Long-term Island Area Alterations in the Indian and Bangladeshi Sundarban: An Assessment Using Cartographic and Remote Sensing Sources

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December 2018

Funding for this research has been provided by the South Asia Water Initiative administered by the World Bank.

The findings, interpretations, and conclusions expressed in this paper are entirely those of the authors. They do not necessarily represent the views of the International Bank for Reconstruction and Development/World Bank and its affiliated organizations or those of the Executive Directors of the World Bank or the governments they represent.
Abstract

The seaboard areas of the western Ganga–Brahmaputra delta (GBD) harbours the largest unfragmented mangrove forest of the world, the Sundarban. The region is shared by India and Bangladesh. Cartographic and remote sensing materials of 1904–24 (Survey of India toposheets), 1967 (Corona images), 2000–02 (IRS-1D LISS-3+Pan fused scenes), and 2015–16 (Resourcesat-2 LISS-4 fmx scenes) are digitally evaluated for this area (12,164 km²) for bringing out area transformations of ~250 forested and reclaimed islands. To facilitate analysis, the islands are sorted into three groups based of their distance from the northern and southern edges of the study region. The outcome show that while its interior channels, mainly in the west, are getting clogged, the bay-proximal islands are decreasing in area at a fast pace. Total island area and island count values detected by the study are: 12,618 km² and 254 (1904–24), 12,371 km² and 250 (1967), 12,227 km² and 243 (2000–02), 12,164 km² and 250 (2015–16). The rate of area reduction kept a near-constant value of ~4.45 km²/yr all through this interval and is reflected both in the India- and Bangladesh-administered portions of the Sundarban. The loss of the bay-facing islands of the region can mainly be attributed to non-availability of fluvial and marine sediments due to degeneration of deltaic distributaries and shelf bypassing through a submarine canyon. The reason for land gain in the northern Sundarban can be related to flood tide dominance due to loss of morphological equilibria in the reclaimed estuaries. It is difficult to link the effects of relative sea level rise and vertical accretion of island surfaces to the alterations in island sizes due to conflicting and overlapping signals. The detected trends of area change are likely to continue in the foreseeable future; therefore, they need to be integrated into planning for the region.
Introduction
Contributed by a combined catchment area of $1.6 \times 10^6 \text{ km}^2$, the Ganga–Brahmaputra delta (GBD) of the northern Bay of Bengal is the world’s largest in terms of land area (about 120,000 km$^2$) as well as yearly release of sediments into the sea (about one billion tons per annum). The Ganga–Padma–Lower Meghna river diagonally divides the GBD into two parts. The southwestern portion, along with the southern coastline of the delta between the Hugli and the Baleswar estuaries, is primarily contributed by the distributaries of the Ganga system—active or dissipated. Its 200-km littoral stretch constitutes about 47% of the GBD coastline and harbours the largest unfragmented mangrove forest of the world—the Sundarban. Delta-building bio-tidal processes, at the southern frontier of the GBD, was responsible for phased accretion of all sea-front islands of the Sundarban c. 5–2 kyr before present (Allison et al, 2003), from what probably was a number of disconnected incipient subtidal and intertidal shoals to its present configuration. The region is shared by India and Bangladesh, with its international border running through the rivers of Ichhamati, Kalindi, Raimangal, and Harinbhanga (Fig. 1).

The Sundarban is exposed to a unique set of natural environmental hazards – storm inundation, saline intrusion, sea level rise, coastal erosion, and channel sedimentation – that are set to aggravate in a warming world. Among these, the problems of erosion of the tidal islands and sedimentation of their intervening creeks did not receive the attention they deserve. In this context, the present work attempts to document the long-term island area changes through coastline shifts that took place in this region since the early 19th century using maps and images.

Sundarban: Reclamation and present status
Although the frontiers of the Sundarban mangroves started to move southward for expansion of rice farms from the 13th century (Eaton, 1990), forests still occupied some 16,500 km$^2$ of tidal seaface of the GBD between the Hugli and the Meghna estuaries about 240 years ago (Rennell, 1779). Rennell reflected in 1781 that ‘this tract ... is so completely enveloped in woods, and infested with tygers [sic], that if any attempts have ever been made to clear it (as is reported) they have hitherto miscarried’. He noted that ‘sand and mud banks ... extend twenty miles off some of the islands’ of the delta and imagined that ‘some future generation will probably see these banks rise above water, and succeeding ones possess and cultivate them!’ (Rennell, 1788:259, 266).

