

# Mapping tidal channel dynamics in the Sundarbans, Bangladesh, between 1974 and 2017, and implications for the sustainability of the Sundarbans mangrove forest

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**Abstract** This study presents the spatial and temporal dynamics of tidal channels in the Bangladesh Sundarbans. Parts of the Passur River system were considered for this investigation. Tidal channel bank layers were extracted from aerial photographs from 1974 and 2011 and a Sentinel-2 image from 2017. On-screen digitizing of a tidal channel was undertaken to create the tidal channel layers, and special care was taken during digitization to obtain more accurate results. Layers were overlaid together so that the tidal channel position could be seen for each date. Tidal channel positions were highlighted to infer the erosion/accretion sectors along the channel, and the tidal channel dynamics were calculated. Remote sensing and Geographic Information System (GIS) platforms were used to analyse, interpret and visualize data on accretion and erosion, as well as the locations of the tidal channel bank over different years. The results revealed that erosion was severe in the larger channels, whereas accretion was dominant in the smaller channels. These erosion and accretion processes played an active role in the displacement of tidal channel banks during the period under

investigation. Displacement of the tidal channel bank has had a profound impact on the Sundarbans mangrove ecosystem, and continued erosion and accretion processes are of concern for the future sustainability of biodiversity in the Sundarbans. While in the short term, these changes may not have much impact; over decades, the dynamics of tidal channels may significantly contribute to the imbalance of fauna and flora in the Sundarbans.

**Keywords** Passur River system · Erosion and accretion · GIS · On-screen digitizing · Aerial photographs

## Introduction

Mangrove forests occupy tropical low-energy depositional coastal and river deltaic regions worldwide (Kuenzer et al. 2011; Kanniah et al. 2015). Mangroves thrive in geomorphologically and hydrologically active areas of large sediment deposition with fresh water inputs and a rapid inflow of terrigenous sand, silt and clay, high salinity, high temperature, extreme tides and muddy anaerobic soils (Giri et al. 2011). However, mangrove communities are sensitive to the adverse effects of some natural and anthropogenic fluvial and oceanic changes (Valiela et al. 2001; Liu et al. 2008; Rakotomavo and Fromard 2010; Ghosh et al. 2015a, b), which usually occur in global, geologically unstable deltas and estuaries. Common phenomena include coastal and tidal channel erosion and accretion processes, salt water incursion and rising sea levels, resulting in

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the loss of mangrove cover and a change in species composition (Danda 2010). Intertidal, sheltered and low-energy muddy sediments provide the most optimal habitats for mangroves (Blasco et al. 1996). Condition changes caused by temperature, soil type, salinity, duration and frequency of inundation, accretion and erosion of soil and tidal and wave energy may affect mangrove species development, composition and distribution and hence impact their sustainability (Islam et al. 2015).

The Sundarbans form one of the most vulnerable deltaic ecosystems worldwide with respect to fluvial and oceanic dynamics such as coastal erosion, sea level rise and tropical cyclones (Roy 2010). Despite these threats, its mangrove flora form an ecologically important natural buffer and bulwark against coastal erosion and seawater ingress and at the same time continue to represent an economic pillar of the most densely populated rich coastal regions in the world. Coastal diversity in the Sundarbans, for example in Sagar Island, has recently come under environmental threat from a variety of anthropogenic activities that cause multiple stressors, resulting in beach erosion, shoreline modifications and the destruction of natural habitats (mud-flats, coastal dunes, mangrove vegetation, etc.) (Rakshit et al. 2015). Besides a human-induced impact on coastal biodiversity, natural forces such as rising sea levels and tidal currents also play key roles. Fluvial dynamics in the upper subaerial delta plain and marine processes in the active Bangladesh Sundarbans are a result of long-term tectonic processes and short-term tidal currents (Das 2004). River-borne sediments deposited annually by the Ganges and Brahmaputra rivers in the Bengal Basin during the monsoon flood pulse find their way to the vast mangrove ecosystem tidal delta through tidal inundation, the seasonal monsoonal rise in sea level and storm surges (Rogers et al. 2013). A large part of the sediment is transported through tidal rivers and channels from the sea to delta flood plains of the Sundarbans by onshore propagation of the tidal currents and relative sea level rise. The western reach of the Sundarbans is no longer connected to significant upstream river sources of sediments (Rogers et al. 2013; Wilson and Goodbred 2015; Allison and Kepple 2001) and greatly benefits from landward advection of sediments from the Ganges and Brahmaputra river mouths. The dense network of funnel-shaped tidal channels and the silt-dominated mangrove habitat of the Sundarbans are maintained by redistribution of onshore fluvial sediment advection by the tides (Wilson and Goodbred 2015). Maintenance of

the elevation of the tidal platform above the mean high water in the Sundarbans estuarine tidal platform and a continued supply of fresh water from rivers are necessary for some of the mangrove vegetation survival and regeneration (Winterwerp and Giardino 2012). Although the elevation of the intertidal landscape of the Sundarbans mangrove forest has kept pace with relative sea level rise for decades (Auerbach et al. 2015) owing to natural forces reworking the sediments, it is not guaranteed that this status quo will continue. Like similar landscapes across the world, the Sundarbans face potential threats from changing climatic and anthropogenic forces (Day et al. 2007; Stanley and Warne 1998; Chu et al. 2006).

The River Ganges system, one of the major sources of fresh water for the Ganges–Brahmaputra tidal delta plains, has changed significantly, partly due to construction of a barrage in 1975 by the Indian government to divert large quantities of fresh water from the Ganges in order to flush the silt of the Hooghly River to save the Kolkata port (Winterwerp and Giardino 2012; Mikhailov and Dotsenko 2007) and partly as a result of a shift in the river bed channel (Wilson and Goodbred 2015; Winterwerp and Giardino 2012). Effects of salinity ingress due to tidal amplification, sea level rise and tidal sediment advections, as well as climate change-induced altered river flows, may have implications for the aquatic mangrove ecosystem environment (Pethick and Orford 2013; Dasgupta et al. 2014).

