CHAPTER 2

GEOMORPHIC SETTINGS OF THE ISLANDS

2.1 Contour plans of the Henry's and Patibania islands

There are some similarities and substantial differences in the topographic characters of the Henry's island and the Patibania island. To analyze the detailed topographic characteristics of the two islands, their micro-zonation maps are prepared based on the Cartosat 2A data of 2019. The spatial resolution of the Cartosat 2A data is 1 m. Owing to their high resolutions, these maps help is identifying the micro level topographic features of the islands. Based on elevation, both the islands are divided in 6 zones. Here, the locations and characteristics of these zones are described.

The micro-zonation map of the Henry's island is presented in Figure 2.1. The average surface elevation of this island is 1.50 m. The elevation boundaries of the six zones in the Henry's island are 0.90 m–1.20 m, 1.20 m–1.50 m, 1.50 m–1.80 m, 1.80 m–2.10 m, 2.10 m–2.40 m and above 2.40 m respectively. The highest elevation in the Henry's island is found along the sand dunes in the southern, the eastern and the north-eastern seashores, which have minimum elevation of 2.40 m. Just behind the southern and the eastern sand dunes, depressions have formed with elevation between 1.20 m–1.50 m. On the other hand, most of the area around the north-eastern sand dunes have elevation between 1.80 m–2.40 m. In the middle part of the islands, where the topography is shaped by human activities, some surface structures have elevation between 1.80 m to 2.10 m. Most of these structures are man-made boundaries between the aquacultural ponds. Majority of the island however has elevation between 1.50 m–1.80 m. Some notable concentrations of the elevation range of 1.20 m–1.50 m can be seen in the central part of the island on account of the aquacultural ponds and other human activities. The depression behind the southern sand dunes with elevation between 1.20 m–1.50 m is expansive, while the depression behind the eastern sand dunes, though lying in the same elevation range, is relatively narrow. The Bakkhali creek flowing through the southern part of the island in a winding fashion can also be traced in this elevation range of 1.20 m–1.50 m. Other regions in this elevation range are scattered across the island. It is notable that the areas with elevation in 1.20 m–1.50 m are almost always surrounded with regions with higher elevation, forming depressions on the surface. The regions with the lowest elevation range are sparse and situated in isolated pockets around the island. Due to the presence of the relatively higher sand dunes in the east, the general slope of the island is from the east to the west.