Under the British colonial government, reclamation of the Sundarban was initiated in 1770. It transformed into an institutionalised effort from 1783 (Pargiter, 1934) manifesting administrative policies that viewed the wetlands mostly as wastelands (Richard and Flint, 1990). By 1831, reclaimable portion of the region between the Hugli and the Pussur was divided into 236 compartments or ‘lots’ south of the Dampier–Hodges (D–H) Line, surveyed in 1829-30 to demarcate the contemporary frontier of the wetlands (Pargiter, 1934). The scheme was later extended up to the Baleswar by adding 22 more lots. This formed the basis of all subsequent reclamation efforts (Ascoli, 1921). At that time, the area of Sundarban forests was 11,610 km$^2$. 
Among the three original districts constituting Sundarban, reclamation of the eastern Bakarganj was nearly complete by 1910 (Jack, 1918). Situated between the Baleswar and the Meghna, the deltaic distributaries of this part had lower tidal range than the west and received freshwater from upcountry sources. This helped to reduced salinity and replenishment of fertile sediments that sustained agriculture. In contrast, reclamation went on up to the start of this century in the western 24 Parganas somewhat sporadically. Occupying the abandoned GBD between the Hugli and the Raimangal, here the salinity as well as the tidal range were higher than the east, requiring higher embankments to arrest tidal spill. Between these two regions, the wetlands of Khulna, bounded by the Raimangal and the Baleswar, mostly remained intact.

F.E. Pargiter detailed the procedure of reclamation of Sundarban in The Calcutta Review of July, 1889. The first task was to embank the low-lying forested islands. This meant that a line was drawn through the forest along the banks of the streams surrounding the area to be reclaimed and an earthen embankment was constructed along the line to prevent tidal inundation. Strong dams were constructed across the mouth of small streams in order to keep salt water out. This work was followed by felling of the forests, digging of tanks, and construction of huts; systematic cultivation could then begin. Apart from depriving the embanked area from sediment accretion, the process exposed the settlers of the reclaimed Sundarban a number of natural hazards enlisted earlier. In Bangladesh, extensive forest-front areas are now protected large-scale polder dykes since 1960s (Bari Talukdar, 1993). In India, the marginal bunds have only recently been started to be reinforced.

Previous works

Among the works that studied coastline shifts of the Sundarban region from comparative cartographic / remote sensing materials or field studies, notable are: Chakrabarti (1995), Bandyopadhyay and Bandyopadhyay (1996), Bandyopadhyay (1997), Allison (1998), Hazra et al. (2002), Bandyopadhyay et al. (2004), Ganguly et al. (2006), Rahman et al. (2011), Rahman (2012), Sarwar and Woodroffe (2013), Raha et al. (2014), Chakrabarti and Nag (2015), Ghosh et al. (2015), Quader et al. (2017), and Ahmed et al. (2018). Although these works detected a prevailing eroding trend of the delta front, none of these, however, estimated alterations in
island-wise data of the area of the interiors of Sundarban. These studies mostly remained confined either to Indian or to Bangladeshi, close to the southern coast of the GBD. The present research fills-up this gap in information.

**Methodology**

*Maps and satellite data*

Finding out the century-scale rates of area change of the islands constituting the Sundarban is the chief aim of this work. To achieve this, four datasets with resolution of ~5 m or finer are selected. These are as follows.

- Survey of India (SoI) 1:63,360 toposheets of 1904–24 (38 maps),
- Corona KH4A space photographs of 1967 (9 images),
- IRS-1D LISS-3+Pan merged False Colour Composite (FCC) of 2000–02 (15 images), and
- Resourcesat-2 LISS-4 fmx FCC of 2015-16 (11 images).

To facilitate orthorectification, a couple of additional mosaics were prepared:
- A map of 16 SoI 1:50,000 toposheets,
- A FCC of four Landsat-8 OLI pan merged scenes.

Table 1 states the details of the above six datasets.

