
Bhangaduani	40.18	37.79	30.74	25.00	37.77	15.18	S	
Bulchery	32.20	26.30	23.12	21.20	34.16	11.00	S	
Jambudwip	7.34	7.14	5.85	4.95	32.56	2.39	S, W, N	E
<b>Moderate Area Loss</b>								
Dalhousie	76.51	70.70	66.58	60.32	21.16	16.19	S	
Chulkati	44.00	42.00	41.76	38.30	12.95	5.70	S	
Mousuni	30.81	30.00	28.62	26.90	12.60	3.91	NW, N, W	
<b>Minor Area Loss</b>								
Dhanchi	36.68	35.47	34.44	33.56	08.50	3.12	S	NNE
Surendranagar	36.02	35.57	34.41	33.36	07.38	2.66	S, SE, SW	W
Namkhana	151.63	150.2	147.30	145	04.37	6.63	NW, S, W	E
Sagar	242.07	237.82	238.92	234.72	03.03	7.35	S, SW	SE, N
Lothian	35.02	33.813	33.05	34.56	01.31	0.46	W	E, S, N
<b>Area Gained</b>								
Nayachar	32.33	42.2	53.23	64.14	Nearly double	31.81	SE	SW, W

**NB:** All figures in km<sup>2</sup>. Major loss >30% area, Moderate loss = 10-30%, Minor loss = < 10%. Total loss of Area in Six Western islands is 23.73 km<sup>2</sup> (5.01 % of the original land; avg. loss per island 15.71%) and in Six Eastern islands is 53.85 km<sup>2</sup> (20.28 % of the original land; avg. loss per island 20.32%).

**Table 2.** Gain and Loss of Land Area of the 14 Studied Islands in Sundarbans

The percentage of loss of land due to erosion in the six western islands (Mousuni, Ghoramara, Jambudwip, Namkhana, Lothian and Sagar) varies from mere 1.31 (Lothian) to 40.40 (Ghoramara) with an average loss per island of 15.71%. We deal with the other western island Lohachar separately as its complete submergence (100% loss) could corrupt and skew the land loss figures of the western islands. On the other hand, the six eastern islands (Bhangaduani, Bulchery, Dhanchi, Surendranagar, Dalhousie, and Chulkati) recorded a percentage loss of land varying from 7.38 (Surendranagar) to 37.77 (Bhangaduani), with an average land loss per island of 20.32%. The total land area lost by the six western islands (23.73 km<sup>2</sup> = 5.01% of the original land area, range 0.46 to 7.35 km<sup>2</sup>) is hence, much less than that of the eastern islands (53.85 km<sup>2</sup> = 20.28% of the original land area, range 2.66 to 16.19 km<sup>2</sup>, Table 2).

Interestingly, except Jambudwip and Lohachar, the western islands are largely impacted by anthropogenic activities, with major pilgrimage center in Sagar. Two major tourist centers- Bakkhali and Frazerganj- located at the southern end of the Namkhana Island might have contributed further to the erosion of soil made loose by human activities. In contrast the eastern islands of ISD, except for some parts of Surendranagar and Dhanchi, are largely inhabited; thickly mangrove forested and falls within the Reserve Forest area. Yet, we find large degree of land loss in the eastern islands, compared to the west. Again, the four relatively southernmost islands (i.e., Jambudwip, Namkhana, Bulchery and Bhangaduani) interestingly show a uniform pattern of erosion, with the southern parts of these islands being largely eroded. Overall in Sundarbans, the southern and western boundaries of almost all the islands are erosion prone and records maximum loss of land area. In contrast, accretion occurs, if any, along the northern and eastern boundaries of these islands.

