CHAPTER 3

COASTAL ENVIRONMENTS AND REGIONAL SETTINGS OF THE ISLANDS

3.1 Regional settings

The two islands under study, the Patibania island and the Henry's island, are located in between the estuaries of the Muriganga river and the Saptamukhi river. There are considerable differences between the estuarine characters of these two estuaries, which affect the regional settings of the two islands. In Figure 3.1, the division of the regional settings is depicted.

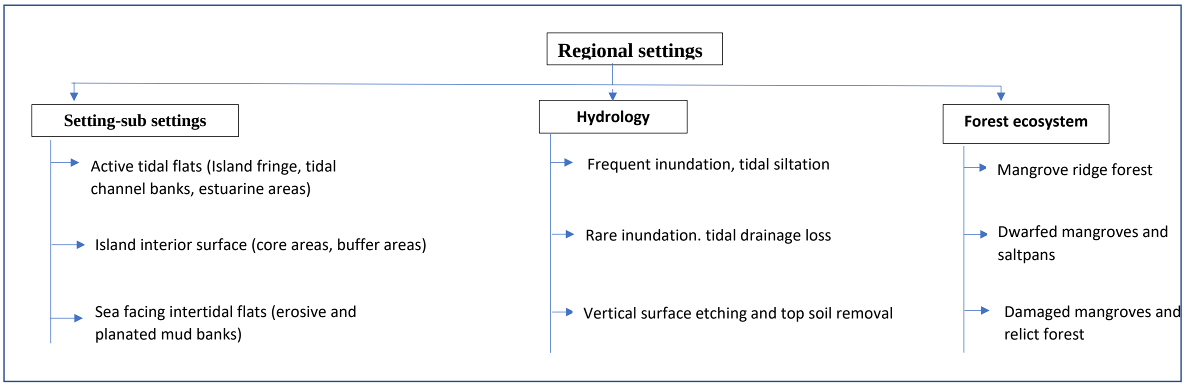


Figure 3.1: Regional settings.

The Muriganga river, being a distributary of the Hooghy river, has a perennial source of freshwater in its estuary. On the other hand, the Saptamukhi river is a tidal river, and has no such source of freshwater. This imbalance of freshwater flow is the chief cause of differences in the estuarine characters of the two rivers. The other main cause of difference is the layout of the two islands in the respective estuaries. The Patibania island is somewhat sheltered from the direct wave action of the Bay of Bengal, while the Henry's island is completely exposed to the wave action of the sea. Due to this, estuarine settings like tidal flats and mudflats are relatively more prominent in the Patibania island, while the Henry's island displays characteristics of an open coast, including wide beaches.

In Figure 3.2, the regional settings of the two islands are depicted. The area between the two islands is densely populated and contains the towns of Bakkhali and Fraserganj. Both are major tourist spots of the south-western Sundarban region. The Henry's island is separated from this area by a narrow creek, which is passable on foot in the non-monsoon season. On the other hand, the larger Edward's creek separates the Patibania island from the region lying in the middle of the two islands. The Edward's creek carries tidal water along the boundary of the Patibania island, and several smaller creeks and man-made canals carry that water in the interior of the island. The Bakkhali creek, the largest creek in the Henry's island, flows through

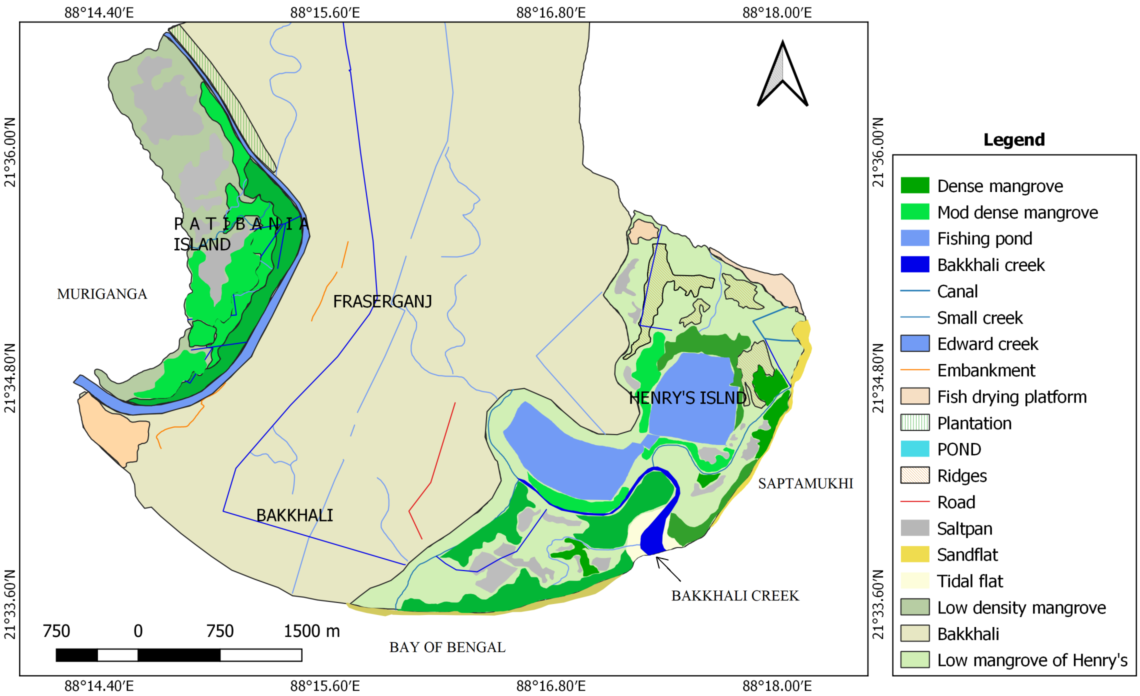


Figure 3.2: Regional setting of the study area.

the central region.

The regional settings of the study area can be divided in three components, which are the sub-settings, island hydrology and the forest ecosystem. Three sub-settings are the most prominent. One sub-setting is the active tidal flats, situated in the island fringe, tidal channel banks and the estuarine areas. The second one is the interior surface of the island, which is composed of the core areas and the buffer areas surrounding the core areas. The core areas are situated in the central region of the islands. The third one is the sea facing intertidal flats, which are affected by wave erosion and consequently contain planated mud banks.

The island hydrological setting can be divided in three parts. The first part covers the areas that undergo frequent inundation. These areas witness tidal siltation. The second part covers the areas that are rarely inundated tidally. These regions are the ones that have suffered tidal drainage loss. And the third part consists of areas that have witnessed vertical surface etching and top soil removal due to lack of soil moisture and associated erosion.

The forest ecosystem in the two islands can be classified in three categories. These are mangrove forest, dwarfed mangroves growing in and around saltpans and damaged mangroves.

3.2 Climate variabilities

The coastal region of south-western Sundarban, where the islands under study are located, experiences tropical dry and wet climate influenced by seasonal monsoon winds and maritime action of the Bay of Bengal (Paul, 2002). Normally, the coastal belt experiences heavy rainfall and humid climate due to its proximity to the sea. The rainy season in this region is confined to the months of June to October, when the south-western monsoon is present. The weather changes sharply in the coastal plains with the onset of south-western monsoon. This monsoon over Bay of Bengal consists of series of cyclonic disturbances which create heavy tidal surge to the low-lying areas of Sundarban.

Climate variabilities severely affected natural ecosystem, altered precipitation, create extreme weather events and causes ocean salinity and global sea level rise. Variability of climate is a continuous occurrence of floods, cyclones and storm surge. Major concerns of the researchers, climatologists, environmentalists, geomorphologists whether these extreme events are of natural occurring or results of anthropogenic modifications to environment. Deltaic ecosystems are most vulnerable to climatic variability and its anthropogenic activities affecting biotic and abiotic communities (Folland et al., 2002). Intergovernmental panel on climate change (IPCC) in its fifth assessment report projected global 1 m sea level toward the end of twentieth century higher than the last two millennia (Mengel et al., 2016). This report project that there would be substantial changes in climate globally by 2100 including ocean acidification, sea level rise to 59 cm, heavy precipitation, rise in temperature 6.4°C. Various scholars have analyzed the climate induced hazards and extremity of climates. The knowledge ofspatial and temporal evidences of climate variability has been instrumental in identifying the drivers of variability and examining implications on society (Oguntunde and Abiodun, 2013).

Climate change has posted huge impacts on biota and social livelihood of the people of Sundarban. Frequent coastal disaster in terms of climate variability have significantly impacted the future prospects of Sundarban. This research work has incorporated several climatic data like temperature, rainfall, relative humidity, evaporation, potential evapotranspiration data, cyclone, supercyclone, storm surge for last 20 years and 100 years consecutively. Detail discussion about the trends have been analysed in chapter 5. Climate changes is expected to have significant changes on hydrological regime of Sundarban. In addition to the altered hydrology sea level rise will have adverse impacts on the forest by frequent inundation and salt water intrusion in the river system.

Sundarban ecosystem is under constant risk due to sea level rise, frequent cyclones, storm surge, flood and coastal erosion. Sundarban has experienced an increase in the average air temperature by 0.50°C over the past 100 years (Sahana et al., 2019). If the present rate of increase continues, the average air temperature will rise by 1°C by 2050 (Hazra et al., 2002).

3.2.1 Increasing temperatures

The temperature of Sundarban has been increasing in accelerated rate by 0.5°C per decade for last 30 years. The projections for global average temperature rise to the end of the twenty-first century is 1.1 to 6.4°C (Ghosh et al., 2015). Increase of this accelerate temperature pattern negatively affect the generative capacity of mangroves including phenological pattern of mangroves like their flowering and fruiting times, mangrove productivity, species composition etc. High temperature also increasesthe aquatic life of the ecosystem. Sundarbans account for 85 per cent of all mangrove habitats of the India, Due to the accelerate temperature, seven of the major mangrove species species group are threatened and require immediate conservation measures, viz., *Aegicerascorniculatum*, *Heritiera fomes*, *Kandeliakandel*, *Nypafruticans*, *Rhizophora spp.*, *S. apetala* and *S. caseolaris. D* (Mahadevia Ghimire and Vikas, 2012).

3.2.2 Rising sea levels

Climate change also induce sea level rise that would increase back water effect in the major distributaries of the rivers, which would tend to push saline water into the island and affect ecosystems. The backwater effect retards the flow of freshwater and make prolonged inundation of the islands and leads to sedimentation. For the last 25 years sea level has risen up at a global average. Intergovernmental panel on climate change (IPCC) in its fifth assessment report projected global 1 m sea level toward the end of twentieth century higher than the last two millennia (Mengel et al., 2016). Gentle slope, lower elevation and very high tidal amplitude are also attributed to sea level rise at Diamond Harbourand surrounding areas of Hooghly estuary (Pramanik, 2015). Continuous inundation at coastal wetlands makes the mangroves as narrow, short and dwarf. Saline water intrusion affects the agricultural system of low-lying areas of Sundarban. Ecosystem functioning disturbed due to sea level rise and coastal flooding.The rising of sea level may affect some edaphic changes, generally changes of soil and salinity, tidal dominated flat surfaces and groundwater also. Though mangroves adapt themselves with