<table>
<thead>
<tr>
<th>Map / Image 1</th>
<th>Scale / Resolution</th>
<th>Year of Survey / data Acquisition [central-value within brackets]</th>
<th>Interval from Preceding database</th>
<th>Area covered by each map / satellite scene</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>38 SoI Topographic Sheets</strong>: Zone 79B, C, F, G, J</td>
<td>1:63,630 (1 inch = 1 mile)</td>
<td>1904–24 [1914]</td>
<td>—</td>
<td>15’ × 15’: 26 km × 28 km</td>
</tr>
<tr>
<td><strong>16 SoI Topographic Sheets</strong>: Zone 79B, C, F, G 2</td>
<td>1:50,000 (1 cm = 0.5 km)</td>
<td>1959–81, 14 sheets surveyed in 1967–69</td>
<td>— 2</td>
<td>15’ × 15’: 26 km × 28 km</td>
</tr>
<tr>
<td><strong>09 Corona KH4A Images</strong>: DS1038-2102DA-183 to -191</td>
<td>~2 m</td>
<td>1967</td>
<td>Interval from 1914: 53 yr</td>
<td>70 km × 17 km (each divided scene)</td>
</tr>
<tr>
<td><strong>04 IRS-1D LISS-3 Images</strong>: Paths 108, 109, 110; Rows 55, 56, 57</td>
<td>23.5 m</td>
<td>2000–02 [2001]</td>
<td>Interval from 1967: 34 yr</td>
<td>140 km × 140 km</td>
</tr>
<tr>
<td><strong>15 IRS-1D Pan Images</strong>: Paths 109, 110; Rows 55, 56, 57; Quadrates A, B, C, D</td>
<td>5.6 m</td>
<td></td>
<td></td>
<td>70 km × 70 km</td>
</tr>
<tr>
<td><strong>04 Landsat-8 OLI Images</strong>: Paths 137, 138; Rows 44, 45 2</td>
<td>15 m (panmerged)</td>
<td>2015</td>
<td>— 2</td>
<td>170 km × 183 km</td>
</tr>
</tbody>
</table>
11 Resourcesat-2 LISS-4 fmx Images: Paths 109, 110; Rows 56, 57; Quadrates A, B, C, D

<table>
<thead>
<tr>
<th>Resourcesat-2 LISS-4 fmx Images</th>
<th>5 m</th>
<th>2015–16 [2015.5]</th>
<th>Interval from 2001: 15 yr</th>
<th>70 km × 70 km</th>
</tr>
</thead>
</table>

1. **Acronyms:** fmx: full-swath multispectral, IRS: Indian Remote Sensing Satellite, LISS: Linear Imaging Self Scanner, OLI: Operational Land Imager, Pan: Panchromatic, SoI: Survey of India

2. Mosaic only utilised for orthocorrection

**Orthorectification and mosaicing**

The orthorectification and mosaicing of the satellite scenes of all datasets are carried out using Geomatica (ver. 2015) software on Universal Transverse Mercator projection (zone 45Q) and World Geodetic System–1984 ellipsoid. The 2015 OLI scenes are used as the reference for orthocorrection of all satellite data. The individual satellite scenes constituting a mosaic are colour matched where necessary to achieve a visually pleasing greyscale image (Corona) or standard FCC (OLI, LISS-3+Pan and LISS-4), with infra-red, red, and green bands / panmerged bands of satellite data shown in red, green, and blue colours, respectively.

All Survey of India toposheets are individually corrected using their graticules on spherical coordinates (degree-minute-second) on Everest ellipsoid. Next, they are mosaiced, and reprojected to Universal Transverse Mercator projection (zone 45Q) and World Geodetic System–1984 (WGS–84) ellipsoid to match rest of the data layers.

**Island area demarcation**

Northward extent of the present study area boundary is determined using the northernmost definable islands in the 1904–24 topographical sheets of Sundarban (Table 1). This means that an active channel separate the upper islands from the mainland of the north; beyond these, no definable island exists. Most of the channels used for delineating the study area remain active in 2015–16, the acquisition year of the latest dataset used here.

The coastline of a given island is delineated by manual digitisation of the spring High Water Level (HWL). A coastline is normally defined as the landward limit of seawater during the high spring tides in fair-weather conditions. (Bird, 1985:5–8). Determining these lines from maps is straightforward, because an HWL is already plotted in a map. Most satellite scenes used in this study represented high-water environment, and did not show intertidal features seaward of the HWL. Moreover, the HWL extraction here is done manually here on the basis of clear understanding of the coastal features of reclaimed and non-reclaimed areas of Sundarban and different types and resolutions of satellite images that represent them.

**Island ID, group, and centroid generation**

In this work, the individual islands in the maps and images are all identified by a numbered prefix of letters representing administrative divisions of either community development blocks (Indian reclaimed Sundarban), or upazilas (Bangladeshi reclaimed Sundarban), or forest blocks (Indian non-reclaimed Sundarban), or forest ranges (Bangladeshi non-reclaimed Sundarban). The identity of a given islet is kept same in all the four mapping / imaging years, if not it gets separated into one or more entities or merges with another island.