Incidentally, there appears an inverse relation between size of the island and percentage of land loss. For example, the islands with originally more than 150 km<sup>2</sup> (e.g., Sagar and Namkhana) show only 3 to 4.5% of land loss. In contrast, smaller islands with original area

less than 25 km<sup>2</sup> (e.g., Lohachar, Jambudwip, Ghoramara) faced severe erosion and lost land to the tune of 32 to 100% (Table 2). The rest of the islands with original size between 25 and 150 km<sup>2</sup> record a moderate land-loss varying between 7 and 38%. The results appear to suggest that larger islands could withstand the impact of high tide surge and circulation of long-shore current (NRC Report 1990).

Increased tidal height and cyclonic activities in Sundarbans over the last few decades have damaged the topsoil, devastated the cattle and rendered people homeless to become environmental refugees (Gopal and Chauhan 2006; Kotal et al. 2009). These calamities forced inhabitants to move to another island and even change their livelihood. Change in shoreline and loss of land area contributes to the vulnerability of any island. Based on the analysis of data collected over a period of the last 32 years, it is possible to quantitatively determine vulnerability of the islands. For example, islands which have lost more than 30% of the land area could be considered as highly vulnerable, while those lost land area between 10 and 30% could be considered as moderately vulnerable. The islands with less than 10% loss of land are least vulnerable. The Lothian Island with only 1.31% of land loss in 32 years (i.e. mere 0.041% average loss per year) can be considered as most resilient and can act as Reference Island. Following this category, five of the 14 studied islands are found highly vulnerable, three are moderately vulnerable, and another four are least vulnerable (Table 2).

Among the islands studied, Nayachar located northwest of Sagar, has been the only island that registered accretion. In fact it has accreted by about 100%. The island experienced continuous enlargement over the past 32 years and had grown by more than 31 km<sup>2</sup> (Fig. 15 a, b, Table 2), almost doubling of its area. Among the reasons for this unique accretion pattern, the location of Nayachar Island on the river Hoogly appears to be important (Fig. 15c). The southerly flowing river Hooghly has a transverse slope towards the east due to which sediment are generally deposited on the western bank as observed from 2001 and 2011 satellite imageries (Ghosh et

al. 2003). It is also possible that the accreting pattern observed in Nayachar Island can be additionally attributed to a protecting wall constructed by Kolkata Port Trust in 1995. This wall was constructed to divert the main flow of River Hoogly towards the western channel from the main eastern channel. Moreover, the field data suggest that the tidal force is aggressive on the eastern channel of Hoogly River, leaving the western channel relatively less impacted (Choudhury 1987; Ganguly et al. 2006). The satellite images derived from IRS 1D LISS III showed emergence of another island called Balari-Bar in the river Hoogly, which clearly indicates the depositional regime in the western channel of the Hoogly River.

4.5. Possible Forcing Parameters

In fact, the Bay of Bengal happens to be one of the most active cyclonic regions of the world, causing extensive erosion especially of the sea facing islands of Sundarbans (Allison 1998; Danda 2007). In fact, the Sundarbans ecosystem is plagued by three major problems such as shoreline modification, sea level rise, and demographic migration. Hence it would be ideal to discuss these problems in the fourteen studied islands vis-à-vis the forcing parameters. Earlier studies (Datta 2010; Roy 2010) had identified a total of number of 75 atmospheric, oceanographic, terrestrial and anthropogenic parameters which are likely to affect any coastal region. A closer analysis of the parameters over the last few decades, however, made us to shortlist the 16 most important and significant parameters that have had short and long-term impact on the coastal environment in Sundarbans (Table 3). The parameters are; Atmospheric (wind speed, wind direction, cyclones & storms, rainfall), Oceanographic (sea surface & water column temperature, salinity, waves, currents, tides, tsunami), Terrestrial (river discharge; sediment & water, geomorphology, earthquake, local neo-tectonics, shelf-slope dynamics), and Anthropogenic pressures (fast-growing tourism sector, mangrove deforestation, infrastructure development, enhancing aquaculture practice, growing population, increasing fishing, wood & honey collection, and unabated soil and water pollution). These forcing parameters also affect biogeochemistry (TOC, DO, nitrate, nitrite, oxygen minimum zone, etc.), and are responsible for modifying coastal landscape, such as, seabed stability, turbidity, shoreline modification (erosion/accretion), sea level rise, wetland formation, humidity & mangrove conservation, coastal economy and demographic characteristics.