Many studies (Alongi 2008; Gilman et al. 2007) have focused on geomorphic changes at the land–ocean interface in relation to mangrove stability, but relatively few studies have examined the land–river interface that comprises a large areal extent in deltaic systems. Few researchers have considered the changing tidal channel patterns of accretion and erosion in the deltaic plains around the world (Day et al. 2007; Chu et al. 2006). Dynamics of accretion and erosion are crucial to understanding coastal and mangrove forest environments, particularly in the highly sensitive Sundarbans coastal inlands. Some works on erosion–accretion processes of the channels and islands of the estuarine delta caused by tidal processes and regional subsidence patterns have been documented (Barua 1997; Brammer 2014; Hassan et al. 2017), but these studies did not cover active tidal floodplains channel dynamics. Allison et al. (2003) studied a sedimentary sequence resulting from lower delta plain progradation in the late Holocene and concluded that the subsidence patterns in the

tectonically active Bengal Basin controlled distributary channel avulsion and migration and the creation of accommodation space. Chatterjee et al. (2015) applied Landsat satellite data and a GIS platform to study coastal shoreline accretion and erosion in the Indian Sundarbans. In the Bangladesh Sundarbans, Allison (1998) used geo-referenced and projection-corrected early and modern charts as well as Landsat imagery to document the morphology of shoal growth of the mouth of the Ganges over the late Holocene as a series of digitate shoal-channel complexes and reported an average accretion of approximately  $7.0 \text{ km}^2/\text{year}$  since 1792, with eastward evolution and westward retreat at a rate of  $1.9 \text{ km}^2/\text{year}$ . The author documented large tidal channel migration that extended inland but did not show evidence of net infilling or widening.

Many studies (Allison and Kepple 2001; Allison 1998; Wilson and Goodbred 2015) have been performed on variations in delta and estuarine sediment deposition, topography and hydrology, but the changing dynamics of the sediments advected from marine areas through the tidal inundation seasonal monsoon set-up of sea level and storm surges by erosion and accretion processes in the Sundarbans hinterland mangrove ecosystem are not yet fully understood. Climate and land use have the potential to vastly alter the sediment and hydrologic regime of rivers, with implications for their morpho-dynamic evolution. The dynamic evolutions of the tidal channel in ecologically sensitive areas such as the Sundarbans can translate to the extreme fragility of biodiversity and may negatively impact on their sustainability. There are virtually no studies on how tidal channels in the Bangladesh Sundarbans region have seen their erosion/accretion rates altered as a result of these tidal disturbances. An understanding of the tidal channel dynamics that maintain the Sundarbans deltaic system elevation is crucial for planning of environmental management strategies.

This investigation is about mapping and assessing tidal channel erosion and accretion in the hinterland areas of the Bangladesh Sundarbans mangrove forest and suggests the factors behind the observed changes in the tidal channel morphology of the Sundarbans forest system. Aerial photographs and satellite imagery have been used in remote sensing and GIS platforms to analyse accretion and erosion and locations at three different time points over a period of 43 years. This study not only provides scientific understanding of mangrove physical geomorphology environment but also adds to a limited tidal

channel erosion and accretion process knowledge base with respect to mangrove forest ecosystems.

## Materials and methods

### Study area

The Sundarbans tidal delta plain, created by the confluence of three major river systems of the Ganges, Brahmaputra and Meghna in the Bay of Bengal, covers an area of approximately  $10,000 \text{ km}^2$  (Chatterjee et al. 2015; Ghosh et al. 2016). The Sundarbans tidal delta plain can be divided into four specific zones: the inactive delta (once an active part of delta, but with currently reduced or no fluvial activity), mature delta (moribund deltas that have ceased), tidally active delta (a still active part with water channelling through it carrying sediment) and sub-aqueous delta (part of the delta that is below the low-tide mark) (Chatterjee et al. 2015). The Bangladesh part of the Sundarbans occupies the entire part of the active delta (Chatterjee et al. 2015) and is crisscrossed by a complex network of tidal channels which are more stable than the main stream of the Ganges, Brahmaputra and Meghna (Ghosh et al. 2016; Islam and Gnauck 2011). Although there have been some microtopographical exceptions due to rivers, streams and tidal flow (Islam and Gnauck 2011; Begum 1987), this deltaic wetland of the Sundarbans is almost flat. The land slope in this region is  $0.03 \text{ m}$  vertically per  $\text{km}$  of horizontal distance from north to south (Islam and Gnauck 2011). The elevation of the forest area varies between  $0.9$  and  $2.1 \text{ m}$  above mean sea level (Ghosh et al. 2015a, b, 2017). The Bangladesh Sundarbans spreads over three administrative districts, namely Satkhira, Khulna and Bagherhat, commanding an area of three fifths of that of the entire Sundarbans (Ghosh et al. 2017). Geographically, it spans the approximate latitudes of  $21^\circ 32' \text{ N}$  to  $22^\circ 30' \text{ N}$  and longitudes  $89^\circ 00' \text{ E}$  to  $89^\circ 51' \text{ E}$ . However, for the present study, parts of the Passur tidal channel from the tidally active delta of the Bangladesh Sundarbans (latitudes  $21^\circ 52' \text{ N}$  to  $22^\circ 06' \text{ N}$  and longitudes  $89^\circ 31' \text{ E}$  to  $89^\circ 36' \text{ E}$ ) have been selected for the study of tidal channel dynamics (Fig. 1). This study site has been selected as a representative of the active delta of the Sundarbans, partly because of the availability of good aerial photographs for this specific site for the year 1974. Secondly, the Passur River channel is strategically located between the eastern and western portion of the Bangladesh Sundarbans, offering a