For simplifying data analysis, the islands are classified according to their locations from the southern seaface and northern limit of the study area. Two 12-km buffers from the 1904-24
northern and southern bounds of the study area are generated and use for designating the islands crossing the northern and southern buffers and *northern islands* and *southern islands* respectively. The islands not transecting the buffers are labelled as *central* (Fig. 11). Two large and elongated islands situated at the eastern and western ends of Sundarban—Sagar and Bhandaria—intersected both the buffers and were kept out of this analysis.

In addition, centroids for the islands are plotted for the four mapping/imaging years for getting an idea on how island-wise land loss and land gain changed in relation to their northward position from the seaface and westward location from 88.04°E, which is the western limit of the study area at the southwestern Sagar island.

To estimate erosion and accretion figures from the island vectors of two consecutive mapping/imaging years, spatial analysis principles of *overlay*, and *intersection* are used. A set of vectors belonging, for example, to 1967 and 2000–02, are overlaid to generate a third vector with superposed areas. In this vector, the different segments are designated either to *erosion* or to *accretion* or to *no-change*. All these vector-related analysis are performed in ArcGIS ver.10.3.1 (centroid creation) and Geomatica v.2015 (buffer formation, spatial analyses). Statistical tasks are done in MS Excel ver.2016.

**Outcome**

The summary of the data generated by this work are displayed in nine maps (Fig. 2–9, 11) and 12 diagrams (Fig. 10, 12–22). The evaluation was done on the basis of the northern, central, and southern island groups, stated in the methods section. Table 2 shows country-specific data of changes in total island numbers, total area, and rate of total area alterations.

The summary table and diagrams connote the following trends for the region.

- Almost the entire coast of the Sundarban facing the Bay of Bengal retrogrades for the last~100 years, regardless its status as non-reclaimed or settled portions. The Indian Sundarban coastline bounded by the Saptamukhi and the Gosaba channels (Fig. 3–6) registers highest rate of erosion at 40 m/yr. The rates of shoreline retreat slows on either sides of this tract, and becomes negligible at the eastern edge of Sundarban.

**Table 2**: Summary of island number and island area data: Indian and Bangladeshi Sundarban

<table>
<thead>
<tr>
<th>Zone</th>
<th>Specifications</th>
<th>Mid-value of Mapping / Imaging Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sundarban Region (Indian and Bangladeshi)</td>
<td>Island count</td>
<td>254</td>
</tr>
<tr>
<td></td>
<td>Supratidal area (km²)</td>
<td>12,617.8</td>
</tr>
<tr>
<td></td>
<td>Area Index: base = 1914</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>Alteration rate since preceding</td>
<td>–4.665</td>
</tr>
<tr>
<td></td>
<td>mapping / surveying year (km²/yr)</td>
<td></td>
</tr>
<tr>
<td>Western Sundarban</td>
<td>Island count</td>
<td>136</td>
</tr>
<tr>
<td></td>
<td>Supratidal area (km²)</td>
<td>4,508.2</td>
</tr>
</tbody>
</table>
• It is possible to group the trends of area loss and gain of the individual islands into six classes: loss (linear), loss (non-linear), gain followed by loss, gain (non-linear), gain (non-linear), and loss followed by gain, as depicted in Fig. 9 and 10.

• In the islands, the land lost (5.68% of total) is close to three times of the land gained (1.82%), which denotes a general erosional trend. In the northern islands, gain (4.31%) is seen to score over loss (3.03%). Conversely, both central and southern islands show greater loss (4.74% & 17.85%, respectively) than gain (1.46% & 1.65%, respectively) (Fig. 12, 17). In the study region, more islands are eroding (68% of total count) than accreting (32%), suggesting an overall erosive inclination. In the north, the growing islands (52% of total count) closely match the count of eroding islands (48%). More of the central islands are affected by erosion (76%) compared to accretion (24%). Similar trends are detected in the southern islands, where, 78% of islets recorded erosion while the rest (22%) eroded (Fig. 13). Overall, the trends of area alterations appear similar and linear in the whole of Sundarban region as well as Indian ad Bangladeshi sectors (Fig. 16).

• From 1967 to 2000–02, the central and southern isles show fast and progressive erosion; while the northern islands recorded massive land gain. However, the overall scenario is that the supratidal area of the studied region show unidirectional decline, with areas of 78% of the islets reducing and just 22% increasing (Fig. 14/15).

• In the entire area and across the periods, minor gaining trend is seen eastward, with very low significance level. Similarly insignificant trends are recorded for the islands of north and central area. For the northern Sundarban, slightly accreting trend of high significance is detected landward. The coast-proximal islands of the south show significant area gain eastwards (Fig. 19). Insignificant trends are brought out for the northern and central islands, while the coastal islands show significant gain in area northwards (Fig. 20).