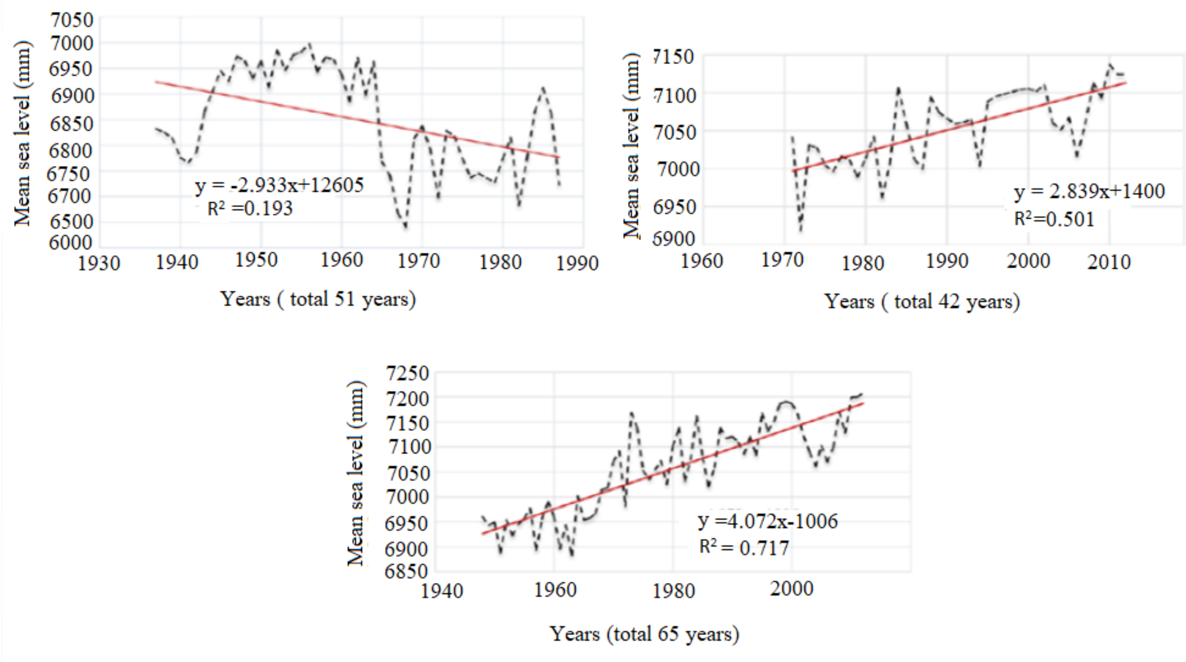


Figure 3.3: Yearly sea level fluctuations.

increasing salinity but if the sea level exceeds their threshold limit then mangrove would not adapt the salinity and change its physiological character. So it can be said that mangrove dominated deltas Sundarban shifted their position due to the responses of sea level rise.

3.2.3 Cyclones

Tropical cyclones and storms are very common in the Bay of Bengal. According to Koteswaram, there were about 346 cyclones that include 133 severe ones in the Bay of Bengal, whereas the Arabian Sea had only 98 cyclones including 55 severe ones between the year's 1891 and 1970 (Mitra et al., 2020). Frequency and Intensity of cyclones has increased in Sundarban since 1960, this is due to the rise of sea water (27°C) temperature at Bay of Bengal. Occurrence of cyclones influence the intensity of storm surge and the height of surge which indirectly affect the ecosystem and livelihood of coastal low-lying people. In Figure 3.4, the number of cyclones in each year from 1876 to 2020 is presented. It is observed that the frequency of cyclones in the Bay of Bengal is increasing. Intrusion of saline water has the high probability to alter chemical composition of soil and water within island area. For example, storm surge reached inland up to 120 km during supercyclone Aila. In Figure 3.5, the seasonal and the monthly frequency of cyclones in the years 2007–2020 are presented. It can be seen that the highest number of cyclones occurred in the months of May and November.

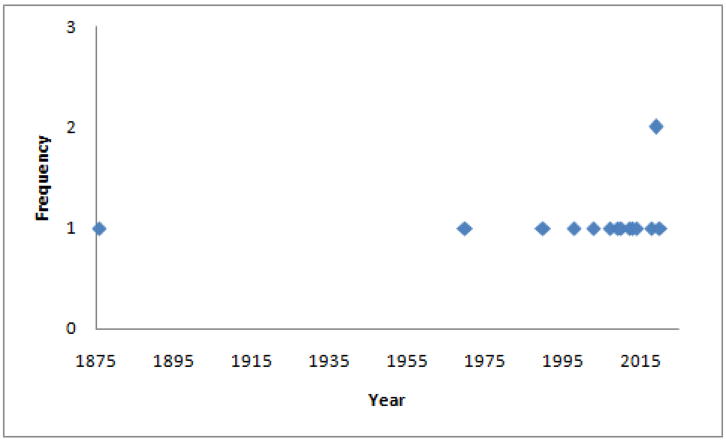


Figure 3.4: Yearly frequency of cyclones in the Bay of Bengal (1876–2020).

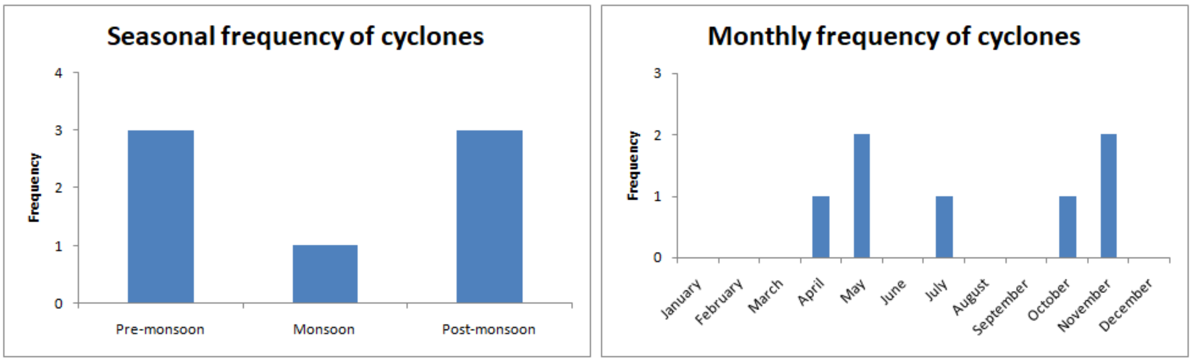


Figure 3.5: Seasonal and monthly frequencies of cyclones (2007–2020).

3.2.4 Rise in salinity

Sea level rise, high storm surge increase salinity in the water and soil that would indirectly alter the agriculture and mangrove ecosystem services. Though mangrove acts as a barrier to the salinity but when the level of salinity exceeds its threshold limit then mangroves would face a severe degradation. The problem of salinization is caused by prolonged time of inundation under the sea water during storm surges. Soil, habitat stratigraphy, groundwater, drinking water all are affected by salt water intrusion. Entire ecosystem of Sundarban would remain under threats. Mitra et al. (2020) identified salinity of sea water has increased by 21.5% after Aila.

3.3 Coastal morphodynamics

Coastal system exists largely within an energy with dissipative environment with temporally variable inputs of wave and tidal energy forcing (Jackson et al., 2005). Morphodynamics of coastal area mainly deals with hydro dynamic and hydro meteorological characters of coastal

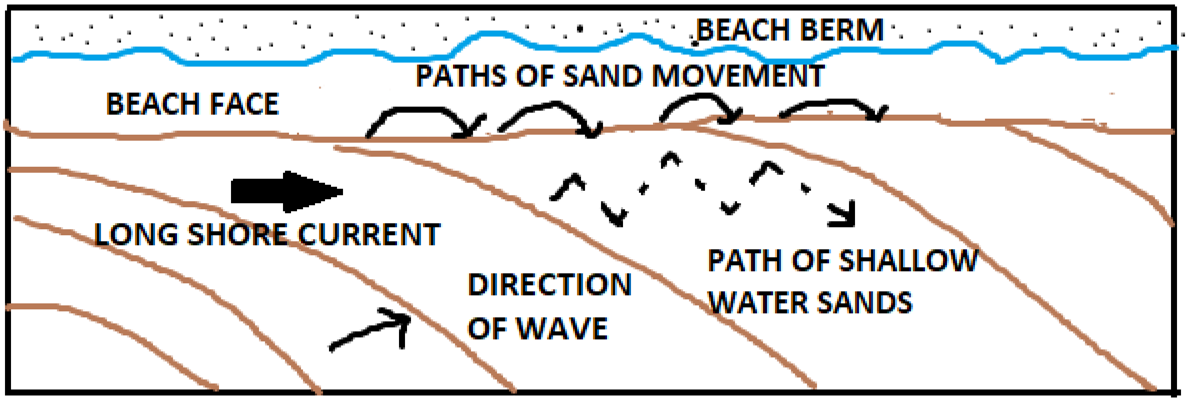


Figure 3.6: Dynamics of coastal processes.

environment. Marine components shaping the coast including wave, tide, currents, wind, sediment load, freshwater influx, sea level etc. When wave breaks its energy, which was received from wind is get dissipated. Some energy reflected back to the sea based on slope of the beach, the shallower the angle of the beach slope the less energy is reflected. Action of wave and swell tend to build up beaches, whereas storm surge erode them out. Wind speed, duration of movement, fetch time of wave determine the wave action on the coast. (Figure 3.6)

South western Sundarban which is a open coast receives a high proportion of long waves that traveled from Bay of Bengal and gradually the shorter waves have been formed with them in the shallow water. Normally longer waves generate during the periods of storm. The fetch of the waves which approaches to the shore, generated by south-easterly wind is 500 to 900 km then the wave which is generated by south westerly wind. Higher velocity waves and greater height bring changes in coastal morphodynamics. Swelling wave which comes from the place of origin not locally generated, propagates energy within an angle of less than 450angle. Breakers are also a integral part of wave dynamics. Breakers are observed on beaches during a storm when the waves are short and steep. In Bakkhali coastal belt plunging breakers are seen. In changing of beach morphology high energy breaking waves remove materials lower beach and deposit on the upper part creating berms. In South western Sundarban specially in Bakkhali beach ridge and runnels are seen in the lower part of the beach. (Plate 3.1) Currents plays vital role in sediment transportation and it accelerates erosion to modify land margins of the coastal tract. Waves increases their energy by the presence of currents. Sundarban estuary has funnel shaped, fed by river mouths and tidal channel mouth. This estuary helps to penetrate storm surge which generates in Bay of Bengal. The energy of tidal currents varying with time and position., at the same time wave propagates into an estuary during ebb tide progress into

Plate 3.1: Beach morphology of Bakkhali coast: ridges and runnels (top left) and beach berms (top right).

stronger currents. Currents at coastal belts which modify the beach topography are long shore currents, rip currents tidal currents and wind driven current.

Longshore currents are the result of breaking of waves on to the beach and it creates extensive beach erosion. Deposition of sands on the beach is played by swash which moves diagonally up the beach. Longshore currents cause extensive beach erosion. Rip current is active on the sloping beach it brings modification on the subtidal reaches of coastal zones. In Hooghly estuary movement of sediments are controlled by tidal currents mixing of fresh and silt water (Paul, 2002). Strong tidal currents move bedloads and suspended loads into channels from sea, so the estuary of Sundarban is dominated by marine sediments.

3.4 Sea level variations in the Holocene Period

Coastal environmental settings are defined on the basis of geomorphic elements, background of geophysical environment, biological activities of coastal region. The influence of physical factors of the coastal environment are discussed at region level in this following section. Holocene defined as 11,650 to 7000 calibrated year before 1950 (BP), at this time a widespread environmental change occurred. Rising of temperature rapidly, and melting of glacier severely affected coastal islands (Smith et al., 2011).