Atmospheric	Oceanographic	Terrestrial
01 Wind Speed	05 Sea Surface Temperature	11 River Input
02 Wind Direction	06 Salinity	12 Seabed Stability (Slumping / Subsidence / Seismicity)
03 Extreme Events	07 Waves	13 Floods
04 Rainfall	08 Currents	14 Hydrography
	09 Tides	15 Mangrove Conservation
	10 Tsunami	16 Socio-economic Pressures

Table 3. Major Forcing parameters impacting Sundarbans ecosystem

For example, data show that during the monsoon period (May-September), the wind coming from southwest direction could attain a velocity reaching at times to 143 kmph (mean 31 kmph) in Sagar and others islands (Varkey et al. 1996; Sengupta 2001). In addition, cyclone and storms with speed ranging between 80 and 120 kmph or

beyond are important atmospheric parameters to cause rapid and large-scale erosion (Michels et al. 1998). In fact, between 1961 and 2000, as many as 31 severe cyclones occurred in the Sundarbans, of which at least in 5 cases the speed reached over 200 km/hour. It seems occurrence of cyclones in Sundarbans has increased by about 26% during last 120 years (CSE 2012). Moreover, the Sundarbans is a tide dominated delta system, where range in tide heights reaches to 5.3 meter, and transports far inland. The diurnal tidal range at spring tide is about 4 m, which increases at the mouth of the estuaries to more than 5 m because of the upsurge. The tidal range is further complicated by the frequent occurrence of the low air pressure in the eye of any impending cyclone (Michels et al. 1998; Mitra et al. 2010). Quantitatively, a significant variation in sea surface temperature is reported as temperature rose by 6.14% in the western part and by 6.12% in the eastern part of Indian Sundarbans over the past 27 years, at a rate of approximately 0.05°C/year (Fig. 16 a, b, Sengupta 2001; Mitra et al. 2010). Again over the last thirty years, the western part of Sundarbans shows a significant and continuous decrease in salinity (1.67 psu/decade, practical salinity unit), whereas the eastern part shows an increase in salt (~6 psu). This difference caused retardation in seed germination and impedes growth of mangroves in the eastern part (mangroves are only salt tolerant and not salt lovers) resulting in increased erosion of land of the eastern islands of ISD (Chowdhury 1987; Mirza 1998; Sarkar et al. 2002; Mukhopadhyay et al. 2006; Fig. 16).