• Many tidal channels of the interior areas are getting clogged, mostly in the reclaimed western areas and partly in the eastern reclaimed stretches. This caused certain trend reversals in the northern islands (Fig. 21, 22). Pearson’s correlation coefficient (r-value) derived through processing of island area change data pertaining to the four mapping/imaging years indicate that significant land gain takes place northwards.
Reasons for change

How can the observed trends be explained in the light of existing knowledge of regional sedimentation? The main reasons seems to be delta abandonment, shelf bypassing of sediments, regional tidal asymmetry, and relative sea level rise.

Delta abandonment and shelf bypassing of sediments

Advancement and retreat of a deltaic coast rest on the relative supremacy of the erosional wave and tidal forces and the depositional fluvial inputs. With most of the Ganga’s distributaries feeding the Sundarban becoming degenerated, the region is now fluvially abandoned. Although some $10^9$ t of sediments are annually routed through the Meghna estuary into the continental shelf off the GBD (Milliman and Syvitski, 1992; Goodbred, 2003), a large part of it is captured by the Swatch of No Ground submarine canyon, and routed into the deep sea Bengal fan as it moves westward (Kuehl et al., 1989, 1997, 2005) (Fig. 23). This lack of sediment supply results in continuous land loss in the coastal islands, aggravated by the periodic effects of tropical cyclones (Fig. 24), and monsoonal waves.

Time–velocity asymmetry of tides

Wright et al. (1973) showed that in a morphological equilibrium condition, length of a resonant macrotidal estuary ($\lambda$), that has a tidal range of more than 4 m, tends to equal a quarter of the tidal wavelength (L) generated in it, that is:

$$\lambda \rightarrow 0.25 \, L$$

Length of the tidal wave, behaving as a shallow water wave in an estuary, is determined by tidal period ($T$: a constant in a given locality), gravitational acceleration ($g$: another constant, 9.81 m sec$^{-2}$) and average depth of the estuary ($D$: the only variable) in the following relationship:

$$L = T\sqrt{(gD)}$$

Reclamation restricts the area of tidal spill through marginal embankments, takes shallow intertidal wetlands away from the realm of the estuary and thereby increases its average depth (Pethick, 1984, 1994) (Fig. 25). This removes the estuary from morphological steady state. For example, both of the 1988-92 and 1992-2002 hydrographical charts of India’s Naval Hydrographic Office indicate that the length of the westernmost estuary of reclaimed Sundarban, the Hugli, equals about one-sixth ($\lambda=0.17 \, L$) of the tidal wavelength entering into it (Bandyopadhyay, 2000; Nandy and Bandyopadhyay, 2010).

The macrotidal estuaries of the Sundarban responds to this by setting up time-velocity asymmetry in tidal cycles. The flood tides span for shorter duration in a cycle, and have higher landward velocity than the longer ebb. This causes active channel sedimentation and, in selected reclaimed stretches, erosion of the embankments to decrease the average depth and to restore the equilibrium condition (Bandyopadhyay et al., 2014). Moreover, the dissimilarity of water current in tidal channels and in adjacent mangrove wetlands leads to dynamic tidal circulation, which maintains the channel depth. Clearing of mangroves disrupts this balance and also results in siltation of the channel (Augustinus, 1995:353). All these put forward a plausible explanation for the accretion seen in the reclaimed northern islands of the Sundarban region.
Relative sea level rise

The relative sea change data of tidal stations of the coastal GBD, available from www.psmsl.org, around the Sundarban region show a range of 1.19–6.25 mm/yr and centres on 3–4 mm/yr (Fig. 26). The effect of this on island size changes in Sundarban remain somewhat inclusive because of known vertical accretion rates from the region. Despite lateral land loss all around, these rates have been estimated to be 0–11 mm/yr (Allison and Kepple, 2001) and 10 ± 9 mm/yr (Rogers et al., 2013) from the no-reclaimed surfaces of Khulna Sundarban.

Concluding notes

The outcome of this study indicate that with present overall rate of area alterations that clearly depict higher land loss than land gain, Sundarban is set to get reduced by 3.12% of its current size (380 km²) at 4.57 km²/yr by 2010. In erosion, the Indian and Bangladeshi parts will lose 1.87% and 1.25% of area, respectively. Most of this is estimated to take place in the south and eight seafront islands, seven of them in India, will get fully eroded within the next few decades (Table 3).