Present sea level has reached its position between 5000 to 6000 years ago. Sea level refers to the level of the sea surface without reference to the land and relative sea level (RSL) refers to the level of the sea as observed at the coastline. For the period from roughly 6000 years ago the amount of sea level rise estimated to have been just a few meters. From the bio stratigraphic,

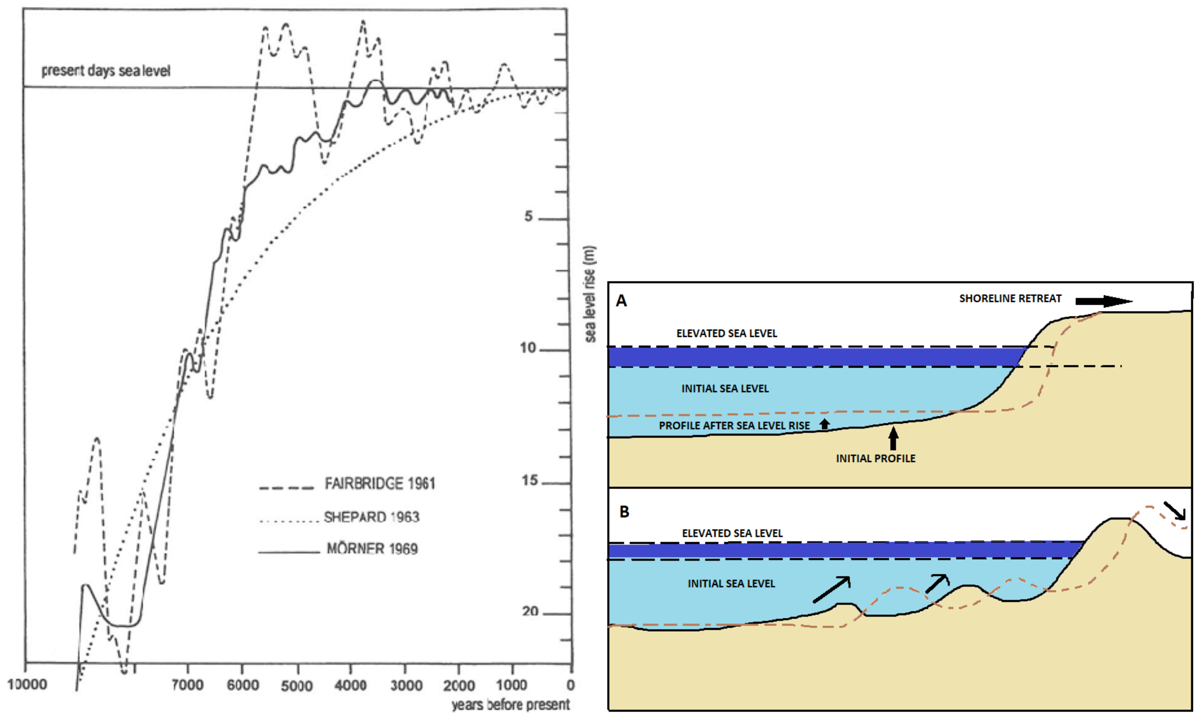


Figure 3.7: Holocene sea level rise (after Gambolati et al. (1998)).

lithofacies and geomorphic records of sea level indicators said that sea level rise was continuous during the early Holocene stage. Early Holocene sea level rise was a significant jump in sea level by 60 metres. During de-glaciation since the last glacial maximum, between about 20000 to 7000 years ago, the sea level rose by a total of about 100 m. It occurred at the time of extremely high rate of rapid melting of Antarctic ice sheets. At the onset of de-glaciation about 19000 years ago during glacio-eustatic event contributed 10 m rise to the sea level water. During the early Holocene sea level varied from a low of about 6.0–9.9 mm per year as high as 30–60 mm per year.

The rapid rise of sea level between 12000 and 10000 YBP in the Bengal basin identified by Umitsu (1987), this phase was called "Flandrian transgression". In this phase sea level was significantly higher above the present sea level. Islam and Tooley (1999) proved the evidence of five periods of marine transgression and each followed by regression during Holocene (9000 YBP). Transgression II and Transgression III (between 6615 – 6415 YBP) and (6315 – 5915 YBP) had higher rates of relative sea level rise then the third Transgression in the sea level. Sea has resided in Indian Sundarban by 4000 $\pm$ YBP due to another stage of marine Transgression. (Figure 3.6)

Sundarbans mangrove forest initially colonized this western area of the delta around 9000 BP, extending south as the delta front prograded (Sarkar et al., 2014). A temporary hiatus of mangrove occurred in 450 BP due to mid Holocene sea level high stand but re advanced to Dampier–Hodges line. Holocene sea level rise increases surface area of the intertidal flow of the creeks of the deltaic islands which indirectly affect flow velocity and erosion rate on the estuarine system.

3.5 Sediments and island system

Sediments of sandy beaches and flats are deposited by tidal waves and rivers. Creek beds become higher with the deposition of eroded materials from the island. Eroded materials of coasts are being deposited in the offshore areas by tidal currents. Waves and tidal currents interact on sand dominated intertidal flats to produce extensive areas of asymmetrical and symmetrical ripples.Ripples are well developed on the sand dunes and dry sand flat when there is relatively low wind energy interact with sand surface.Several ripple marks are identified on Bakkhali, Henry's and Patibania islands of south western Sundarban due to combined action of tides and waves.Parallel, cross laminations, lenticular, planer types of ripples which are disrupted by roots of plants and rootless of dune plants (Plate 3.2).

During pre- and post-monsoon season muds are deposited in the adjoining sea ward edge of salt marsh and mangrove swamps by the process of flocculation.

Wind system and tidal current dispersed silt which accumulate over the marshes and swamps in huge amount because the fully grown vegetation with the intricate pattern of roots and its trapping capacity. Sources of sediments are land driven inorganic sediments by riverine floods, sea derived sediments by cyclonic storms. Organic sediment is supplied by suspended load. Sediment trapping is operated by saltmarshes and mangroves, Sediments are accreded into tidal flat plains. Algal mats agglomerate suspended sediments. Flocculation increases at the seaward edge at the time of high salinity, where coagulation of particles increases through biological activity.

Henry's and Patibania islands lie in between Saptamukhi and Muriganga estuary, sediments of these islands are composed of clay and clay loam. Sedimentary structures are well developed in these sandy shores,sand flats and sand dunes.Ripples are more or less common features of the coasts of these two islands.Wave generated ripples are found in the beach face they are symmetric and asymmetric both types. Some ripples are flattened top, some are straight crested, sinuous bends bifurcated in plan. Asymmetrical ripples are formed without wave influence.

Plate 3.2: Wave action in Bakkhali coast: symmetrical wave ripples at Bakkhali beach (top left), symmetrical ripples with continuous and straight lines at Bakkhali beach (top right), asymmetrical ripples with flat topped crest at Kiran beach at Henry's island (middle left), asymmetrical ripples with continuous crestlines at Fresergunj beach (middle right), wave ripples with transverse ridge crests at Patibania island (bottom left), biogenic activities on wave ripples at Frasergunj beach (bottom right).

Those are formed based on water depth and velocity. Shoaling wave caused straight crestline ripples. Rhomboidal ripples (Plate 3.3) are seen in Bakkhali coastal region, which are formed by backwash current at the steeper part of the beach.Swash marks are observed in the intertidal swash zone developed by upward movement of wave.

Plate 3.3: Rhomboidal ripple marks and mud balls: rhomboidal ripple marks in Bakkhali (left), mud balls along intertidal zone (right).

Micro rill marks are developed on seaward sloping surface of swash ridges. These marks are seen in Frasargunj and Bakkhali coastal belt mostly where low wave energy prevails. Erosional structures like sole marks are found in upper and middle foreshore of the sandy coast. Large size clay balls. (Plate 3.3), dead shells, wood fragments, bricks are seen at sea beach. These structures create obstacles to the backwash waves on the shore. As a result, a crescentic shape scour develops around that obstruction at upstream side. The eddy pattern movement of water create various size of scour pools. (Paul, 2002). Another type of scour mark named flute marks are observed on sediment surface by the action of current direction and slope action of tidal surface (Plate 3.3). Longitudinal scour marks found in closely spaced parallel ridges and furrows in the sloping flats of clay and silty beds. In transverse scour, scour troughs are rather sharp. The rate of erosion reduces beneath ascending limbs of spiral eddies where stress effect of current is low. This longitudinal scour is found in Bakkhali, Fresargunj area.

Cohesive sediments on the upper surface are eroded away by the strong winds. When some objects are dragged on the cohesive surface, then some semi rounded and disc shaped grooves are formed on the sandy shore.

Plate 3.4: Beach features: series of longitudinal scour channels at Henry's island coastal stretch (top left), tree stumps of degraded mangroves at Fresargunj coast (top right), formation of clay mud balls at Patibania island coast (bottom left), mud balls at Patibania island coast (bottom right).

3.6 Tides and waves as physical drivers of the coastal environment

Tide plays vital role in modern coastal process. Several coastal landforms like mudflats, marshes, estuaries, beaches are developed on the basis of frequency and range of tides. Tidal amplitude records4.88 m to 5.93 m during September at the Hooghly mouth, whereas the range is 4.41m to 6.80 m at Garden reach (Paul, 2002). The semi-diurnal tidal fluctuation experiences by Bakkhali coastal region. Sundarban estuary is a macro tidal funnel shaped estuary (Wells, 1995). If the tidal range exceeds 4 m it produces strong tidal currents which reaches upto hundreds of km.Tidal water flows to 300 km inland up to Nabadweep in Hooghly estuary. Estuaries with such a tidal range do not possess the ebb-flood delta of the meso-tidal range (2–4 m) instead the central channel near the estuary mouth is occupied by long linear sand bars parallel to the tidal flow (Pethick, 1984). Flow and ebb tides occur twice daily and the current changes its direction in the estuary. Spring tides which occur at the HAT (phase) during August and September produce the maximum rise and fall due little currents in water. Meteorological conditions can considerably change the height of a particular tide and time at which occur (Wright and Thom, 1977). Wind can hold back the tide and push it along to pile up along coastlines. From the record of tide water table of Sagar island presence of two neaps in a month, completing spring and two incomplete spring tides.

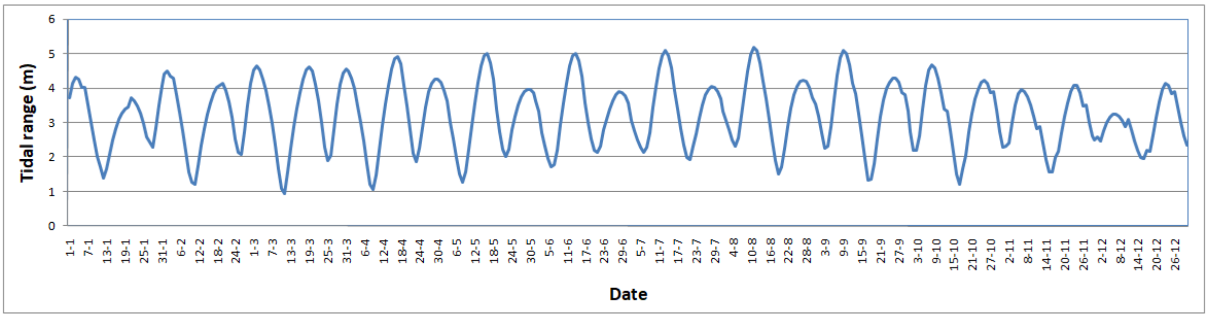


Figure 3.8: Tidal range of Sagar station, based on tidal data 2018

Atmospheric pressure and wind cause the actual tidal level Deflected from expected level. Tides tends to unusual rise when spring tides coincide with cyclones in the coast. But in the monsoon season enormous discharge of freshwater through riverine water modify the tide surge situation in the coastal environment. To estimate the tidal range at Sagar station a graph has been prepared on the basis of tidal data of 2018(Figure 3.8).

Surge originating in the Bay of Bengal cause Saline water intrusion, and inland flooding which affected groundwater quality, agriculture of the coastal areas. Pre-monsoon, monsoon and post-monsoon season tidal fluctuations are maximum. To get the idea of tidal fluctuation in three seasons at Bay of Bengal three months tidal data plotted (January, March and September) (Figure 3.9).

On the basis of height and time of the high tides and low tides, frequency and range has been estimated for the all months of a year. January, March and September months plotting have taken for considerations as pre monsoon, monsoon and post monsoon season. In January, March and September maximum tidal frequency reaches to the tidal range 0.56 m to 1.76 m, 0.36 m to 1.46 m and 0.68 to 1.98 m respectively. In September month i.e., post monsoon season when maximum cyclones occur exceed the height of normal tidal level create disaster. (4.59 to 5m).Tidal range is maximum in post monsoon season(September),then monsoon and pre-monsoon season (Figure 3.10, Figure 3.11, Figure 3.12).