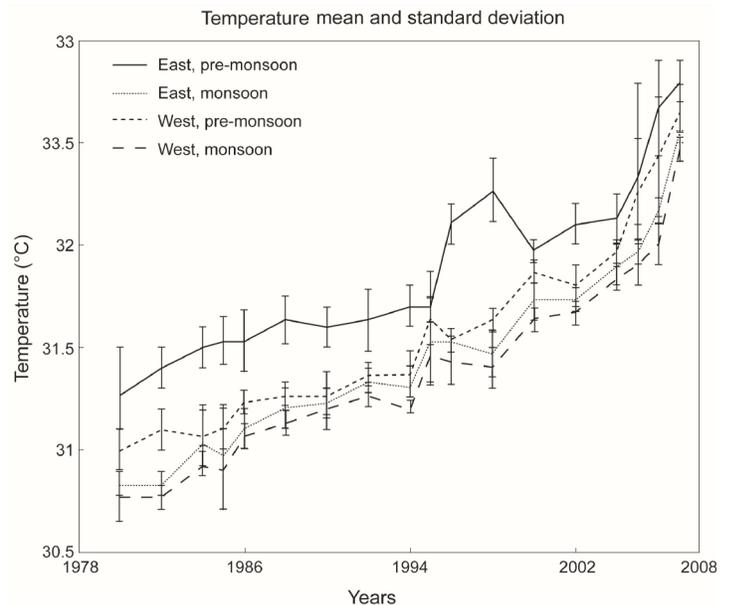


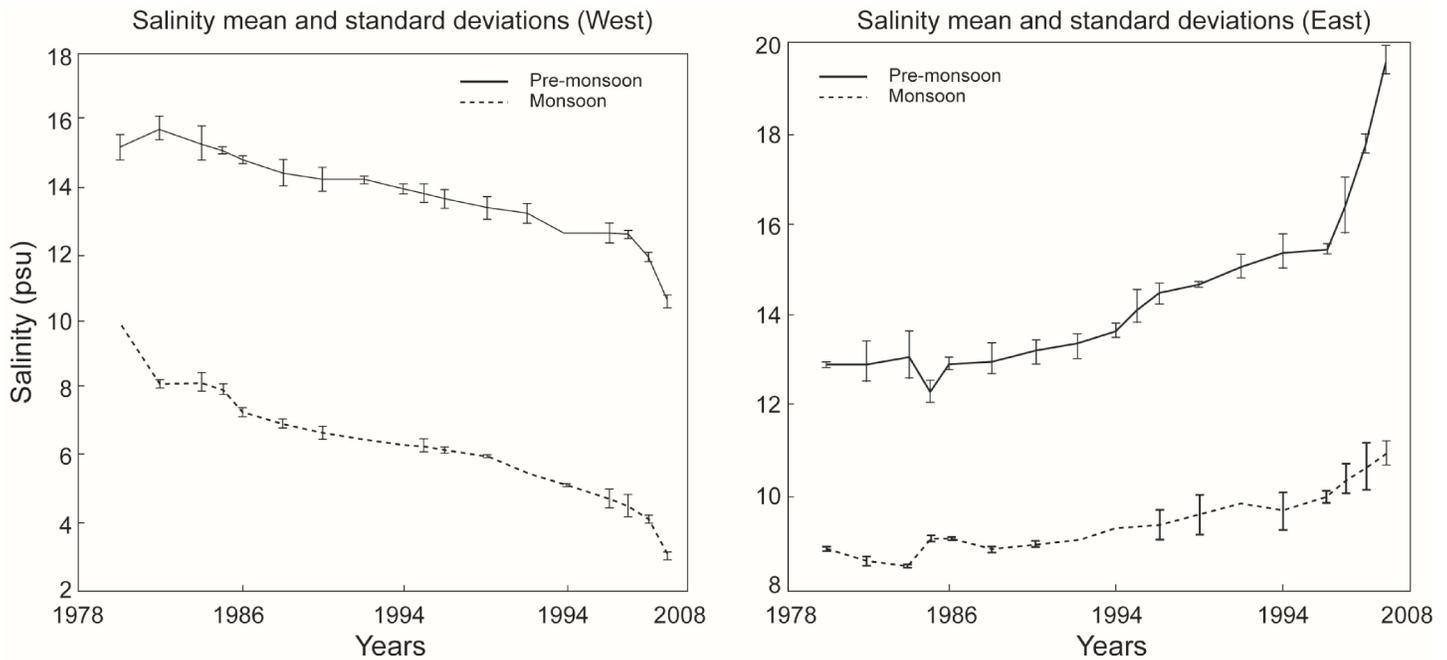
Fig. 16. (a) Observed warming trend of Sea Surface Temperature SST (in °C) in western and eastern ISD during pre-monsoon and monsoon (after Mitra et al. 2010)