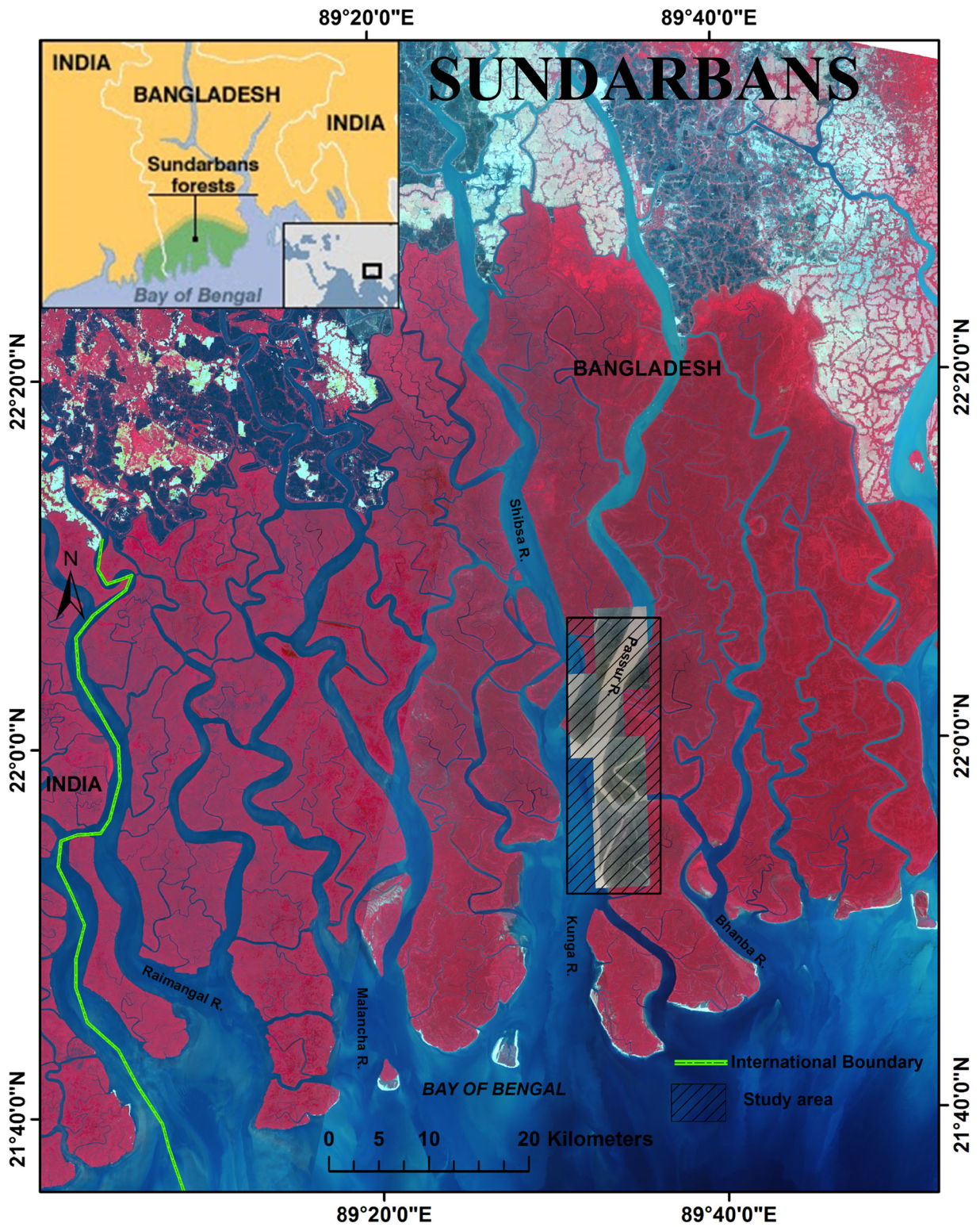


Fig. 1 Location of the study area marked in the shaded box within the map (false colour composite) of the Bangladesh Sundarbans



suitable area where anthropogenic and natural forces (tidal currents, sea level set-up and storm surges) of tidal channel dynamics may be at play. The Passur River system contains large intertidal areas affected by high floods during the monsoon season and receives fine sediments transported by tidal advection (Winterwerp and Giardino 2012). These changing patterns were observed by Aziz and Paul (2015) and were re-confirmed during our field visit in February–March 2016.

## Data

To understand tidal channel dynamics of the study area, aerial photographs from 1974 and 2011 and a satellite image from 2017 were used. Satellite images from 1974 with good spatial resolution of the area were not available, and therefore, aerial photographs of comparatively high and fine resolution were considered adequate to obtain information on tidal channel dynamics. Although high-resolution satellite imagery was available for 2011, aerial photographs were used for this study due to their effectiveness in terms of cost and also ease of comparison with the 1974 photographs. The aerial photographs were sourced from the Survey of Bangladesh (SOB). The Sentinel-2 satellite image from 2017 was downloaded from the European Space Agency (ESA) website (<https://scihub.copernicus.eu/>). The aerial photographs from 1974 and 2011 were taken with scales of 1:30000 and 1:20000, respectively. The satellite imagery of Sentinel-2 (10 m spatial resolution) acquired in April 2017 was used to identify the changes in tidal channels which occurred only at larger scales because the resolution of the image was not sufficiently high as compared to aerial photographs. Comparatively, larger changes in the tidal channel were considered for the period from 2011 to 2017, keeping in mind the possible error of identification of tidal channels due to spatial resolution of the image and with the assumption that the error was low compared to the scale of tidal channel shifts. A Sentinel-2 image was used in this study, as aerial photographs for this date were not available and the Sentinel-2 image provided the only high-resolution data among the freely downloadable datasets.

## Identification of tidal channel dynamics

The aerial photograph frames from 1974 were scanned from black and white (B/W) printed copies at a resolution of 600 dpi, whereas the photographs from the year

2011 were supplied in digital form by the SOB. All the images were imported into ArcGIS (ESRI Inc. version 10.1) as digital images and were georeferenced to the UTM 45° N, WGS 84 map system using at least 16 ground control points (GCPs) since none of the photographs were georeferenced. The image to image registration technique was used for the registration of the images. A satisfactory root-mean-square (RMS) error was achieved (less than 4 m) for the registered images. Visual inspection was also undertaken to confirm that the overlaid images matched each other well. Thereafter, aerial photographs were mosaicked for the whole study site. Registration of the Sentinel-2 image was undertaken using 47 GCPs with an RMS error of 0.002439 pixels. Tidal channels were then extracted from both of the mosaicked aerial photographs and Sentinel-2 image.

On-screen digitization of the tidal channel was undertaken to create the tidal channel layers, and special care was taken during digitization to obtain more accurate results. Layers were overlaid together so that the tidal channel position could be seen at each date. Tidal channel positions were highlighted to infer the erosion/accretion sectors along the channel, and the tidal channel dynamics were calculated. Demarcation of tidal channel banks showed some uncertainties because of the existence of indistinct boundaries due to tidal effects. However, the uncertainty of demarcation of tidal channel banks was minimized by including the muddy areas with grasses (accretion) and by excluding the muddy areas with no grasses in the calculation, keeping in mind that muddy areas with grasses are already established and could be considered as an established tidal channel bank (see Fig. 2a). In addition, tides would not make a difference in calculations as banks are vertical in most of the places, and for others with floodplains, we have taken the vegetation edge as a tidal channel bank. Ideally, for the best accuracy, comparisons over long periods of time must be made at exactly the same tide level. However, the reality is that over such long periods of time (in this case 1974–2017), data management is limited by the data available. Satellite overpasses are also at a fixed time of the day and cannot be modified for each capture. These are sources of error in studies of this kind that use historical data. However, we travelled extensively through the Sundarbans study area over a 3-week period and are certain that most of the channels, especially the wide channels, have vertical banks (for instance see Fig. 2b). For the narrower channels, instead of the water line, the mud line was used for the channel



**Fig. 2** Photographs showing **a** tidal area with grasses, **b** evidence of tidal channel bank erosion and **c** accretion and sediments deposits. These photographs were taken on 25 February 2016 in the Sundarbans

widths. This improves the accuracy and is a standard technique in remote sensing work.