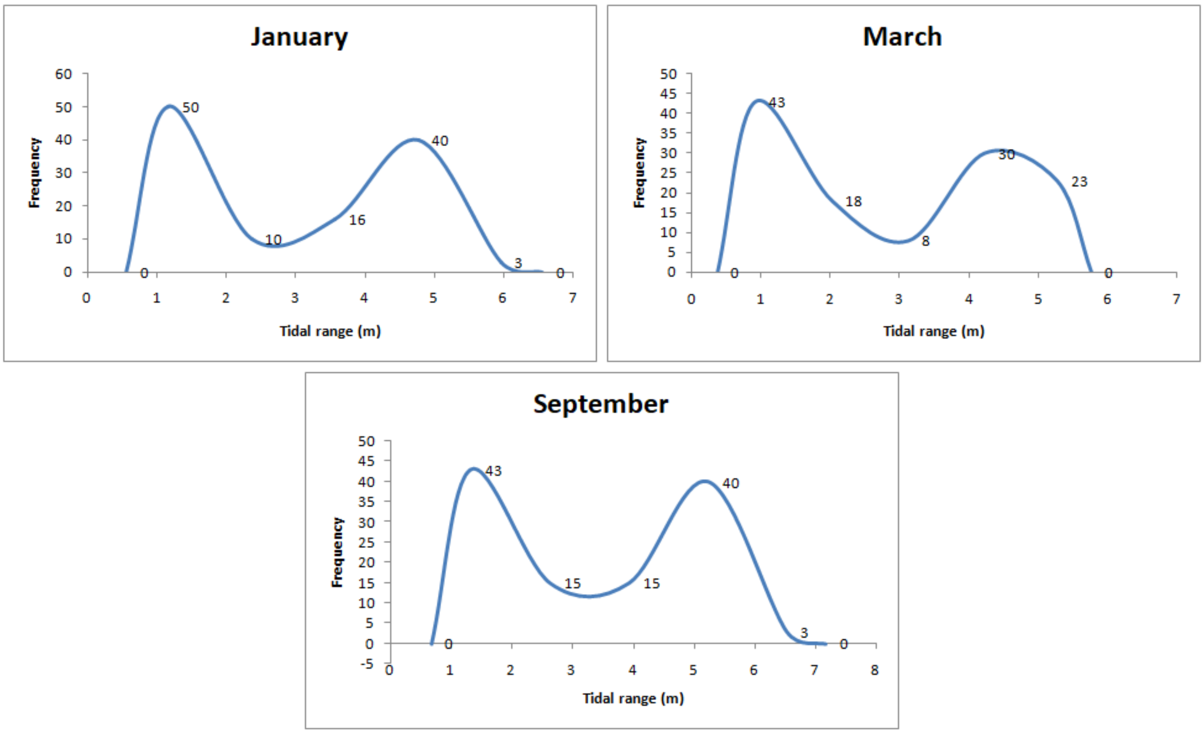


Figure 3.9: Types of tidal fluctuations at Sagar Island in January, March and September. Source: Tidal data of Port trust, Kolkata, at Sagar station (2018).

When there is a rising of tide propagate wave front into he river or bay it is called tidal bore. Most of the time this bores are large and three metre height. This energy of tides sweeps out the riverbeds silts from lower section and deposit them on the narrower part of the river. Siltation causes deterioration of channels and tends to rise the tide level at coastal stretch.

Among the marine energy wave is the prime capacity to alter, shaping and reshaping the coastal morphodynamics. Wave contributes in mixing deep and shallow water.as turbulent kinetic energy is enhanced at the surface by wave breaking.The mean wave momentum, or Stokes drift contributes advection as a surface intensified current as a mean current.

Surf zone, beach morphometry for every depositional landform is governed by wave activity. Temporally, spatially variable energy regime is dominated by waves.The nature and severity of the hazards which are attendant on the rapid advances and retreats of bars and shorelines and on the associated water motions also vary with time and place (Wright and Short, 1984). Irregular bathymetry, position of bars and offshores control wave movements and they break at greater heights along the bars and islands. Wave strike almost parallel to the shoreline. When storm wave coincides with high tides it produces scouring on the beach face. Unconsolidated sediments of dune and the mudbanks may erode by the strong sea level wave, Therefore, it is said

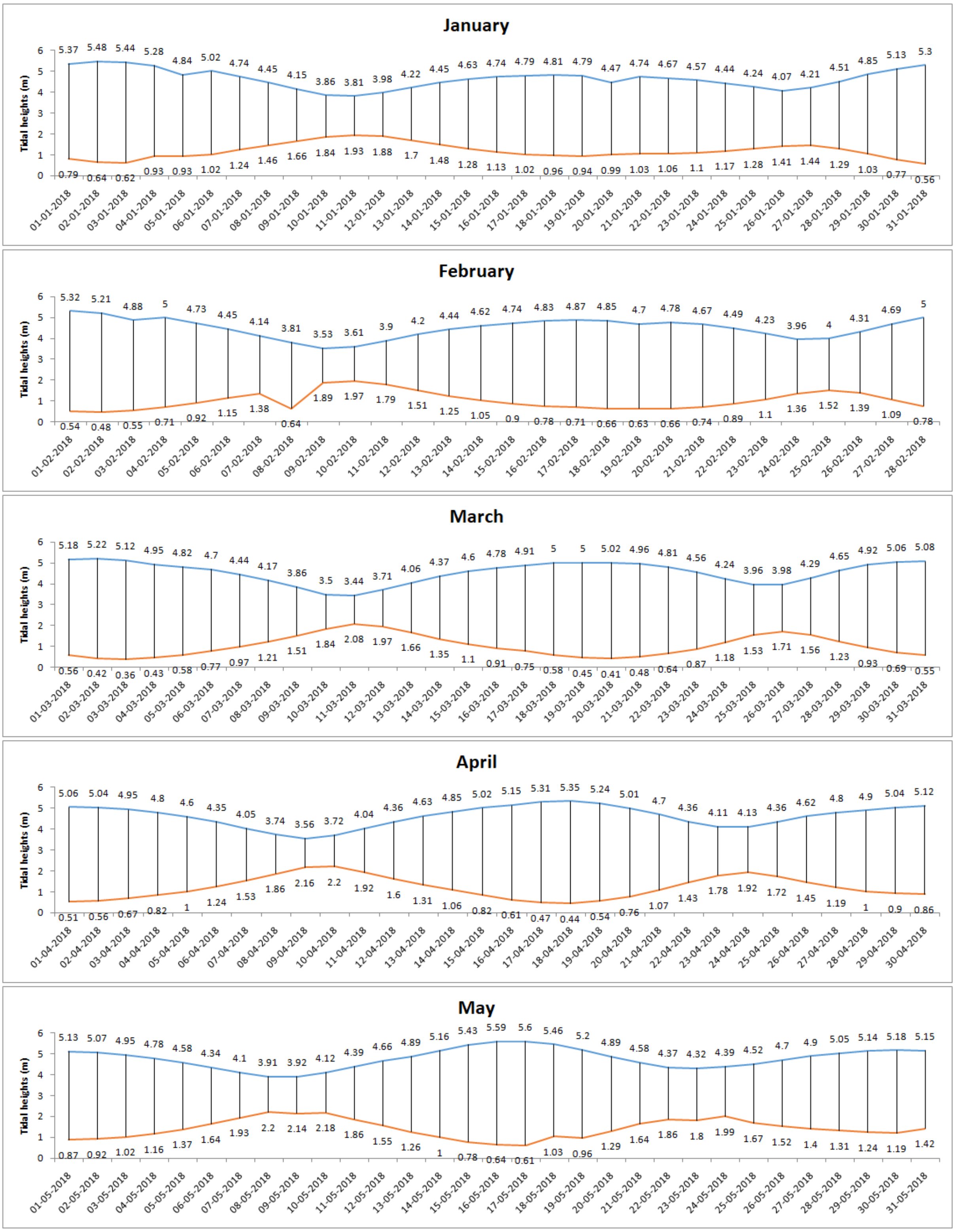


Figure 3.10: Tidal fluctuation map of all year in Sagar island based on tidal data of Port Trust, Kolkata, at Sagar station (2018).

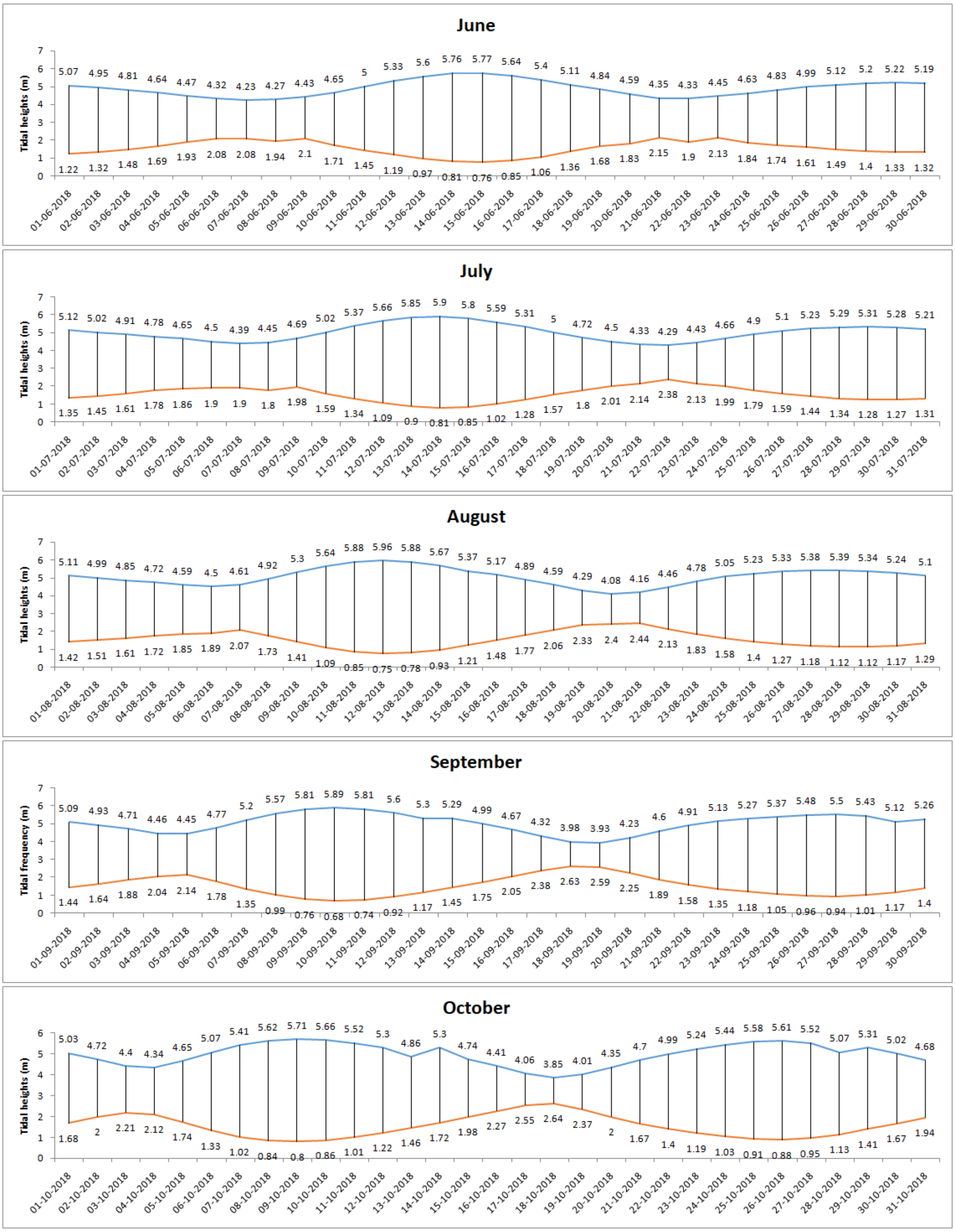


Figure 3.11: Tidal fluctuation map of all year in Sagar island based on tidal data of Port Trust, Kolkata, at Sagar station (2018).