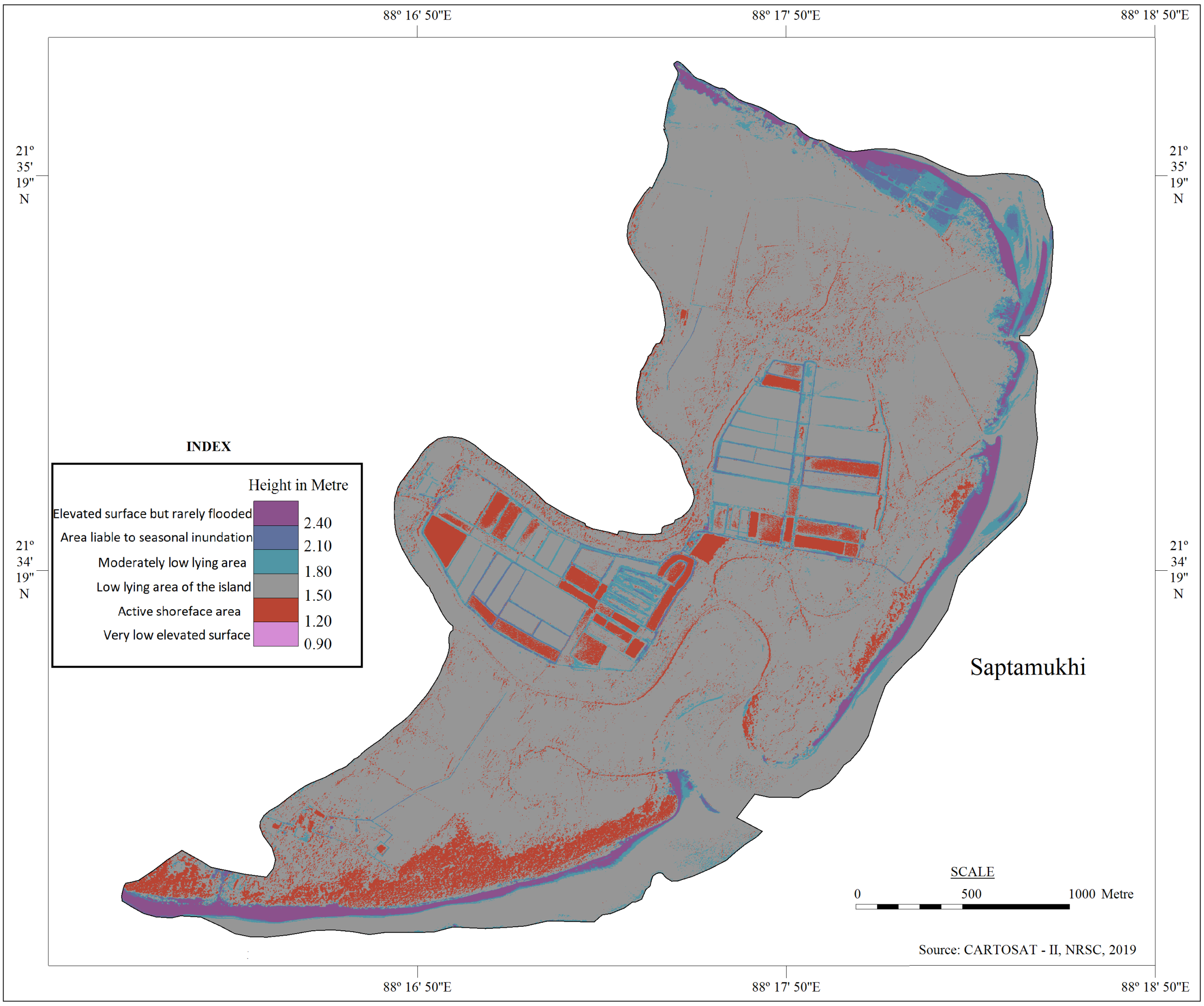


Figure 2.1: Contour zonation map of the Henry's island, 2019.

In Figure 2.2, the elevation profile of a cross section of the Henry's island is depicted, which also exhibits the geomorphic features of the island.

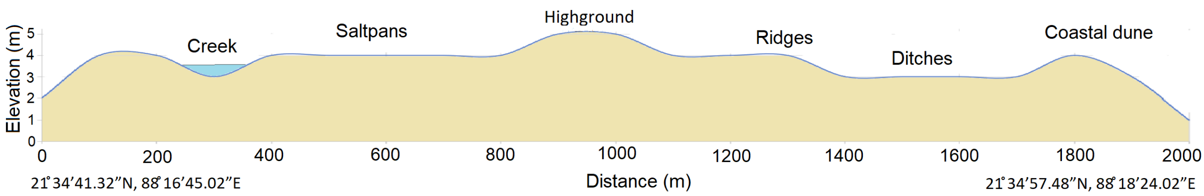


Figure 2.2: Elevation profile of a cross section of the Henry's island.

The above elevation profile is drawn from the west to the east in the Henry's island. It can be seen that at 200–400 m distance from the starting point, there is a creek, whose stream bed has an elevation of 3 m. At 400–800 m distance, the flat surface with elevation 4 m is covered by a saltpan. The elevation is higher between 800–1100 m distance, and at 5 m, this region has the highest elevation covered in this cross section. At 1100–1400 m distance, there are ridges, with elevation 4 m. At 1400–1700 m distance, there are ditches with elevation 3 m. Finally, at the distance of 1700–2000 m, there are coastal dunes with elevation 4 m.

The micro-zonation map of the Patibania island is depicted in Figure 2.3. The average elevation of this island is 1.78 m. The six elevation zones in the Patibania island has their elevation boundaries as 1.18 m–1.48 m, 1.48 m–1.78 m, 1.78 m–2.38 m, 2.38 m–2.68 m, 2.68 m–2.90 m, and above 2.90 m respectively. From the average elevation and also the elevation ranges, it can be seen that the Patibania island has relatively higher elevation compared to the Henry's island. The areas with the lowest elevation, i.e., between 1.18 m–1.48 m, are observed in the middle part of the island. These areas are scattered and always surrounded by regions with higher elevation. This configuration makes the those areas with low elevation form depressions. The areas with elevation in 1.48 m–1.78 m are scattered across the island with some notable concentrations. Most of the part in the protrusion at the southern end of the island has elevation between 1.48 m–1.78 m. In the middle part of the island also, there is a concentration of regions with elevation between 1.48 m–1.78 m. Along a north-south axis running along the center of the island, many of the regions with elevation in 1.48 m–1.78 m are clustered, albeit with a lower concentration compared to the middle part and the middle-northern part. Most of these areas with elevation in 1.48 m–1.78 m are encircled by higher areas which makes them form depressions. Majority of the island has elevation within 1.78 m–2.38 m. The regions with elevation within 2.38 m–2.68 m are found along the western shore of the island interspersed with higher regions with elevation in 2.68 m–2.90 m. The regions with elevations above 2.90 m are relatively tiny and only found in small pockets in the western shore perched within lower regiosn with elevation between 2.38 m–2.90 m. These elevated regions with elevation above 2.38 m form a natural but porous barrier running along the western shore. Significant gaps in this barrier are found in the middle-north and the middle-south. The barrier vanishes in the deep south of the island. Overall, it is found that the western areas in the Patibania island have higher elevation and several disjoint depressions have formed in the central part along the north-south axis.