## Results

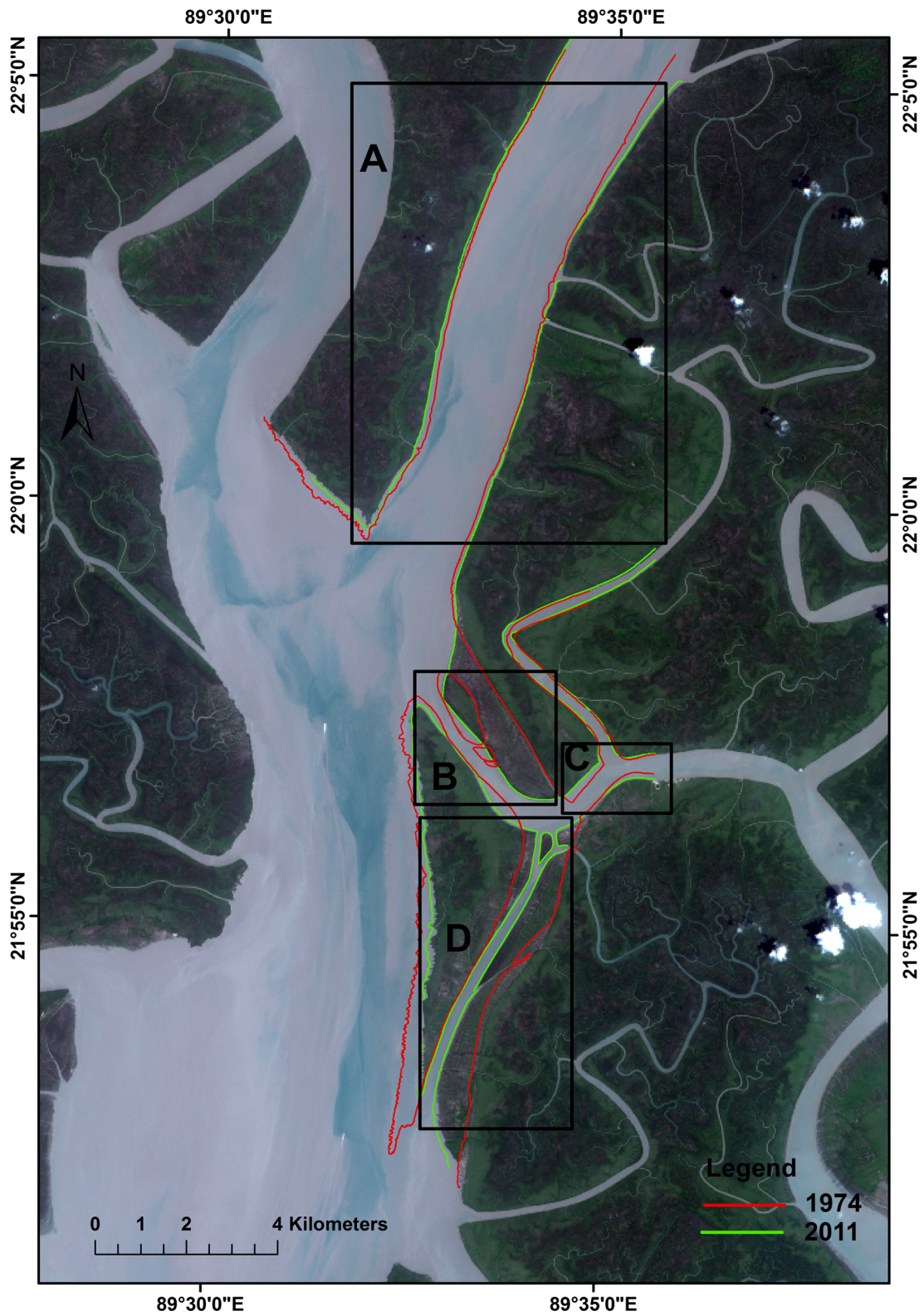
Mapping and assessing tidal channel erosion and accretion to obtain information on tidal channel dynamics indicated large displacement of tidal banks. The shift in the tidal channel bank between 1974 and 2011 is shown in Fig. 3. The red line in the map represents the position of the tidal channel bank in 1974, whereas the green line shows the position of the tidal channel bank in 2011. The most remarkable result observed in this study is the large shift of the tidal channel bank. In this study, four channel locations (A, B, C and D) were identified from aerial photographs where the shift of the tidal channel bank was prominent. Channel locations A and C were erosion-dominant, while channel locations B and D were dominated by accretion. There were also some unaffected channel locations in the study area between these erosion and accretion-prone segments. The changes in tidal channel bank positions for these four sites are shown in Fig. 4a–d (the red line in the map represents the position of tidal channel bank in 1974 and the green line represents the position of the tidal channel bank in 2011) while the changing width of the channel and the extent of the shift are given in Tables 1 and 2, respectively.

Figure 5 further illustrates the images and changes in the selected sites in Fig. 4 for the years 1974, 2011 and 2017. Channel location A, which extended for 12.18 km with a maximum channel width of 2.17 km and a minimum channel width of 1.66 km in 1974, experienced major erosion, with the tidal channel bank displacement ranging between 0.007 and 0.36 km in the right bank and between 0.012 and 0.15 km in the left bank. The maximum and minimum widths of this

channel location became 2.43 and 1.85 km, respectively, in 2011 due to the displacement of the tidal channel bank as a result of erosion. Channel locations B, C and D, which extend for 4.15, 2.25 and 7.50 km respectively, had maximum channel widths of 1.33, 0.42 and 1.16 km and minimum channel widths of 0.26, 0.29 and 0.67 km, respectively, in 1974. They had maximum channel widths of 0.71, 0.60 and 0.26 km and minimum channel widths of 0.50, 0.46 and 0.11 km, respectively, in 2011. The displacement of the tidal channel bank for the channel locations B, C and D ranged between 0.063 and 0.82, 0.013 and 0.12 and 0.046 and 0.80 km in the right bank and 0.015 and 0.26, 0.014 and 0.20 and 0.014 and 0.34 km in the left bank, respectively. The total land area within the study landscape was 130.54 km<sup>2</sup> in 1974 and 130.75 km<sup>2</sup> in 2011, giving a net accretion of 0.21 km<sup>2</sup> and a yearly rate of accretion of 0.0057 km<sup>2</sup> within this period. Channel locations A and C, where the overall trend is towards erosion, witnessed a retreat of the tidal channel bank, and this played an influential role in the widening of the tidal channel, while channel locations B and D, where the overall trend was towards accretion, experienced an advancement of the tidal channel bank which played a vital role in raising the tidal channel bed and also making the channel narrower.