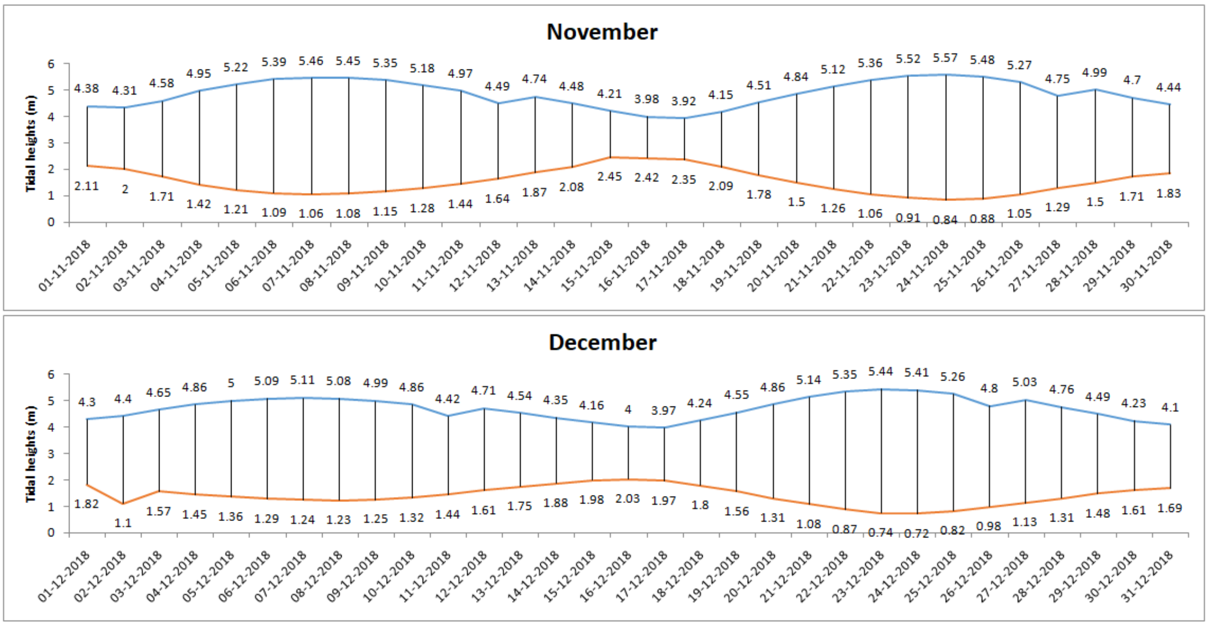


Figure 3.12: Tidal fluctuation map of all year in Sagar island based on tidal data of Port Trust, Kolkata, at Sagar station (2018).

that Coastal environment and its nomenclature is controlled by action of wave and its frequency at the tract. There are several rills marks, swash backwash marks are found in the Bakkhali and Henry's island coastal region. Extensive beach ridges, sand flat, beach cusp, beach berm, sand dunes are developed due the action of waves for a prolonged period. These features are the indications of raised surface of the South Western coast of Bay of Bengal. Based on the raised landform and wave height and frequency growth of vegetation along the beach ridge and dunes are grown up. This is how tide and waves act as a major driving force in the coastal belt.

3.7 Coastal hazards: storms and floods

Sundarban experiencing more frequent and intense natural disaster since last few decades. South Western part is more vulnerable as it exposed to many weather events like stroms, coastal flooding, sea level rise and storm surge. Occurrence of cyclones and formation of depression in the Bay of Bengal are mainly due to high surface temperature of Bay of Bengal than Arabian sea. Apart from these low-lying plain topography and flat surface (1.7 to 2.5m) elevation are exposed to any kind of coastal hazards. Storms and coastal floods, river floods are extensive in the deltaic low lands due to poor drainage condition, high and low water table. Prolonged and high intensity rainfall during the post monsoon season (September-November) coastal lowland experience flooding. Coastal plain of Sundarban prone to storm surge. Due to funnel shaped estuary at the mouth of Bay of Bengal provide enough scope for the amplification of surge in the period of cyclones.During in monsoon season Ganga Delta experience depressions formed at the Bay of Bengal. Monsoonal surge or depressions modify local tides as well as the surging wave heights into severe storm surge during cyclones in this period. Damage potentials increases in Sundarban in last few decades. There are several factors are responsible for the coastal storms identified by Paul (2002).

Table 3.1: Factors affecting the severity of coastal storms in West Bengal (after Paul (2002)).

FACTORS	EFFECT
Coastal shape	Funnel shaped river mouths sustain more damage because the water is driven into a confined area by the storm, which increase storm surge and storm flooding.
Nature of coast	Low lying deltaiccoast criss crossed tidal creeks, islands, sand bare flats, shorelines are exposed to severe destructions by over washes and storm surges.
Wind velocity	Damages of storms are controlled by wind velocity and direction. Severe cyclonic storm has high wind velocity higher than 80 km per hour. According to Irrigation and Waterways Dept. West Bengal Govt flood banks of reclaimed lowlands can withstand only 50-60 km wind speed and wave dash activities.
Human activity	Property damage increases in the successive storms, due to over populated areas of coastal low-lying region.
Previous storm surge	Sundarban areas were affected severe storms since 1942 to till date. Thus, the coast is subject to proportionally greater damage in a subsequent storm.
Storm surge height	The storm surge height exceeds 3m can cause immense damage in the coastal tract of Sundarban.
Storm centre velocity	Slow movement of storm centre cause greater damage. It develops over Bay of Bengal and move north, northwest or north east of the West Bengal coast with sufficient time.

Cyclones hit Sundarban with high wind speed,torrential rain and tidal wave which causes massive damage on the living population of coastal belt. Breaching of embankments, create coastal flooding, bring physiographic change to the isolated islands and intrusion of salt water into the islands, erosion of bank lines, land use changes, loss of human population, changes in socio-economic condition of the coastal region. The factors behind such devastation already discussed but some issues should be emphasized more. Increased pressure on land and economic activities blocks tidal channels. Land reclamation strategy not only reduce tidal spill but it reduces tidal prism also. All the estuaries of Sundarban are different from each other so unscientific building of embankments along the coastline create negative impacts on hydrological regime. A table has been prepared of cyclones on the basis of tidal surge, windspeed and occurrence in Bay of Bengal (Table 3.2). All the storms associated with high wind speed, torrential rain and tidal wave caused massive damage to the coastal areas. Among all the cyclones and super cyclones, impact of Aila was massive. It hit Sundarban on 23rd May, 2009. Wind speed was 110 km/h. It was the worst natural disaster then Sidr in 2007. Storm surge height was 3 m. Approximately 9,20,000 houses were uprooted.The major rivers like Matla, Gosaba, Piyali-Bidyadhari, Saptamukhi, Kalindi, Muri Ganga, Hugli and Harinbhanga were flooded and about 500 km embankments on the village side were washed out and have caused large scale flooding, leaving lakhs of people marooned in the area.Saline water gushed in through breaches in the river dykes and inundated houses and lands.

Table 3.2: Occurrence of cyclone in different year at Bay of Bengal (source: IMD).

DATE	NAME	LOWEST PRESSURE (mbar)	WINDS (km/h)	STORM SURGE HEIGHT	FATALIITY
November 3,1970	Bhola super cyclone	966	185	6-7m (20-25 ft)	300,000 to 500,000
	Bangladesh Super Cyclone	918	250	6m(20ft)	1,38,866
	Odisha Super Cyclone	912	276	5-6m(16ft)	9887 to 12000
November 15, 2007,	Cyclone Sidr	944	215	3m(9.8ft)	3447 to 15000
	Cyclone Rashmi	996	85	2m(6ft)	28 to 100

May 23, 2009	Cyclone Aila	970	120	2-3m	339
	Cyclone Komen	986	85	1-2m(3.3ft-6.6ft)	187 to 280
26-Apr-19	Cyclone Fani	932	215	2-3m	89
05-Nov-19	Cyclone Bulbul	980	145	1-2m	41
20-05-2020	Amphan Super Cyclone	925	260	5-6m(20ft)	118

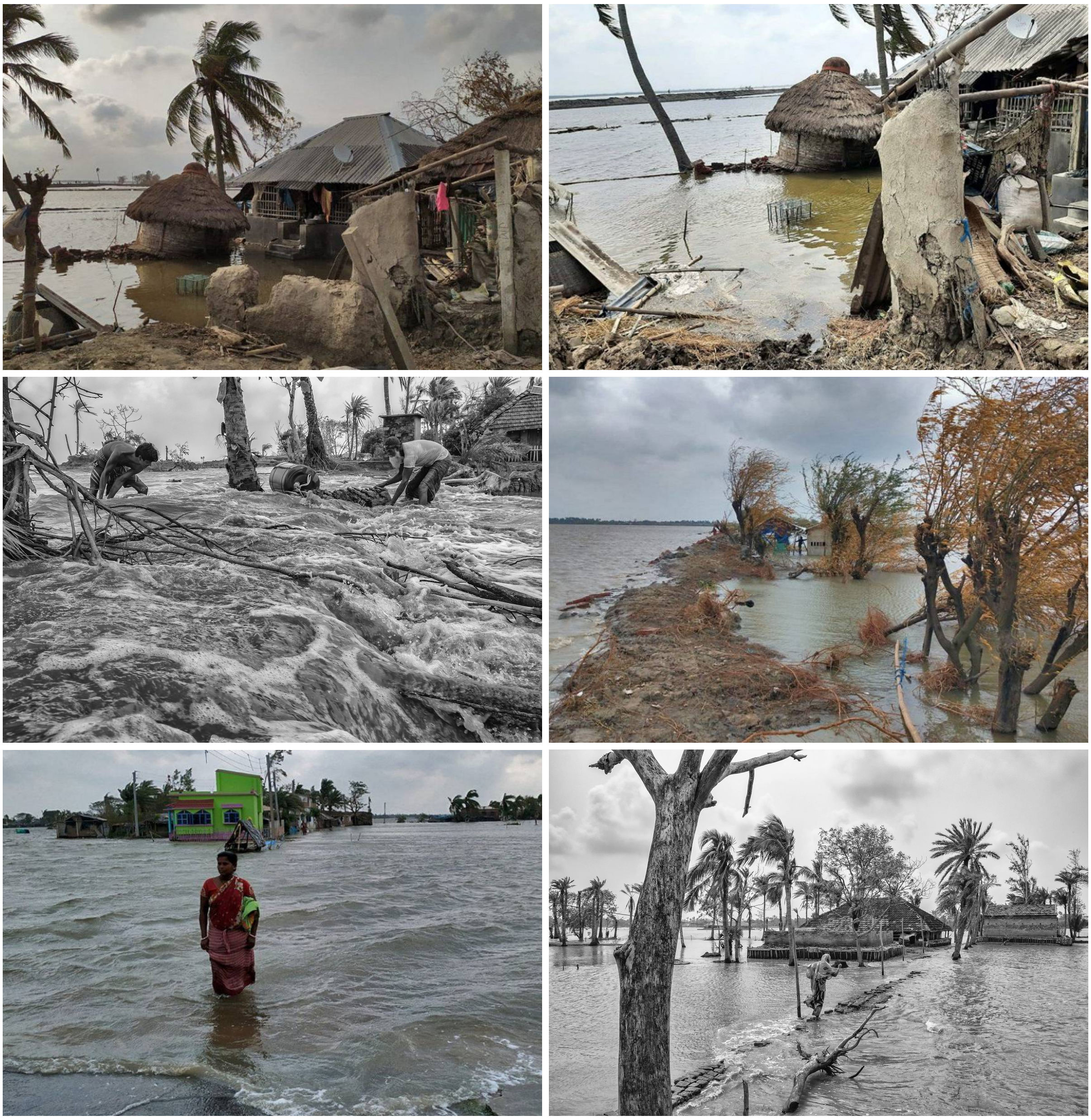


Plate 3.5: Impact of Amphan on the coastal belt of Sundarban (source: ABP).

In West Bengal 32 percent of cyclones cause flooding on coastal low lands occur main in post monsoon season. Sometimes in the pre-monsoon season few cyclones cause coastal flooding that coincide with onshore winds and spring high tides. High downstream discharge, annual tidal level amplifies the storm surge in lower delta of Sundarban (Paul, 2002). As an impact of coastal flooding, salt encrustations on the soil has increased which leads to the development of saltpans within basinal areas. The area of saltpans increases after Aila in 2009. Recent super cyclone Amphan which hit Sundarban in 20th May 2020 with 260 km/h wind speed. Storm surges estimated 2 m. Wind speed was maximum then Aila.Inundation period of Amphan is less then Aila (Plate 3.5).