A sizable extent of mangroves protects the settled areas of Bangladesh, defending them from the intimidations of coastal retreat and other sea-front hazards associated with landfalls of tropical cyclones. In the western section of the Indian Sundarban, the mangroves are obliterated right up to the southern coastlines, exposing the resident population to all adverse eventualities. Future planning for the region must accept the change that have been introduced into the system by the humans and choose a moderate course between the requirements of the nature and the needs of the people.

Table 3: Islands projected to erode completely within 21st century.

<table>
<thead>
<tr>
<th>Island Name</th>
<th>Island ID</th>
<th>Forest Block / Range</th>
<th>Projected year of erosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haliday</td>
<td>Hd</td>
<td>Haliday, India</td>
<td>2030</td>
</tr>
<tr>
<td>Bhangaduni</td>
<td>Md-04</td>
<td>Mayadwip, India</td>
<td>2067</td>
</tr>
<tr>
<td>Kankramari West</td>
<td>NK 10 ms</td>
<td>Namkhana, India</td>
<td>2061</td>
</tr>
<tr>
<td>Kankramari South</td>
<td>NK 11 ms</td>
<td>Namkhana, India</td>
<td>2061</td>
</tr>
<tr>
<td>Ghoramara</td>
<td>Sg 02</td>
<td>Sagar, India</td>
<td>2036</td>
</tr>
<tr>
<td>Chhota Haldi (b)</td>
<td>Ch-03</td>
<td>Chhota Haldi, India</td>
<td>2100</td>
</tr>
<tr>
<td>Bulchery</td>
<td>Cl-04</td>
<td>Chulkati, India</td>
<td>2100</td>
</tr>
<tr>
<td>Sutarkhali</td>
<td>Khl 25</td>
<td>Khulna, Bangladesh</td>
<td>2045</td>
</tr>
</tbody>
</table>

Acknowledgments

This research was conducted under the South Asia Water Initiative – Sundarbans Targeted Environmental Studies. We thank Karabi Das, Pritam Kumar Santra, and Abhijit Das for their help with data processing.

The results, analyses, and conclusions presented in this article are entirely those of the authors.
They do not necessarily stand for the views of the International Bank for Reconstruction and Development / World Bank and its affiliated organizations, or those of the Executive Directors of the World Bank or the governments represented by them.

References


Oldham, T. 1870. President’s Address, Proceedings of Asiatic Society of Bengal for February, 1870: 40–52.


Figure 1: Composite map of the Sundarban region. Selected populated places and boundaries are shown in the map. Comparison between 1904–24 topographical maps and 2015–16 satellite images brings out the extent of erosion along nearly the entire seaface of the delta and accretion in the interior parts, chiefly in the west. Source: See Table 1. D–H Line extracted from 1:253,440 Atlas of India map # 121 & 122 of c. 1860 (modified from Bandyopadhyay, in press).
Figure 2. Tidal islands of the Sundarban region identified by centroids and unique identification code of mapping year 1904–24. Outlines of the islands in 2015–16 are represented in ochre. Island centroids of 1904–24, 1967, 2000–02 and 2015-16 are shown in red, green, grey, and blue, respectively. Source: See Table 1.

Figure 3: Lost and gained island area between 1904–24 and 1967 (53 yr), shown in red and green, respectively. Source: See Table 1.
LONG-TERM ISLAND AREA ALTERATIONS IN INDIAN AND BANGLADESHI SUNDARBAN: AN ASSESSMENT

Figure 4: Lost and gained island area between 1967 and 2000–02 (34 yr), shown in red and green, respectively. Source: See Table 1.

Figure 5: Lost and gained island area between 2000–02 and 2015-16 (14 yr), shown in red and green, respectively. Source: See Table 1.
LONG-TERM ISLAND AREA ALTERATIONS IN INDIAN AND BANGLADESHI SUNDARBAN: AN ASSESSMENT

Figure 6: Lost and gained island area between 1904–24 and 2015-16 (102 yr), shown in in red and green, respectively. Source: See Table 1.

Figure 7: High Water Level polygons of southern seafront islands of Sundarban indicate continuous land loss throughout the mapping / imaging years. Source: See Table 1.
LONG-TERM ISLAND AREA ALTERATIONS IN INDIAN AND BANGLADESHI SUNDARBAN: AN ASSESSMENT

Figure 8: Sedimentation and emergence of new islands in the northern areas of Sundarban within the estuaries of Saptamukhi (left) and Thakuran (right). Source: See Table 1.