Most of the islands studied were formed and grew during Late Holocene (Allison 1998). It seems the oldest group of islands was formed in active delta region far upstream of the estuary almost 6000 years ago by the river Brahmaputra and Meghna. In contrast, deltaic plains formed by the river Ganges within the ISD were formed much later (between 5000 and 200 years, and older towards west; Allison 1998). The studied 14 islands of Sundarbans delta region also fall under the highly active zone IV in the seismic map of India (GSI 2004), where episodic neo-tectonic movements with latest at about 900 and 200 years ago resulted in an easterly tilt of the Bengal Basin (Curry et al. 1982; Mirza 1998). Later studies suggested that most

part of the Bengal Basin is undergoing subsidence, with the lower deltaic areas subsiding more rapidly as they are located on active troughs, like Faridpur, Shylet and Hatiya Troughs. The subsidence has been caused thus by tectonic and isostatic adjustment of the crust, with some contribution may have come from compaction of peat deposits and overpressure (Hoque and Alam 2009; Roy 2010). In contrast to norther reaches of Sundarbans (near Kolkata and Dhaka city), there is no evidence to suggest that the abstraction of ground water is playing a role in subsidence in southern reaches of Sundarbans.

### 5. Conclusions

The change in shoreline pattern and nature of coastal erosion since 1979 in fourteen selected islands from the world's largest deltaic ecosystem in the Indian part of Sundarbans (ISD) was analyzed. The study was based on single band image using the processed NIR bands of the LANDSAT-TM and IRS 1D LISS III satellite images. Almost all the islands, except Nayachar, are facing threat from erosion, sea level rise, subsidence, and have lost a total land area of more than 80 km<sup>2</sup> during the last 32 years (eastern islands are eroding rapidly than the western islands).



**Fig. 16. (b)** Salinity decreased during the last 30 years on the western (left) sector whereas it increased on the eastern (right) sector of the ISD. Trends are similar in both pre-monsoon and monsoonal periods. The left panel shows the increasing freshening in the western station due to ice melt-water, whereas the right panel shows the increasing salinity towards east (after Mitra et al. 2010).

The local sea level rise in Sagar Island in Sundarbans and nearby Diamond Harbour have reported to be 5.22 mm/year and 3.14 mm/year, respectively (Unnikrishnan and Shankar 2007). Both these values are much higher than the Indian national average rise in sea level of 1.88 mm/year. Such anomalous rise in sea level in Sundarbans may have probably caused by subsidence, coupled with tilting and isostatic sinking of the delta (Curray et al. 1982; GSI 2004; Ganguly et al. 2006; Bhattacharya 2008), together with large scale winds and low elevation of the coast (NRC Report 1990; Kotal et al. 2009).

The erosion, subsidence and sedimentation, along with subsequent churning of sediment due to tidal surge and apparent rise in sea level could increase the concentration of suspended solids, and consequently reduce the transparency in water column. The increasing turbidity has the potential to destabilize photic zone affecting the growth and survival of phytoplankton, the small microscopic plants in the oceans that produce three-fourths of the earth's oxygen supply. Damage to this community would adversely affect the food chain in this mangrove-dominated deltaic complex, which also acts as nursery and breeding ground of aquatic lives (Choudhury 1987; IPCC 2007).

The larger islands appear to withstand the impact of high tidal surge and effect of long-shore current. The southern and western stretches of the coasts of all the islands are largely eroded compared to their northern and eastern banks. From vulnerability aspect five islands are found highly vulnerable, three are moderately vulnerable, and four are least vulnerable. While Lohachar is completely submerged, Nayachar Island has been the only island that registered accretion by about 100%. The transverse slope of River Hoogly towards the east, construction of a protecting wall, and visit of less aggressive tidal force might have contributed to the accretion in Nayachar.

The study further suggests that a series of natural and human activities have contributed in the process responsible to modify the shorelines of the islands. Among the natural forcing parameters, the long shore current pattern, abnormal tide heights, unusual rise in sea level (3.14 to 5.22 mm), and sub-surface geomorphology (tilting towards east and localized subsidence) appear to be responsible to cause variable pattern of shoreline erosion in different islands in ISD. In addition several anthropogenic activities, such as, deforestation of mangrove vegetation, loss in cultivable land, and infrastructure development to cater to major pilgrimage centre in Sagar island and tourism centre in Namkhana have multiplied erosion of islands.