Plate 3.6: Impact of coastal hazards in Fraserganj, Sundarban.

Amphan pushed 15 km water inland part of Sundarban. Bakkhali, Henry's islands are severely affected by Amphan breaching of embankments, human loss, salinity level increases, coastal flooding, Land use change, severe impacts on aquaculture, submergence of mangrove, ecosystem disrupted due to changing level of salinity in the coastal systems (Plate 3.5).

Embankments are designed by the Irrigation department to prevent flood but these can't withstand with the devastating effects of super cyclones like Amphan (Plate 3.6).

3.8 Beaches and bars

Any physiographic region can be characterized by several morphogenetic and hydro genetic landforms. They are developed by sediment supply, transportation capacity of wind, subaerial process, relative level of land and sea, low lying deltaic surface, Phyto geomorphological and zoo geomorphological factors and lastly human control on catchment areas. Beaches are linear coastal features those are developed along the shoreline act as a buffer to absorb or diminish the wave energy driven by tides and winds (Paul, 2002). Sediments are being supplied to the beaches by sea. These sediments are transported to the shoreline with the interacting process of wave and longshore currents. Beach can change its shape with changes of wave energy in the annual storm signatures. A tropical coast is affected by swell wave and it has wide sandy beach along with berms. To analyse the beach morphometry, several beach profiles are drawn on Bakkhali and Kiran beach of Henry's island. Sediment movement within this zone are modified by the wave action which indirectly change beach profiles.

There is a close relationship between gradient of the beach and wave steepness. From field visits it can be said that breaker types and narrow or wide beaches have close relationship. To examine the beach profiles, beach sediment size, wave height and sediment transport process must be studied. In Henry's and Bakkhali areas lowering of beach plains are very significant characters.

In Bakkhali six profiles are drawn. The first profiles starts with backshore or upper dry part and covering sand flats, runnel and finally reaches lower mud bank which is nutrient rich zone therefore animal burrows and activities of beach organism are prominent. Wave action is able to penetrate to the backshore areas in the high tide and as a result cliff erosion is accelerated. Coarser to medium sand size particles are distributes from foreshore region. In other profiles tidal was over deposits supply finer sands which accumulate at beach face. However, the sands are moderately sorted, probably with variable seasonal energy distribution over the beach face angle.

Beach profiles always get changed after a coastal floods or super cyclones. In winter season low flat waves with higher onset velocity modify beach morphology by up drifting sediments. Beach profiles reveals that high angle beach face is the favourable condition of backwash effect and produce high velocity rip currents. The action of rip cells able to transport sediments seaward. There for in Bakkhali coastal belt it is seen that shore parallel flats are segmented. Formation of bars, ridge and runnel topography are formed due to weak wave action in foreshore areas during winter season in Bakkhali coast. Low tidal flats are exposed during winter season. Normally sediment transport is recorded into the foreshore and nearshore areas by waves and rip currents. In Bakkhali and Henry's island shows that beach sands are transported towards the lower facets. In Kiran beach mud banks are exposed with removal of upper layer of sand. In some parts of the Bakkhali beach recession of coastline takes place with net sediment transport.

In the sandy beaches biogenic structures are well developed. Intertidal mudflats, sandflats

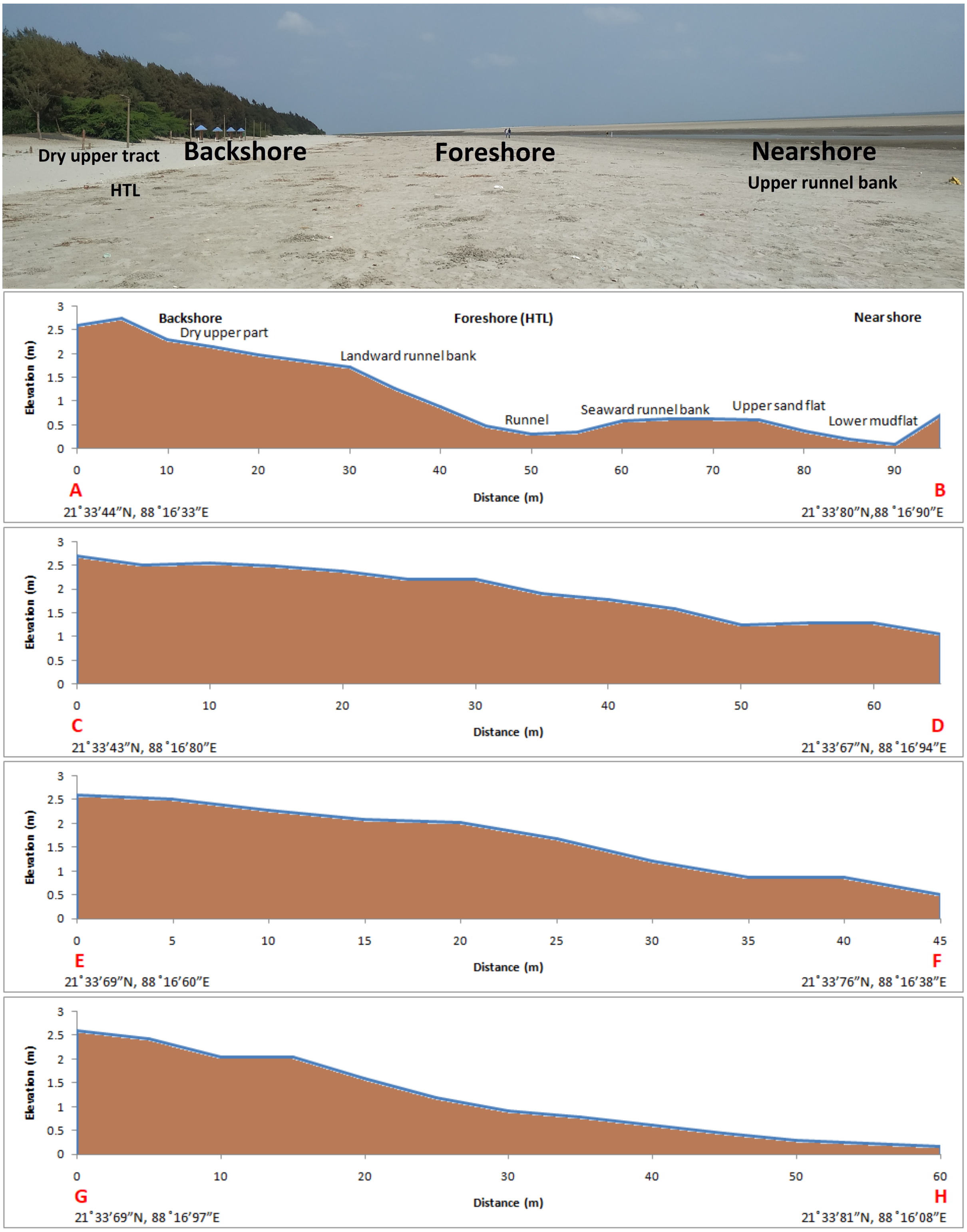


Figure 3.13: Beach morphology as the energy gradient, sediment character.

Plate 3.7: Beach topography: Biogenic formation at intertidal region (top left), Ridge runnel topography (top right), Beach profiling (middle left), Swash and backwash effect on sandy shore (middle right), Exposed clay flats at lower beach faces (bottom left), Mud bank exposed due to removal of top soil (bottom right).

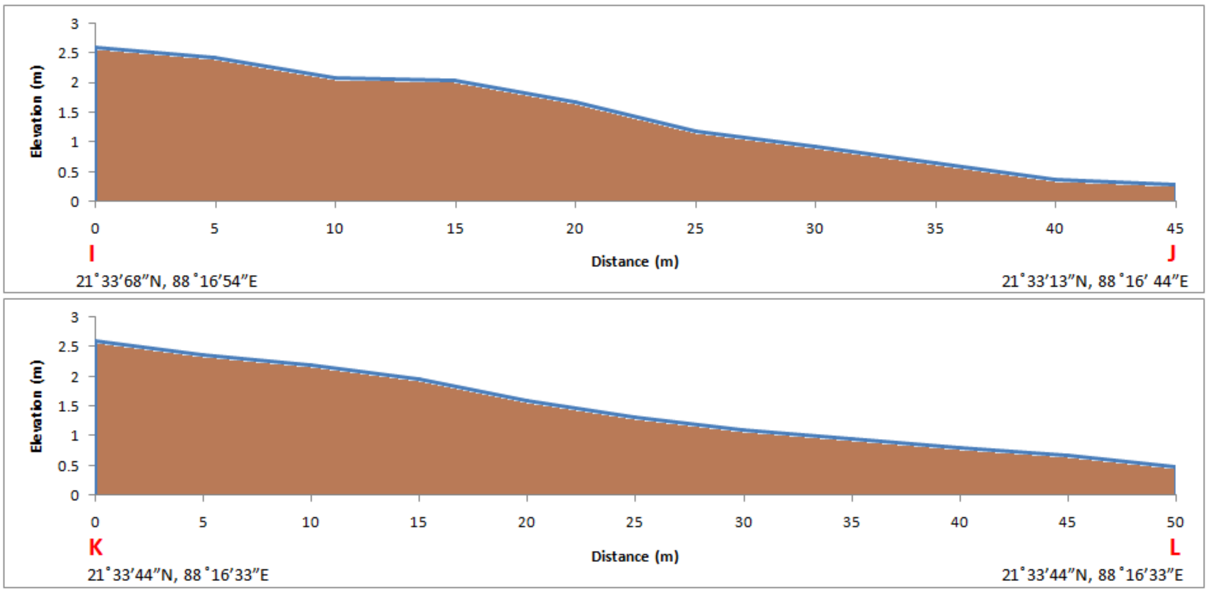


Figure 3.14: Beach morphology as the energy gradient, sediment character.

sandbars and sand dunes are the favourable place for biogenic growth. Micro sedimentary structures are forms in lower mudflats and lower beach faces. Beach morphology reflects the impacts of longshore sediment transport during seasonal change. In this context it should be mentioned that the onshore where foredunes are absent, erosion of a large volume of sediments or beach materials are transported towards the lower strata of the beach segment. In Kiran beach coastal recession and exposed mudbanks clearly indicate the lowering of sea beach and evidence of sea level rise.

3.9 Coastal sand dunes and habitat diversity

Coastal dunes provide protection to the shoreline from erosion. They are developed along the coastal tract by wave action, sediment supply to the beach plain, wind movement and growth of vegetation. Dry weather situation, winter season as well as hot and humid summer months are favorable for the formation of dunes.But in tropical humid coast prevent the maximum growth of sand dunes due to meso to macro tidal range and low velocity of winds. Sand dune formation mainly controlled by sand supply which is trapped by vegetation and stabilized. Mangrove trapped the sediments and dissipate energy of wave,protect coast from coastal erosion. Formation of coastal dunes initiates by vegetation cover on the back of the beach. In south western Sundarban specially in Bakkhali, Henry's, Fresargunj coastal belt have distinct formation of sand dunes. Hooghly supplies huge sediment load to the beach in its full monsoonal discharge.In the month of July and October South-Western monsoon and storms destabilize sand dunes from beach plain and backshore region and supply these sands to the offshore and on shore regions (Paul, 2002). Paul (2002) has identified six stages of development of sand dunes. Henry's, Fresargunj, Bakkhali island experience dominant onshore winds due to the presence of south facing open sea Bay of Bengal and open areas of funnel shaped Hooghly estuary.

Plate 3.8: Dune Vegetation: Embryo dune at Fresargunj coast (top left), Hairpin sand dunes are formed beside Amarabati sand spit (top right), Colonized dune vegetation at Bakkhali shoreline (bottom left), Casurina plantation at Bakkhali area (bottom right).

Heaps of tidal litters are deposited at the limit of spring tides by shore wash in the early summer.

Mangroves tend to colonize the drift line sandy surface and produce resistance against wind movement.