Figure 9: Types of supratidal area alterations in the islands of Sundarban during the four survey / imaging years used in the study. Figure 10 provides examples of representative islands. See Fig. 2 for ID of islands. Source: See Table 1.
Figure 10: Types of supratidal area alterations in islands of Sundarban during the four survey / imaging years shown by type-islands. The islands can be located using their identity code in Fig. 2. Source: See Table 1.
Figure 11: Classification of the study area islands into northern (represented in yellow), central (represented in ochre) and southern (represented in green) groups on the basis of two 12-km buffers drawn from the northern and southern (coastal) boundaries of the study area, shown here in red and cyan lines, respectively. All diagrams in Fig. 12–15, and 17–22 are based on this division. Sagar island (Sg-03) of India and Bhandaria island (U-08) of Bangladesh are excluded from all of the three groups because of their north–south extension. Shown in light grey, these two islands occupy the western and eastern extremities of Sundarban, respectively.
Figure 12: Change in supratidal area of the Sundarban islands between 1904-24 and 2015-16, the first and last year of mapping/imaging. (A) In entire Sundarban, area lost by erosion (5.68% of total area) is near about three times of the area gained by accretional processes (1.82% of total area) which signifies an overall erosional trend. (B) In case of northern island group, accretion (4.31% of total area) is greater than erosion (3.03% of total area). (C) & (D) Both the central and southern group of islands are experiencing greater erosion (4.74% & 17.85% of total area, respectively) than accretion (1.46% & 1.65% of total area, respectively). Sagar Island (Sg-03) of India and Bhandaria island (U-08) of Bangladesh are excluded from the spatial groups (B–C). Please see text and Fig. 11 for details. Source: See Table 1.
Figure 13: Islands with positive and negative change in area between 1904-24 and 2015-16, the first and last year of mapping/imaging. (A) In entire Sundarban, majority of islands faced erosion (68% of total count) over accretion (32% of total count) which indicates an overall erosive inclination. (B) In case of northern island group, accreting (52% of total count) islands nearly matches the numbers of islands facing erosion (48% of total count). (C) In central part, most islands are affected by erosion (76% of total count) than accretion (24% of total count) (D) Trends similar to central group is seen in southern part. Here, 78% of the total islands are eroding whereas only 22% of islands are accreting. Sagar Island (Sg-03) of India and Bhandaria (U-08) island of Bangladesh are excluded from (B), (C), and (D). Source: See Table 1.
Figure 14: Changes in supratidal area through the years of mapping/imaging. Progressive and rapid loss of land area is observed in case of central (C) and southern islands (D); though the northern island group (B) experienced massive accretion between 1967 and 2001. The overall trend is that the land area of the entire Sundarban (A) is progressively declining. Here, 78% of the total islands are eroding whereas only 22% of islands are accreting. Sagar island (Sg-03) of India and Bhandaria (U-08) island of Bangladesh are excluded from (B), (C), and (D), as shown in Fig. 11. Source: See Table 1.
Linear rapid loss of land area is observed in case of central (C) and southern islands (D) though northern island group (B) experienced massive accretion between 1967 and 2001 and connoted positive trends. The overall trend is that the land area of the entire Sundarban (A) is progressively reducing. Sagar island (Sg-03) of India and Bhandaria island (U-08) of Bangladesh are excluded from (B), (C), and (D). See Fig. 11. Source: See Table 1.
Figure 16: Country-wise changes in supratidal area through the years of mapping/imaging. If the changes in net supratidal area of the Sundarban region is viewed in its entirety (A), or as western Indian (B) or eastern Bangladeshi (C) sectors, the trends of changes appear noticeably similar and linear, irrespective of their absolute values. Source: See Table 1.
Figure 17: Individual island-wise change in area between 1904-24 and 2015-16, the first and last year of mapping/imaging for the entire Sundarban (A), and northern (B), central (C), and southern (D) groups of islands. The diagrams show that the islands of the southern group are most affected by coastal erosion. Sagar island (Sg-03) of India and Bhandaria island (U-08) of Bangladesh are excluded from (B), (C), and (D) because of their north–south extension. See Fig. 11. Source: See Table 1.
Figure 18: Distribution pattern of the Pearson’s correlation coefficient (r-value) generated by analysing the time series trends of area change of individual islands considering all mapping/imaging years for the entire Sundarban (A), and northern (B), central (C), and southern (D) groups of islands. The diagrams show that most of the islands of Sundarban are eroding at a rapid rate having r-values very close to (−1). Some of the islands, especially in the northern group, are also accreting at a high rate. Sagar island (Sg-03) of India and Bhandaria island (U-08) of Bangladesh are excluded from (B), (C), and (D). See Fig. 11. Source: See Table 1.
Figure 19: Relationship between easting and area change between 1904-24 and 2015-16. In case of the entire Sundarban (A), very slight increasing trend (accretion) is seen towards east though the significance level is low. Very insignificant trends are also observed for northern (B) and central (C) island groups. However, the coastal islands show significant increase in area towards east. Sagar island (Sg-03) of India and Bhandaria island (U-08) of Bangladesh are excluded from (B), (C), and (D). See Fig. 11.
Figure 20: Relationship between northward distance from shoreline and change in area between 1904-24 and 2015-16, the first and last years of mapping/imaging. In case of the entire Sundarban, (A) only slightly increasing trend (accretion) is seen northwards but this trend is of emphatic significance. Insignificant trends are detected for northern (B) and central (C) island groups, but the coastal islands are showing significant increase in area towards north. Sagar island (Sg-03) of India and Bhandaria island (U-08) of Bangladesh are excluded from (B), (C), and (D) because of their north–south extension. See Fig. 12. Source: See Table 1.
**Figure 21:** Relationship between island easting and rate of change, i.e. Pearson’s correlation coefficient ($r$-value) generated by analysing the time series trends of area change of individual islands considering all map/image years. No significant trend is observed for the entire Sundarban (A). Increasing trend (accretion) is seen for the southern islands (D) and the trend is of high significance. Central islands are also having significant trends and show accretion towards the east. Interestingly, the northern islands (B) are showing significant opposite trend.
Figure 22: Relationship between northward distance from shoreline and rate of area change in Pearson’s correlation coefficient (r-value) generated by analysing the time series trends of area change of individual islands considering all mapping/imaging years. Significant accretion is observed northwards for the entire Sundarban (A). Increasing trend (accretion) is seen for the southern islands (D) and the trend is of high significance. Notably, the northern islands (B) are showing significant trend in opposite direction. Central islands (C) are also showing erosion towards north but the trend is insignificant. Sagar island (Sg-03) of India and Bhandaria island (U-08) of Bangladesh are excluded from (B), (C), and (D). See Fig. 11. Source: See Table 1.
LONG-TERM ISLAND AREA ALTERATIONS IN INDIAN AND BANGLADESHI SUNDARBAN: AN ASSESSMENT