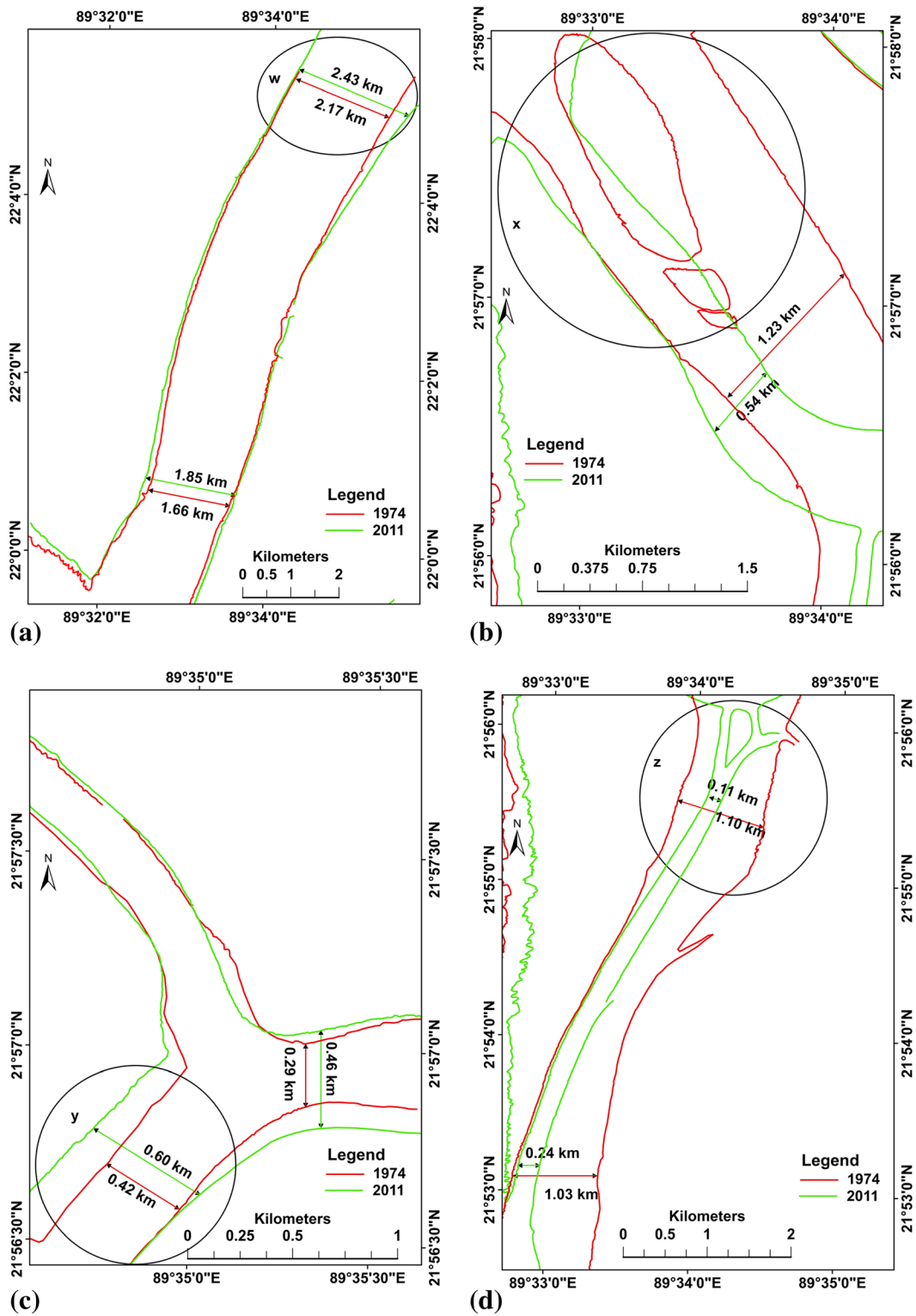
Figure 6 illustrates the changes of the tidal channel bank between 2011 and 2017. The positions of the tidal channel bank in 2011 and 2017 in the map are represented by red and black lines, respectively. Channel locations A1 and B1, which extend for 1.1 and 0.8 km, had maximum channel widths of 0.65 and 0.26 km and minimum channel widths of 0.57 and 0.083 km, respectively, in 2011, but the maximum and minimum channel widths at location A1 were found to be 0.73 and 0.58 km, respectively, in 2017. For location B1, the maximum and minimum channel widths were 0.26 and 0.059 km, respectively. The displacement of the tidal channel bank for channel locations A1 and B1





**Fig. 3** Tidal channel bank change map of selected channel locations in the Sundarbans, Bangladesh between 1974 and 2011





**Fig. 4** Tidal channel bank change map of selected channel locations in the Sundarbans, Bangladesh between 1974 and 2011. **a** Channel location A. **b** Channel location B. **c** Channel location C. **d**

Channel location D. Aerial photographs and satellite images for circles marked with w, x, y and z are shown in Fig. 5

**Table 1** Changing patterns of channel width at selected channel locations in the Sundarbans, Bangladesh (1974–2011)

Channel Location	1974 (width in km)		2011 (width in km)		Dominant Process
	Highest	Lowest	Highest	Lowest	
A	2.17	1.66	2.43	1.85	Erosion
B	1.33	0.26	0.71	0.50	Accretion
C	0.42	0.29	0.60	0.46	Erosion
D	1.16	0.67	0.26	0.11	Accretion

was 0.016–0.041 and 0.011–0.048 km in the right bank and 0.030–0.063 and 0.012–0.030 km in the left bank, respectively. At channel location A1, the sedimentation process was dominant in the right bank, while the erosion process was dominant in the left bank. On the other hand, the sedimentation process was dominant in channel location B1 on both sides of the tidal channel.

**Discussion**

The Sundarbans mangrove forest ecosystem is a wetland of international importance. It was designated a Ramsar site in the year 1992 and a UNESCO World Heritage site for the conservation of unique plant and animal communities. Although natural processes, such as cyclonic storms and tidal surges, have always existed, recent years’ events have severely affected the biotic life of the deltaic system by uprooting plants, eroding tidal channels and coastal soils, breaking stems and branches and threatening human livelihoods.