In Figure 2.4, the elevation profile of a cross section of the Patibania island is presented along with the geomorphic features. The cross section, which is drawn from the west to the east, depicts several geomorphic features in the island along with their elevations. Up to 200 m distance from the starting point is occupied by the beach face with elevation 2 m. At 200–400

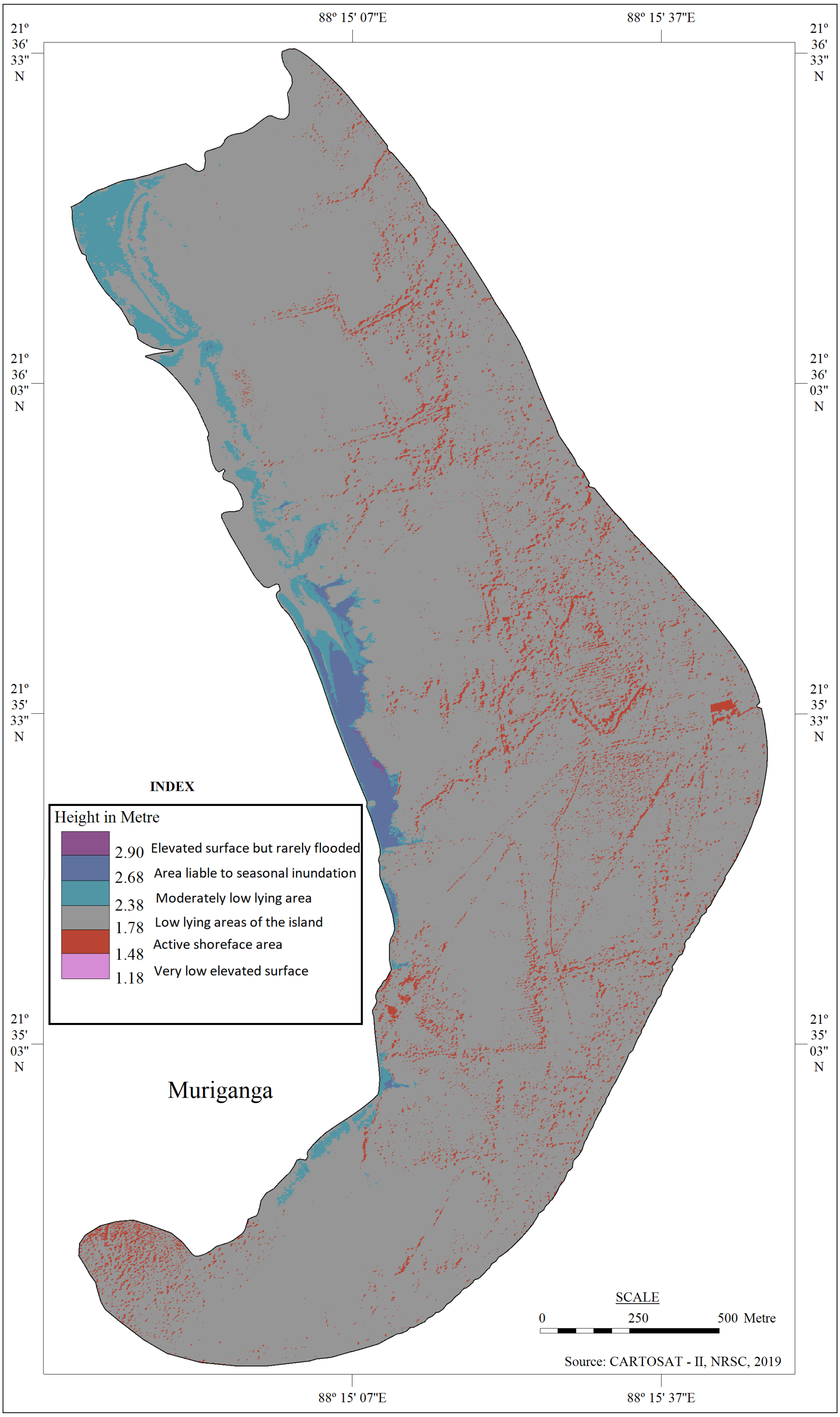


Figure 2.3: Contour zonation map of the Patibania island, 2019.