This stage is called embryo dunes. Aeluropus lagopoids, Sasuvium portula-castrum only can survive. Inundation at high tide only. Arrest more aeolian sands to increase height of the dunes.

Dunes move inland after sufficient growth. Embryo leave earlier position for new drift line colonizer. Colonization of new species takes place. Embryo dunes grow vertically and laterally.

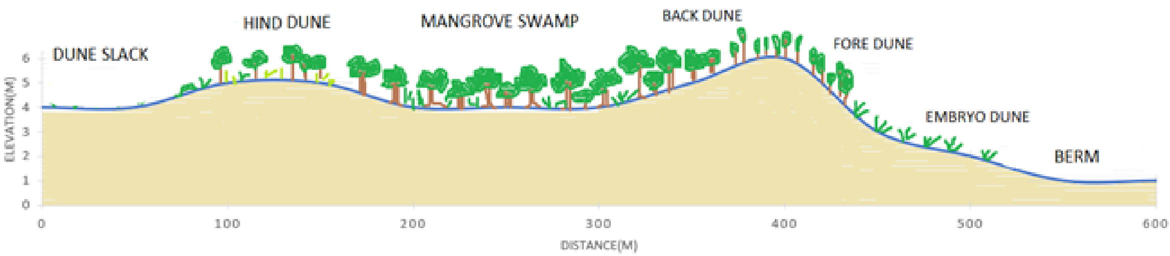


Figure 3.15: Vegetation succession at coastal dune of Bakkhali sea beach.

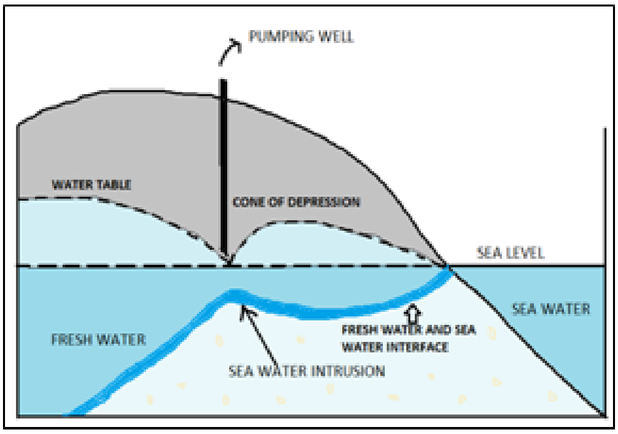
Larger foredunes will grow with slow migration of dune ridge, no of species increases and full of complete vegetation cover.

Deformation of dune starts when the further growth of fore dune has already stopped. New species join the existing plant community on the basis of moisture availability.

Coastal dunes represent not only topographic highs but it acts as a natural barrier against tidal waves which occasionally take place in the highest high tidal phase with violent storms. Field study helps to identify several primary dunes, secondary dunes, remnant dunes in the different parts of Henry's island, Bakkhali coast and Fresargunj coastal belt (Figure 3.15).

These pictures are showing that in Fresargunj area the dunes are found which are premature.They are developed by the sand transportation of sand in onshore winds.But in Bakkhali shoreline area the dunes are found are of mature. They have significant vegetation cover,this kind of dunes are related to shoreline shifting.In Bakkhali, beach fringed parallel coastal dunes appear as sand ridges, some are fully developed behind the new set of frontal growing dunes. Dune vegetation is not only stabilize the dune it has habitat and maintain coastal ecosystem. Dune vegetation are of three category primary vegetation which are found at the embryo stage of dune, then secondary vegetation are seen on the fore dune and third level of vegetation succession are found at the Back dune.

Dune vegetation plays important role in accretion cycle in wind protection specially to the hind dune. Primary vegetation zone grows at the harsh environment at embryo dune. These plants are resilient to sand blasting and salt spray, strong winds. Grasses holds much of the sand in place. The secondary vegetation is formed at fore dune which are shrubs, those can protect salty wind. Sasuvium portula-castrum this tree has strong root system and low growing plat plays vital role in stabilizing the foredune. The third category vegetation zone,where taller trees dominate which are protected from wind and salt spray. Soils of this region has high organic matter.



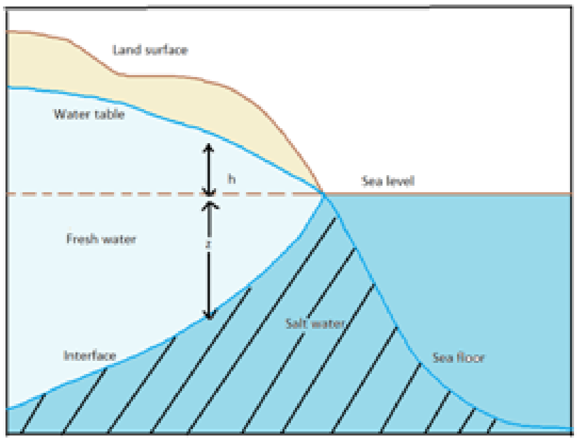


Figure 3.16: Groundwater extraction through well (left), Groundwater recharge and cycle (right).

3.10 Coastal groundwater system

Sundarban region is composed of alluvium soil provided by Ganga and its tributaries. It lies below 3 m below mean sea level, interlaced by creeks, tidal inlets, and small distributary channels. Sedimentation and siltation in the drainage channel is one of the problem of Sundarban. The average tidal amplitude lies in between 3.5 to 5.0 m (Gayen and Zaman, 2013). Presently Sundarban Biosphere region is exploited in terms of tourism and commercial activities. Major hotels, local people, tourism activities are fully dependent on underground water.The top saline water bearing aquifers are generally separated from the underlying fresh water group of aquifers by a thick impermeable clay layer (Gayen and Zaman, 2013). Fresh groundwater is found below unconfined condition. Piezometric level lies below 0.50 m to 2.00 m below MSL and hydraulic gradient tends towards sea. The upper aquifer occurs within 160 m bgl having brackish water. Below aquifer confined beyond 160 m to 490 m bgl, separated by clay blanket. All tube wells extract water within 160 m to 300 m bgl. The main source of drinking water is handpump in both the islands. A balance on water availability is controlled by fresh water influx by monsoonal rain and riverine flood with the tidal brackish water influx. Over exploitation of groundwater due to population pressure deplete groundwater level.Normally the water which is available in Sundarban is brackish. Recharge of groundwater is very essential to maintain ecosystem functioning and mitigation of drinking water demand. In coastal aquifers, fresh groundwater discharges to the ocean along fresh water sea water interface. This interface moves in response to tidal fluctuations where groundwater pumping and changes in recharge creating a transition zone.

In Sundarban, the coastal plain is densely populated, and one of the chief source of livelihood is agriculture. The freshwater requirement is almost entirely met by groundwater extraction. However, overexploitation of groundwater has led to seawater intrusion in the groundwater table, which has contributed to salinization. The groundwater extraction levels have accelerated the deterioration of the aquifer, which is reflected by the increasing amounts of chlorides and nitrates and other organic and inorganic pollutants in the groundwater.

3.11 Human influences in the islands

The two islands under study are next to dense human settlements. However, the degree of human influence on the topography and the ecology of the two islands differ due to the Patibania island being a protected forest area and there being no such restrictions in the case of the Henry's island. In this section, the human activities and the anthropogenic impacts on the two islands are described.

As mentioned before, human activities in the Patibania island is minimal, and economic activities and unauthorized dwelling are prohibited there by the forest department of the government of West Bengal. Two forest department officials are stationed there to monitor that these regulations are not broken. The lodging space in the Patibania island is set up to accommodate these two personnel. The required water for their consumption is obtained from the ground using tubewells. Electricity needs are fulfilled by installed solar facility and also electricity brought from the mainland through high-voltage cable.

Despite prohibition on human economic activities and dwelling, some cattle enter for grazing in the island through the northern creek, which is very narrow and shallow. Significant siltation in this creek, especially in the western side close to the shore, has made it relatively comfortably passable by foot.

Though everyday human activities are prohibited, the artificial canals, planned and constructed by the government, have significant impact on the island topography and ecology. It was observed that the natural streams in the island were being degraded due to high siltation and subsequent loss of carrying capacity. Due to their deterioration, the water influx in the island during high tides decreased, and the mangroves suffered as a result. To counter this problem, several artificial canals were developed to bring tidal water in the inland areas of the island. As a result of this inflow of water, mangroves of relatively moderate to high density have propagated along the banks of the canals. There are many other streams bringing tidal water in the islands. The man-made canals augment this natural drainage system un the Patibania island.

Along the areas in the western shore of the island with relatively higher elevation, a small mangrove plantation is developed by the government. The aims for this plantation were to hinder shoreline erosion and provide protection against storm damages in the inland. However, these mangroves also exhibit lush vegetation growth, and as a result, the vegetation quantity in that area has increased.

On the other hand, the Henry's island is deeply influenced by human activities. This island is older than the Patibania island, and once supported a larger and denser mangrove forest. However, most of it are cleared on account of the expansion of economic enterprises in this island. The two chief economic activities in this island are aquaculture and tourism.

The aquacultural enterprises are situated in the middle of the Henry's island, and they occupy the majority of the central region of the island. The aquacultural ventures are managed by both the fisheries department of the government and private enterprises. Shrimp, crab as well as some freshwater fishes are reared there. Most of the required water for this activity are extracted from the ground using tubewells.

Apart from the aquacultural ventures, the other significant center of human activities in the island is tourism. To support the local populace, the government has taken an initiative to promote ecotourism in this island. As part of this initiative, several cottages are constructed. However, recently several bigger two to three storied buildings are constructed inland away from the beach by private players to provide lodging space for the incoming tourists. The required water for the consumption by the tourists as well as the employees in this tourism industry is obtained through tubewells. Most of the power needs are met by electricity brought through high-voltage cables from outside of the island.

Apart from aquacultural activities and tourism, there are some minor sources of human activities, which include agriculture and small industries. Agricultural activities are meager in this island, chiefly due to the salinity in the soil. There are some small plots in this island, and the crops are mostly certain varieties of salinity tolerant rice. The water required is again obtained from the groundwater. The small industries are mostly related to manufacture of tobacco products. Some shops are also there in the island to meet the everyday needs of local populace.

In addition to the economic and societal activities, there are two other ways through which human influence has left a major impact on the island topography and mangrove ecology. One of them is the construction of several canals bringing tidal water inland of the island. Due to heavy siltation of the natural creeks and resulting loss of tidal drainage, the water inflow decreased considerably in the island, which negatively impacted the mangrove and other vegetation present, and aided the formation and propagation of saltpans. To guard against further deterioration, several canals are constructed, through which tidal water flows into the island. This increment in water availability has resulted in mangroves flourishing on the banks of those canals. The other human endeavor which has noticeable impact on the island ecology is the plantation of mangrove trees on the sand dunes behind the beach. The aim of this plantation was to provide a cover to dampen the impact of severe storms in the island and prevention of soil erosion. The trees in the mangrove plantation have now grown up and proliferated to create a densely vegetated mangrove patch on the sand dunes of the island.

In summary, the major avenues of human impact in the Patibania island are artificial canals and mangrove plantation, while those in the Henry's island are economic and societal activities, artificial canals and mangrove plantation. The water required for consumption is almost exclusively obtained through tubewells. Due to high total requirement, the amount of groundwater extracted in the Henry's island is also high.

3.12 Regional changes in shoreline configuration

The dynamics of the shoreline configuration is driven by the interplay of deposition and erosion. In the south-western Sundarban region, the source of deposition is the sediment load transported through distributaries like the Hooghly river and tributaries like the Damodar river, Rupnarayan river, etc. The causes of erosion are several. Firstly, there is the natural erosion process due to high energy of the tidal waves faced by the coast. This high energy loosens and sweeps away the smaller grains from the beaches. Then, there is also erosion caused by storm surges.