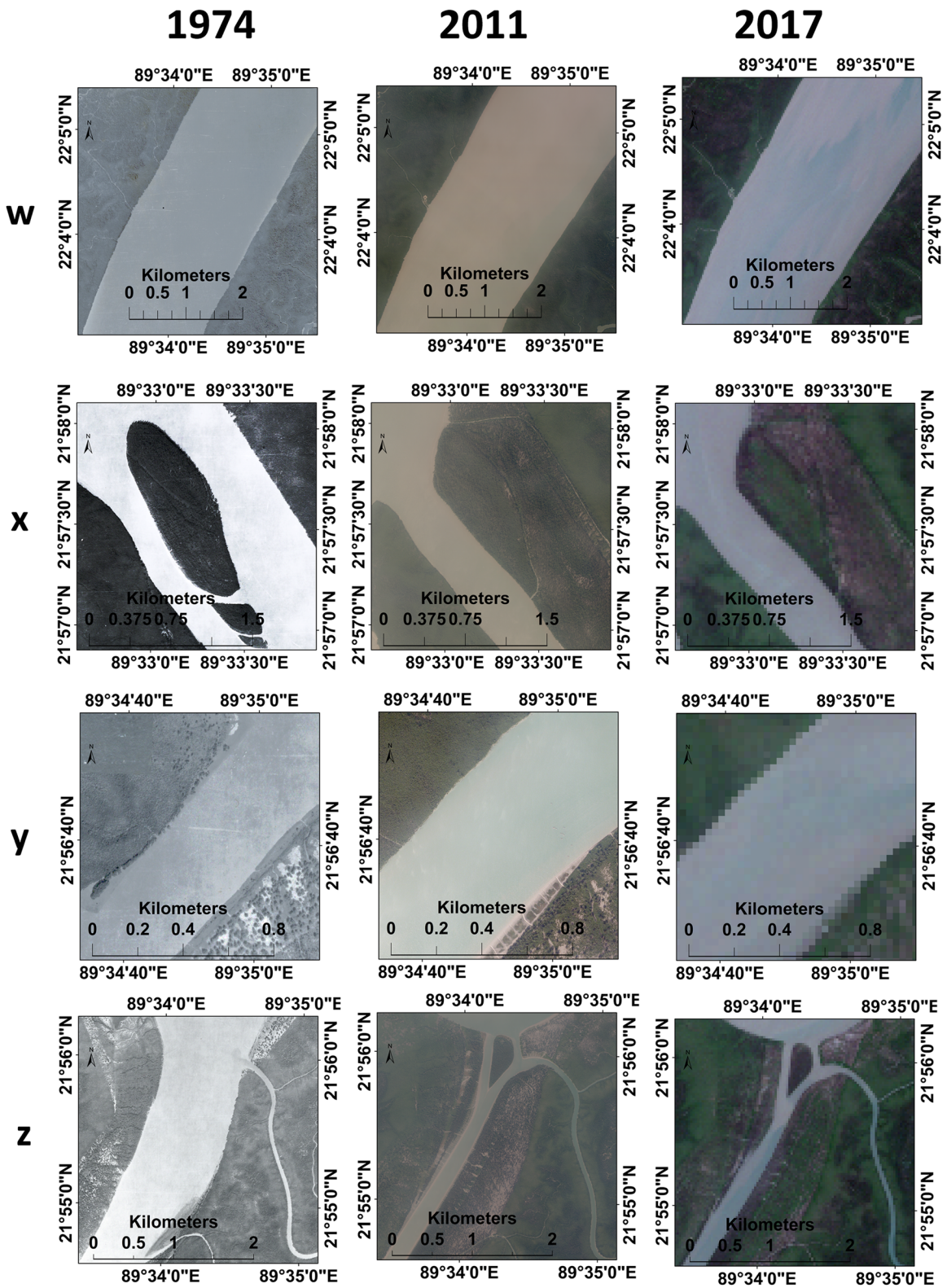
**Table 2** Displacement of the tidal channel bank at selected channel locations in the Sundarbans, Bangladesh (1974–2011)

Channel location	Displacement of the tidal channel bank between 1974 and 2011 (in km)			
	Right bank		Left bank	
	Highest	Lowest	Highest	Lowest
A	(-) 0.36	(-) 0.007	(-) 0.15	(-) 0.012
B	(+) 0.82	(-) 0.063	(-) 0.26	(-) 0.015
C	(-) 0.12	(-) 0.013	(-) 0.20	(-) 0.014
D	(+) 0.80	(+) 0.046	(+) 0.34	(+) 0.014

The (-) sign represents retreat (erosion) and the (+) sign represents advancement (accretion) of the tidal channel bank

At least one major tropical cyclone strikes Bangladesh each year (Paul and Routray 2011). Historical records also show that, within the period covered in this study, two main disastrous cyclonic/major flood hazards occurred. The first was a cyclone in April 1991 which affected the Sundarbans coastal region, and the second was the super cyclone SIDR of 2007, which had huge negative impacts on the Sundarbans ecosystem (Bhowmik and Cabral 2013). Other hazardous events include the devastating floods of 1998 which inundated one third of the Sundarbans (Ali 1996; Kunii et al. 2002) and 14 other cyclones reported since 1990 (Siddiqui 2013). The tidal channel morphology dynamics observed in this investigation are partly attributed to the disturbance of these cyclones. It was found that large mangrove forests in the riparian areas at the study site were washed away in the period between 1974 and 2017. The erosion–accretion processes of the tidal channels between 1974 and 2011 are fundamentally the result of channel dynamics as observed in the study area. A similar observation has been reported by Ghosh et al. (2015a) and Kumar and Ghosh (2012) for the Meghna River estuary. Amalgamation of factors and processes offers an explanation of the patterns and dynamics of tidal and intertidal channels in the Sundarbans. The morphologic changes of the Passur tidal channels are attributable to oceanographic, terrestrial and anthropogenic factors which commonly affect coastal regions.

The results observed in this study can be attributed to many factors driving the processes. As for oceanic factors, tidal currents have also been suggested to have a strong influence on coastal tidal channel erosion and accretion processes due to their modulation and their different response to dynamics of the natural propagations (Kumar et al. 2014). Erosion processes in some channels (channel location A in Figs. 2 and 3a) occur due to the strength of intertidal mud, level of compaction