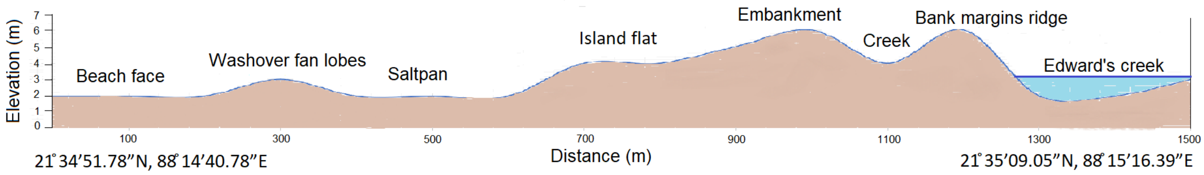


Figure 2.4: Elevation profile of a cross section of the Patibania island.

m distance, there are washover fan lobes with elevation 2–3 m. Beyond the washover fan lobes at 400–600 m distance, the saltpan region has elevation 2 m. After the saltpan, there is a lagoonal flat at 600–800 m distance with elevation 2–4.5 m. At 800–1000 m distance, there is an earthen embankment with elevation 4.5–6 m. Next to the embankment, there is a creek at 1000–1200 m distance, whose stream bed has a relatively high elevation of 4.5 m. There is a bank margins ridge on the other side of the creek at 1200–1300 m distance, whose elevation decreases from 6 m to 3 m towards the Edward's creek. The Edward's creek is observed at a distance of 1300–1500 m, with the lowest elevation of its stream bed being 2 m.

The elevation layout of the islands plays an important role in determining how the various natural processes shape the geomorphic settings of the islands. However, the elevation configuration itself is in turn shaped by the ongoing natural processes in the long term, which include hydrological and geomorphic processes. The elevation structure along with the hydrological processes and the climatic influences determine the ecological set-up in these islands. In the later sections, the different geomorphic settings in the islands are detailed. The roles of these geomorphic settings on the ecological configuration supported by them are also described. In Section 2.2, the two islands are classified in the various geomorphic settings observed within them.

2.2 Classification of geomorphic settings

The geomorphic settings of the south-western Sundarban region, where the two islands are located, are influenced by several geomorphic and hydrological processes like sediment deposition, tidal wave action, channel avulsion, subsidence caused by sediment compaction, monsoonal rainfall, etc. The geomorphic settings in turn also influence the mangrove characteristics and the tidal effects on the local ecosystem (Yuvaraj et al., 2014). Though the two islands have the same climatic conditions, they have conspicuously different hydro-geomorphic characters. In this section, the distinct geomorphic settings in the two islands and the process of their identification are described.

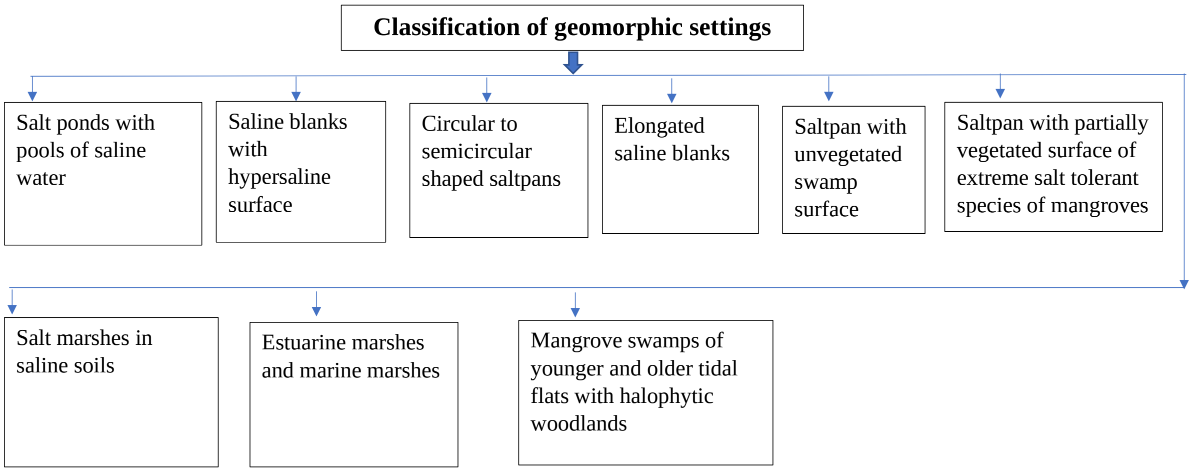


Figure 2.5: Classification of geomorphological settings identified in the islands.