Figure 23: The Swatch of No Ground submarine canyon in the continental shelf of the GBD that intercepts the outpoured sediments of the Ganga–Brahmaputra system from replenishing the fluvially abandoned Sundarban region. Red arrows indicate main pathways of sediments received from riverine sources. Green arrows denote possible direction of net movement of reworked sediments that flood-dominated tidal currents carry into the interiors of Sundarban, aiding northern and vertical accretion. Source: isobaths from National Hydrographic Office chart No. 31. (From Bandyopadhyay, in press)
Figure 24: Tropical cyclones landfalling in the Sundarban region between 88° and 90° E. Storm-driven surges and waves work as powerful forcings that cause coastal erosion in the exposed seafront islands of the region. *Depression*: a storm with 10-min average wind speed of 31–61 km h⁻¹; *Cyclonic Storm*: 62–88 km h⁻¹; *Severe Cyclonic Storm*: >89 km h⁻¹. *Source*: <http://www.rmcchennaieatlas.tn.nic.in>
Figure 25: Diagrams explaining consequences of deforesting and reclaiming macrotidal Sundarban estuaries. A: Intertidal areas are not reclaimed—estuary is in morphological equilibrium. B: Intertidal areas are reclaimed—mean depth is increased and the estuary is removed from morphological equilibrium. Feedback includes in-channel siltation and erosion of the embankments, requiring year-round maintenance. (after Bandyopadhyay, 2000).
Figure 26: Available RMSL trends (in mm yr\(^{-1}\)) in the coastal Ganga–Brahmaputra delta at or close to the Sundarban region. Data of Khepupara and Sagar are not represented by bars due to their anomalous values. Blue and magenta dotted lines denote the limits of the Sundarban Biosphere Reserve in India and the proposed Sundarban Impact Zone in Bangladesh, respectively; black line is the international boundary. Source: Permanent Service for Mean Sea Level (PSMSL: www.psmsl.org), retrieved on 30 May 2016; data for Mongla from Orford and Pethick (2013), originally sourced from Mongla Port Authority; data for Rayenda and Amtali from Sarwar (2013), originally sourced from Bangladesh Water Development Board. (From Bandyopadhyay, in press)