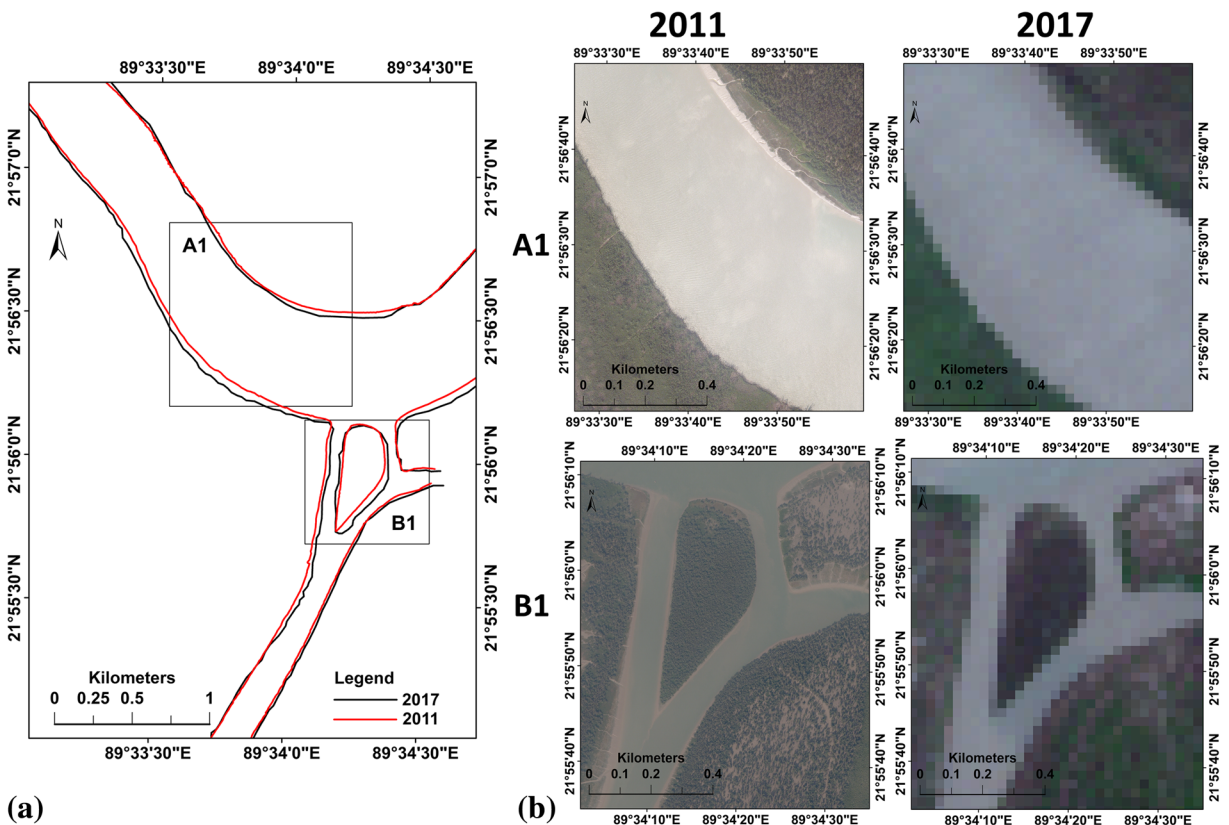


◀ **Fig. 5** Tidal channel bank images showing changes of selected channel locations in the Sundarbans, Bangladesh between the time points in 1974, 2011 and 2017. w, taken from channel location A; x, taken from channel location B, y, taken from channel location C; and z, taken from channel location D. Each set of three images has the same scale, for ease of comparison

of the mud and also the absence of salt marsh vegetation supported by the shape and size of the channels. Channel banks erode in very sharp bends where the flow separates from the inner-bend channel boundary and impinges directly on the bank on the opposite side of the channel (Winterwerp and Giardino 2012; Kleinhans et al. 2009) as can be observed in channel location C of Figs. 2 and 3c. The eroded soils deposited when the channels banks overtop were dynamically rearranged in the deltaic floodplains. The river propagation of the sediment loads during monsoons and channel storm discharges, combined with sea level rise, Earth subsidence and floods, enhances the erosive capacity and widening of the tidal channels (Barua

1997; Brammer 2014; Hassan et al. 2017). On the other hand, the accretion of fine sediments (channel location D in Figs. 2 and 3d) occurs as a result of overbank sedimentation enhanced by several factors including river slope, lateral channel movement at inner bends, base level and the occurrence and increased magnitude of channel discharge (Zwoliński 1992). Accretion processes, due to overbank flooding, create a shallow stratigraphy of finer-grained soil deposits, with sand deposits restricted to the channel thalweg, proximal levees and small crevasse splays along the stable, meandering channel floodplains. There is a later stabilization in aggradation which forms gained lands of shallow, intertidal flats colonized with mangrove vegetation (Wilson and Goodbred 2015). The interaction between the flood plains, channels and vegetation drives the tidal channels dynamics of the Sundarbans mangrove vegetated floodplains.

Terrestrial factors include river discharge, sediments, earthquakes, local neo-tectonics and land slope, which strongly influence the dominant erosion–accretion



**Fig. 6** Tidal channel bank change map of selected channel locations in the Sundarbans, Bangladesh between 2011 and 2017. **a** Tidal channel bank layers. **b** Tidal channel bank images. A1 was

taken from channel location A1, and B1 was taken from channel location B1. Each set of two images has the same scale for ease of comparison

processes in the tidal areas (Wadman 2008). Although the Ganges hydrological regime has generally reduced since the early 1970s in the Bangladesh part supplied by Gorai River, for instance from 3338 m<sup>3</sup>/s in 1962 to 500 m<sup>3</sup>/s in 2003 (Islam and Gnauck 2009), the Ganges River system delivers a significant amount of sediment to the coastal delta (Winterwerp and Giardino 2012). This sediment is usually transported by tides to the Passur tidal channel system. The seasonal monsoon (July to September) causes a major increase in streamflow, which erodes and accretes the tops of predominantly fine sand bars created by dynamic processes of erosion and deposition, natural levees and crevasse splays formed along local distributaries and breaches and proximal floodplains within the Ganges–Brahmaputra–Meghna delta (Wilson and Goodbred 2015). The sediment supply is due to the advection of river sediment transport and the reworking of sediment deposited in the lower deltaic plains by tidal currents. Upstream human activities, viz. establishment of dams and barrages and water withdrawals for irrigation, can have profound impacts on the morphology of the tidal channels in the Sundarbans. For instance, low sediment deposition as a result of very low discharge (sometimes nil) in the dry period, and erosion of the tidal channel banks and marginal areas of the forestland due to high discharge (around 4000–8880 m<sup>3</sup>/s) in flood periods, could be considered an effect of the Farakka Barrage (Aziz and Paul 2015) during this time.

The net accretion in the study area within the study period was 0.21 km<sup>2</sup> (130.75 km<sup>2</sup> in 2011 compared to 130.54 km<sup>2</sup> in 1974). Although variability in the physical environment and differences in subsidence, compaction and alterations of the tidal regime exist in the Sundarbans, the local tidal dynamics observed in the study area may be applicable to many parts of the Bangladesh Sundarbans, owing to similar floodplain areas, soil sediment types and vegetation homogeneities. The sedimentation process in the mangrove vegetated floodplains plays an active role in the increment of the aerial extent of mangrove forests, in mangrove species composition dynamics and also in maintaining forest elevation and stability in response to sea level rise. Rogers et al. (2013) observed that the Sundarbans is capable of mean annualized accretion rates of 1.1 cm/year on the tidal delta plain, which is roughly equivalent to the mean regional rate of relative sea level rise (RSLR) of 1.0 cm/year. This sedimentation process has helped the Sundarbans mangrove forest to remain relatively stable

over the past several thousand years (Allison et al. 2003) with no major land loss like in other parts of the world (Auerbach et al. 2015). The long-term stability of the Sundarbans reflects the robust capacity for the Ganges–Brahmaputra delta to disperse and aggrade sediment in response to historical and recently increased rates of effective sea level rise (Auerbach et al. 2015). If these rates of sedimentation and subsidence persist over the next century, the Sundarbans may continue to maintain its elevation and stability.