Although the shoreline variations may have been aggravated by change in the land use practice by human being at some places, the majority of the variations are mainly caused by natural forcing like erosion-accretion, cyclone, storm surge, subsidence and flooding.

## Acknowledgements

A part of this work was carried out while NC was in CSIR-National Institute of Oceanography, Goa on a dissertation project from VIT, Vellore. We thank two anonymous reviewers for their critical reviews. This is NIO contribution 7542/100214.

## References

- Allison, M. A., 1998. Geologic framework and environmental status of the Ganges Brahmaputra delta. *Journal Coastal Research* 14, 826-836.
- Allison, M.A., Kepple, E.B., 2001. Modern sediment supply to the lower delta plain of the Ganges-Brahmaputra River in Bangladesh. *Geo-Marine Letters* 21, 66-74.
- Bhattacharya, A. K., 2008. The morphodynamic setting and substrate behavior of the Sundarbans mangrove wetland of India. *Sarovar Saurabh* 4, 2-9.
- Centre for Science and Environment, 2012. Report on development deficit to worsen effect of Climate change in Sundarbans, 57pp,
- Chowdhury, A., 1987. Mangrove ecosystem of Sundarbans, A long term multidisciplinary research approach and Report. Department of Science & Technology, Govt of India, Dept of Marine Science, Univ. of Calcutta, 139pp.
- Cornforth, W.A., Fatoyinbo, T.E., Fremantle, T.P., Pettorelli, N., 2013. Advanced land observing satellite phased array type L-Band SAR (*ALOS PALSAR*) to inform the conservation of Mangroves: Sundarbans as a case study. *Remote Sensing* 5, 224-237.
- Curry, J.R., Emmel, F.J., Moore, D.G., Russel, W.R., 1982. Structure, tectonics and geological history of the Northwestern Indian Ocean. In: Nairn, A.E.M., Stehli, F.G. (Eds), *The Indian Ocean (The Ocean Basins and Margins- 6)*. Plenum, New York, pp 339-450.
- Danda, A., 2007. Surviving in the Sundarbans: Threats and Responses. PhD Thesis, University of Twente, The Netherlands. Unpublished.
- Datta, D., 2010. Development of a Comprehensive Environmental Vulnerability Index for Evaluation of the Status of Eco Development Committees in the Sundarbans, India. *International Journal of South Asian Studies* 3, 258-271.
- Ganguly, D., Mukhopadhyay, A., Pandey, R.K., Mitra, D., 2006. Geomorphological study of Sundarbans deltaic estuary. *Indian Society of Remote Sensing* 34, 431-435.
- Geological Survey of India Report, 2004. Plate tectonics, Earthquake and Tsunami in Sundarbans Delta Complex. <http://www.portal.gsi.gov.in/>
- Ghosh, T., Bhandari, G., Hazra, S., 2003. Application of a bio-engineering technique to protect Ghoramara Island (Bay of Bengal) from severe erosion. *Journal Coastal Conservation* 9, 171-178.
- Goodbred, S.L., 2003. Response of the Ganges dispersal system to climate change: a source-to sink view since the last interstade. *Sedimentary Geology* 162, 83-104.
- Goodbred, S.L., Kuel, S.A., 2000. The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta. *Sedimentary Geology* 133, 227-248.
- Gopal, B., Chauhan, M., 2006. Biodiversity and its conservation in the Sundarbans Mangrove Ecosystem. *Aquatic Science* 68, 338-354.
- Gopinath, G., Seralathan, P., 2005. Rapid erosion of the coast of Sagar Island, West Bengal – India. *Environmental Geology* 48, 1058-1067.
- Hoque, M., Alam, M., 1997. Subsidence in the lower deltaic areas of Bangladesh. *Marine Geodesy* 20, 105-120.