The Bay of Bengal region regularly witnesses cyclones, and the waves associated with them have very high energy and amplitude. Consequently, these waves inundate even the areas away from the beaches, and sweeps away much debris. The inadvertant human impact in hastening erosion is also not negligible (Paul, 2002). In many parts of the region, sea walls are built to prevent inundation. But building hard structures without proper knowledge of the coastal dynamics may not be usefull, which is reflected the accelerated erosion in this region (Paul,

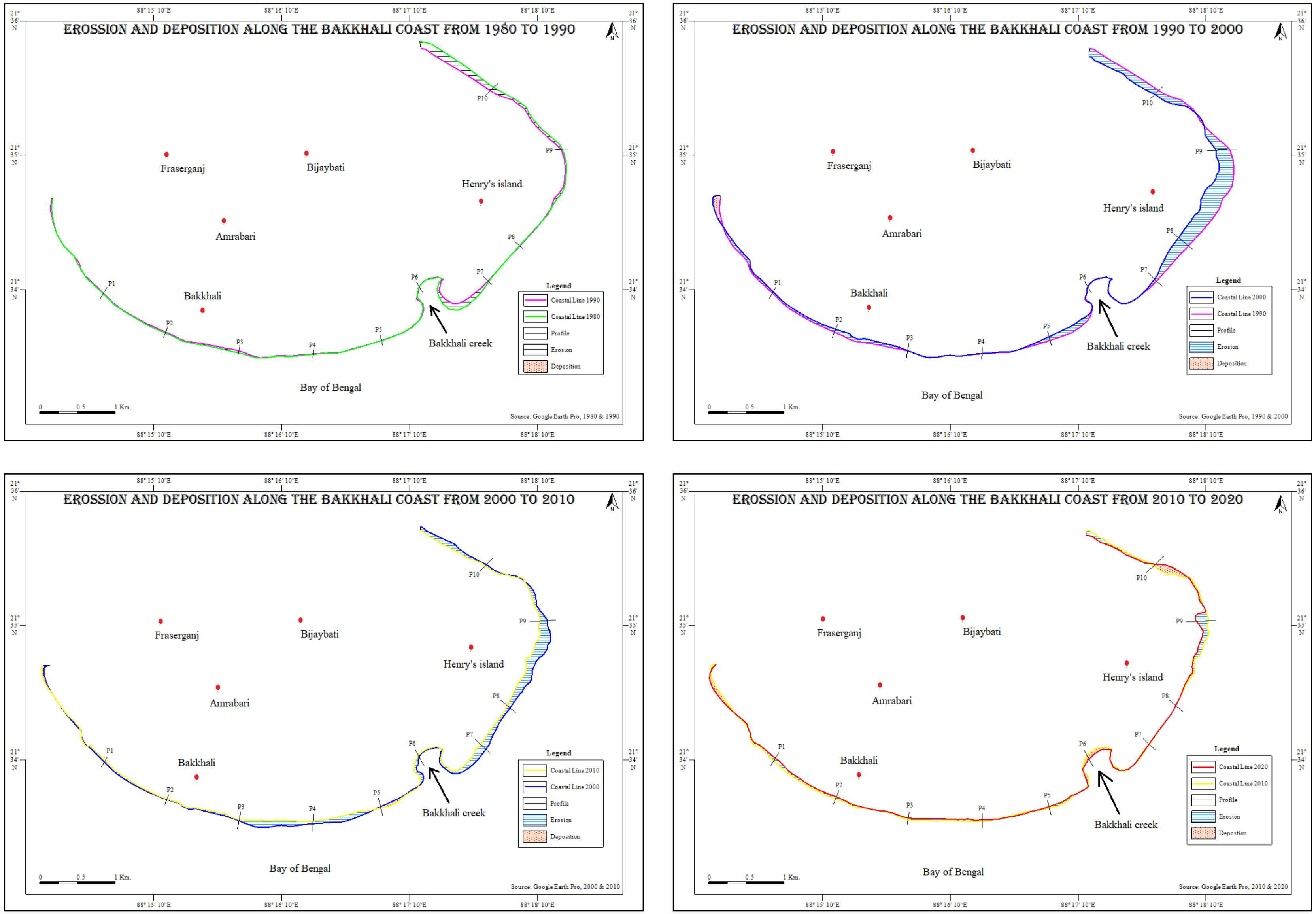


Figure 3.17: Schematic maps of shoreline change.

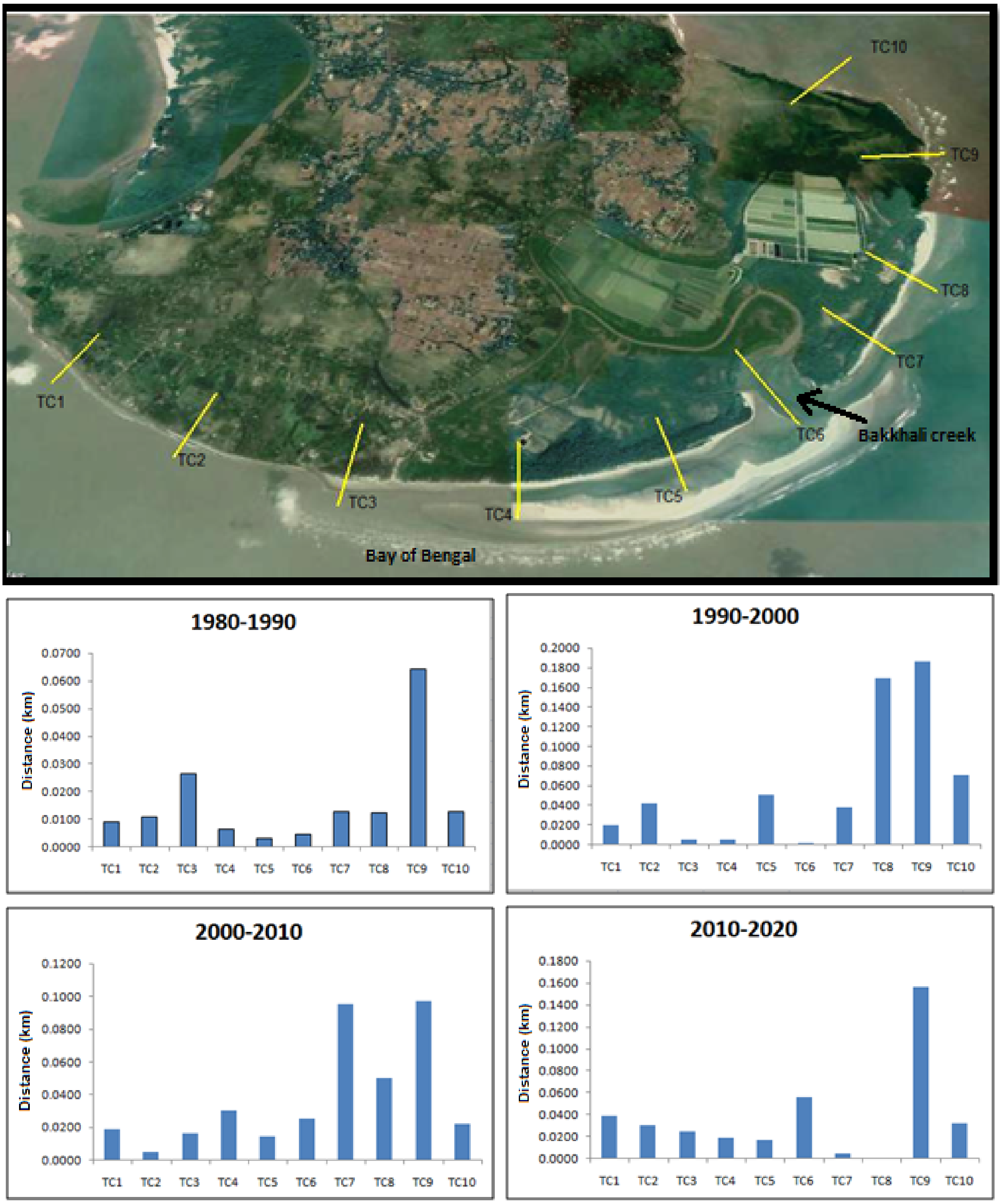


Figure 3.18: Map of the coastline monitored and linear shifts at the places observed (Linear shift of shoreline (1980–2020)).

2002). The erosion is mainly experienced by the beaches and the sand dunes forming the barriers to the beaches.

The changes in shoreline configuration of the south-western Sundarban region is monitored over a 40-year period from 1980 to 2020. Apart from estimating the total amount of deposition and erosion, the length of shoreline advance or receding is measured at 10 places in the coastline. The changes occurring over each 10-year period is presented here. In Figure 3.18, the map of the shoreline under observation is presented, along with the amount of linear changes of shoreline in the observed places over each 10-year period, which are presented in the bar plots. It can be seen that each of the monitored places suffered net erosion. However, there is considerable spatial variation in the amount of erosion among the places monitored. The highest linear shifting of the shoreline is observed at the positions TC7 and TC9. These positions are located on the south-eastern shore of the Henry's island. Maximum linear shifting is observed over the period of 1990–2000. At a few places, which include the southern shore of the Henry's island and the Bakkhali coastal tract, some deposition bis also observed. In Figure 3.19, Bar graphs showing areas of erosion and deposition in different years of south-western Sundarban coastal tract are presented.

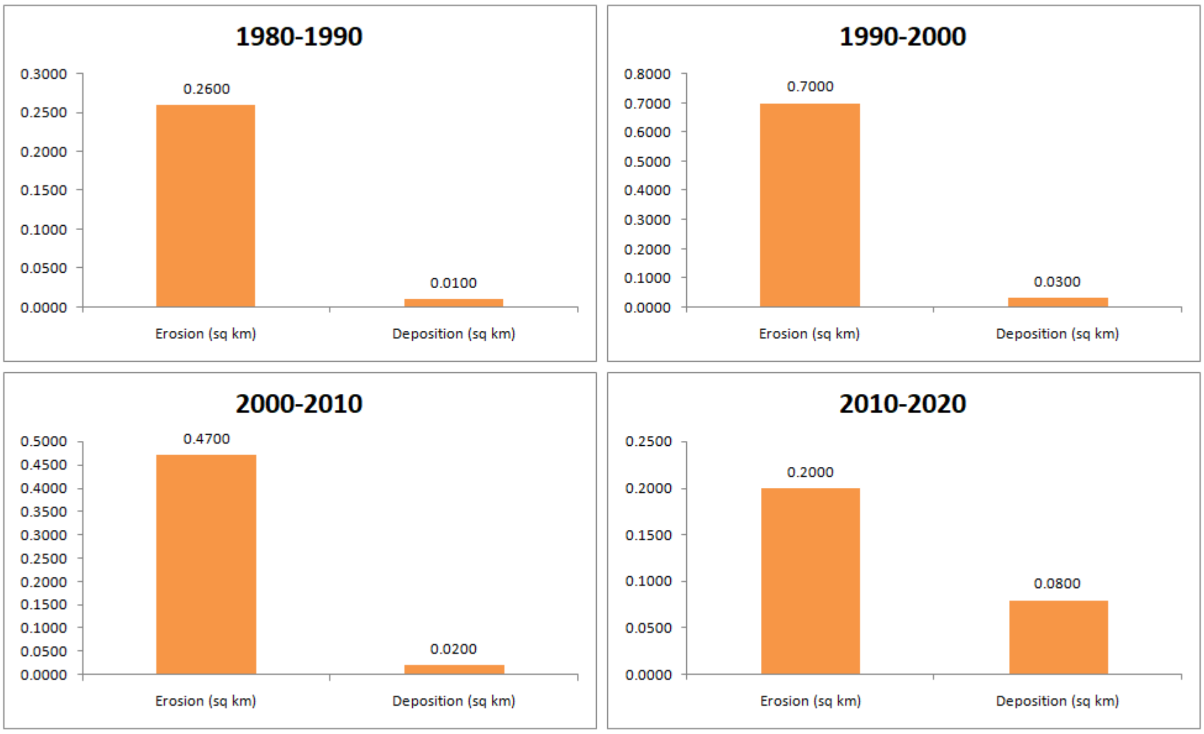


Figure 3.19: Bar graphs showing areas of erosion and deposition in different years of south-western Sundarban coastal tract.

In Figure 3.17, the schematic maps of shoreline change are depicted over 10-year periods. It can be seen that the eastern area has undergone the most change in shoreline.