The channel dynamics of the study area may be the result of erosion (Fig. 2b) and accretion (Fig. 2c). Observed erosion dominance in the wider channels and accretion dominance in smaller channels (Figs. 3 and 4) may be a function of channel discharge currents via waves and tides. Wider channels are principal tidal/river channels with strong tidal and wave-driven bed shears that prevent the deposition of fluvial sediments and encourage erosion. Smaller channels are basically intertidal channels, and these channels are sometimes starved by discharge, which encourages accretion. Loss of land due to erosion causes tree falling (see Fig. 2b). On the other hand, new lands are gained through the accretion process, for example the island in the north-eastern part of channel location D in Figs. 3, 4d and 5 (z), which had developed by 2011. Texture of the soil in these areas is characterized by mainly silt loam and silty clay loam. The elevation of the newly accreted lands is comparatively lower than the other parts of the forest as these lands are still under the development process. Due to this comparatively lower elevation, which is below the average tidal level (varies between 1 and 6 m; Islam et al. 2014), most of the newly gained lands receive frequent inundation. As a result, these lands become more saline (salinity level 38,898 to 54,025 ds/m) (Islam and Gnauck 2009) and are dominated by salt-tolerant mangrove species such as *Ceriops decandra* and *Sonneratia apetatala*. The area under consideration for this research is occupied by mainly four different mangrove species viz. *Heritiera fomes* (8507 ha), *Excoecaria agallocha* (4673 ha), *S. apetatala* (925 ha) and *C. decandra* (188 ha). The salinity tolerance levels of various mangrove species found in the Sundarbans vary spatially (Ghosh et al. 2016). The bank line of the channel location A that experienced the major erosion during the study period was occupied primarily by the salt-tolerant species *C. decandra*, followed by the less salt-tolerant species *H. fomes* in the left bank, whereas the right bank was occupied by *H. fomes* entirely. As a result of

erosion, both the banks lost their bank line tree species and exposed the freshwater-loving *H. fomes* to salinity and made them vulnerable. Details are documented in Ghosh et al. (2016). On the other hand, in channel locations B and D, where the accretion was the dominant force, the newly accreted lands are colonized by the salt-tolerant *S. apeltata* trees. Most of the newly accreted lands are afforested by this particular tree species in the preliminary stage to help the sedimentation process, as a part of land reclamation policies and afforestation programs of the Forest Department (Ghosh et al. 2016). When newly accreted land is colonized by salt-tolerant trees, it is usually not replaced by other trees unless a deforestation process by artificial means or natural forces occurs. As a result, mangrove species that forests lose through land erosion, and new mangrove species that forests gain through accretion, are not always the same and this may have implications with respect to the composition and sustainability of some non-salt tolerant species, as documented by Ghosh et al. (2016). In addition, sedimentation in the forest has a substantial impact on the existence and vigorous growth of some mangrove species, since it raises the forest floor and the flow of tidal water becomes irregular. As a result of the irregular flow, some mangrove species that require regular inundation for their regeneration are not properly regenerated. While in the short term these changes are minor, over decades, the dynamics of tidal channel might have significant implications in mangrove species composition change in the Sundarbans, and these continued erosion and accretion processes raise concerns with respect to the future sustainability for some of the mangrove species and also the biodiversity of the Sundarbans.

The observations from this study and many others indicate that the delta coast as a whole can be considered relatively robust against environmental variability and perturbations, as reflected in the land gains which are largely consistent with rates over the last five decades. However, coastal areas of Bangladesh are potentially sensitive to changing sea levels, extreme weather events (viz. cyclones), increased levels of precipitation and warmer sea temperatures. As a part of Bangladesh's coastal area, the Sundarbans mangrove forest is not an exception. The situation could become more serious due to the changing patterns of global climate. It is expected that changing climate will influence and exacerbate those issues that the coastal areas are sensitive to. Several factors, such as rapid glacier melt, enhanced

monsoon precipitation and sea level rise, are expected to contribute to increased flooding risk and higher levels of storm surges along the Bangladesh coast, and the Sundarbans will be the innocent victim of these events (Mahadevia and Vikas n.d.). Although the sedimentation process helps the Sundarbans mangrove forest to remain relatively stable in response to rising sea levels, other aforementioned factors can affect the mangrove forest in the future. Continuous monitoring of tidal channel dynamics or tidal channel morphology is important for a thorough understanding and management of the forest ecosystem, as tidal channels act as a lifeline for the mangrove forest ecosystem.

## Conclusions

Tidal channel dynamics have been mapped in parts of the Sundarbans in this study over a period spanning 43 years (1974–2017). Aerial photographs and satellite imagery were used in remote sensing and GIS platforms to analyse accretion and erosion and locations in different years. The results showed that substantial displacement of tidal channel banks took place over the period 1974–2017. Although the demarcation was difficult for the Sentinel-2 image due to its coarse resolution, the large changes in tidal channel widths observed would not have been greatly affected by the less than 5-m error (the root-mean-square error was less than half a pixel during geo-registration) commonly associated with Sentinel-2 images. The channel changes were an order of magnitude higher than the errors associated with the images. Our analysis shows that the change in tidal channel bank location in some places was over a kilometre, and if this rate of change continues, then there could be major changes in the forest ecosystem. This could also affect the sustainability of the forest ecosystem and the biodiversity therein.

Moreover, studies are recommended to link data on rising sea levels, snow melt in the Himalayas, sedimentation rate, rainfall in the overall catchment, hydrological data, anthropogenic activities and other processes taking place in the Ganges delta and Sundarbans mangrove ecosystem. To predict the future of this important mangrove ecosystem in terms of mangrove community and their habitat, the results of this study could be integrated with other datasets such as those on mangrove species composition, sea level rise, snow melt in the Himalayas, sedimentation rate, rainfall data,



hydrological data and anthropogenic activities. These findings can also be shared with sustainable management planners, other relevant stakeholders and policy-makers for use in decision-making with respect to forest management planning in a sustainable manner.

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#### Compliance with ethical standards

**Conflicts of interest** The authors declare that they have no conflict of interest.

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