- Intergovernmental Panel on Climate Change-IPCC, 2007. Summary for policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H. L., (Eds). *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of IPCC*. Cambridge University Press, Cambridge, UK, and New York, NY, 18pp.
- Jayappa, K.S., Mitra, D., Mishra, A.K., 2006. Coastal geomorphological and land-use and land-cover study of Sagar Island, Bay of Bengal (India) using remotely sensed data. *International Journal of Remote Sensing* 27, 3671-3682.
- Kotal, S.D., Kundu, P.K., Roy Bhowmik, S.K., 2009. An analysis of sea surface temperature and maximum potential intensity of tropical cyclones over the Bay of Bengal between 1981 and 2000. *Meteorological Application* 16, 169-180.
- Lillesand, T.M., Kiefer, R.W., Chipman, J.W., 2008. *Remote Sensing and Image interpretation*. John Wiley & Sons, 6<sup>th</sup> edition, 756p.
- Michels, K.H., Kudrass, H.R., Hübscher, C., Suckow, A., Wiedicke, M., 1998. The submarine delta of the Ganges-Brahmaputra: Cyclone-dominated sedimentation patterns. *Marine Geology* 149, 133-154.
- Mikhailov, V.N., Dotsenko, M.A., 2007. Processes of delta formation in the mouth area of the Ganges and Brahmaputra Rivers. *Water Resources* 34, 385-400.
- Milliman, J.D., Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. *Journal of Geology* 91, 1-21.
- Mirza, M.M.Q., 1998. Diversion of Ganges water at Farakka and its effect on the salinity of Bangladesh. *Journal Environmental Management* 22, 711-722.
- Mitra, A., Chowdhury, R., Sengupta, K., Banerjee, K., 2010. Impact of Salinity on Mangrove of Indian Sundarbans. *Journal Coastal Environment* 1, 71-82
- Mukhopadhyay, S.K., Biswas, H., De, T.K., Jana, T.K., 2006. Fluxes of nutrients from the tropical River Hooghly at the land-ocean boundary of Sundarbans, NE Coast of Bay of Bengal. *Indian Journal of Marine Science* 62, 9-21.
- National Research Council, 1990. *Managing Coastal Erosion*. Washington: National Academy Press, 163p.
- Nicholls RJ, Wong PP, Burkett VR, Codignotto JO, Hay JE, McLean RF, Ragoonaden S, Woodroffe CD (2007) Coastal systems and low-lying areas. In Parry ML, Canziani OF, Palutikof JP, Linden PJvd, Hanson CE. *Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 315-356
- Purkait, B., 2009. Coastal erosion in response to wave dynamics operative in Sagar Island, Sundarbans delta, India. *Frontier Earth Science China* 3, 21-33.
- Roy, A., 2010. Vulnerability of the Sundarbans ecosystem. *Journal Coastal Environment* 1, 169-181.
- Sarkar, S.K., Bhattacharya, B., Debnath, S., Bandopadhyay, G., Giri, S., 2002. Heavy metals in biota from Sundarbans Wetland Ecosystem, India: Implications to monitoring and environmental assessment. *Aquatic Ecosystem Health Management* 5, 467-472.
- Sengupta, D., 2001. Oscillations of Bay of Bengal sea surface temperature during the 1998 summer monsoon. *Geophysical Research Letters* 28, 2033-2036.
- Unnikrishnan, A.S., Shankar, D., 2007. Are sea level rise trends along the coasts of the north Indian Ocean consistent with global estimates? *Global Planetary Change* 57, 301-307.

- Varkey, M.J., Murty, V.S.N., Suryanarayana, A., 1996 Physical oceanography of the Bay of Bengal and Andaman Sea. *Oceanography Marine Biology Annual Review* 34, 1-70.
- Woodroffe, C.D., Nicholls, R.J., Saito, Y., Chen, Z., Goodbred, S.L., 2006. Landscape Variability and the Response of Asian Mega deltas to Environmental Change: The Asia-Pacific Region. In: Harvey N., (Ed) *Global Change and Integrated Coastal Management*, Springer, The Netherlands pp. 277-314.