Plate 2.1: Identified geomorphological setting in the Henry's island and the Patibania island: salt pans of unvegetated swamp surface (top left), semi circular shape saltpans (top right), salt ponds with pools of saline water (bottom left), saline blanks with hypersaline surface (bottom right).

Plate 2.2: Identified geomorphological setting in the Henry's island and the Patibania island: estuarine marshes (top left), mangrove swamps of older tidal flats with halophytic woodlands (top right), mangrove swamps of younger flats with halophytic woodlands (middle left), marine marshes (middle right), salt flats with partially vegetated surface of extreme salt tolerant species (bottom left), salt marshes of salt affected soils characterized by short plants and grasses (bottom right).

In Figure 2.5, the geomorphic settings identified in the islands are classified. The categories are salt ponds, saline blanks, circular to semicircular shaped saltpans, elongated saline blanks, saltpan with unvegetated swamp surface, saltpan that is partially vegetated with extreme salt tolerant mangroves, salt marshes of salt affected soils characterized by short plants and grasses, estuarine marshes and marine marshes, mangrove swamps in younger and older tidal flats with halophytic woodlands. In Plate 2.1 and Plate 2.2, some photos of the different geomorphic features in the two islands are depicted.

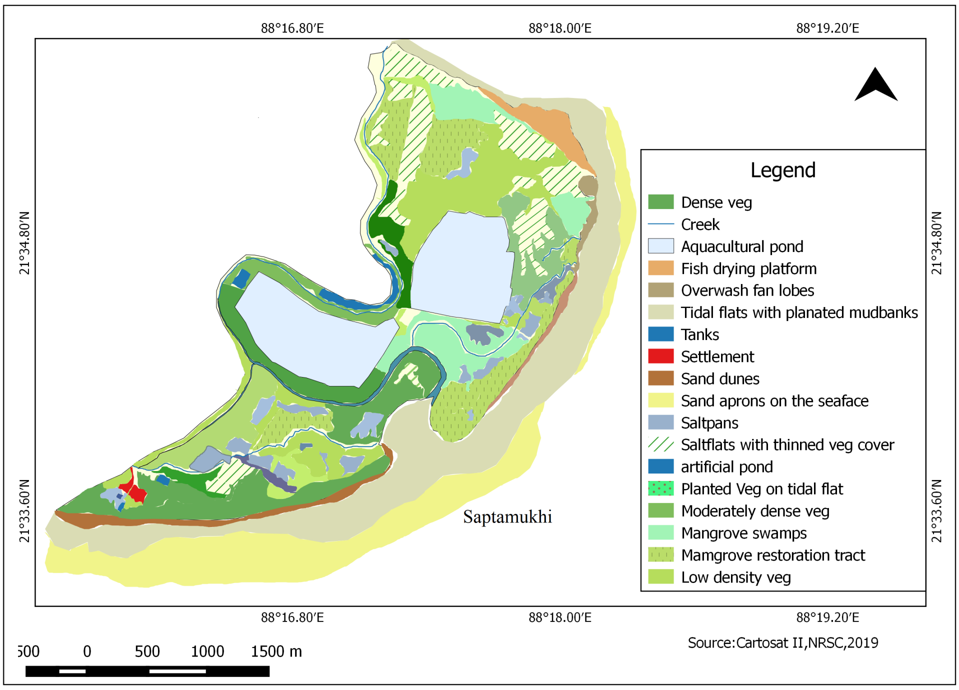


Figure 2.6: Map of the geomorphic settings in the Henry's island, 2019.

To identify the different geomorphic settings present in an island and classify the regions in that island into those settings, a combination of data sources is used, which consists of the Cartosat-2A DEM of 2019, satellite imagery and field observations. The Cartosat-2A DEM provides a very high spatial resolution of 1 m, facilitating a detailed and accurate map preparation. The satellite imagery used in this endeavor is mostly sourced from the Google Earth Pro application. These images provide valuable insights in the spatial layout of the geomorphic settings. However, field observations are found to be essential to accurately identify the distinct geomorphic settings in the islands.

Total 18 distinct geomorphic settings are identified in the Henry's island, and they are presented in Figure 2.6. Each geomorphic unit is different in terms of surface texture, composition and soil characteristics, the vegetation supported on them and ecosystem services and functionality. The 18 settings in the Henry's island are regions with dense vegetation, regions with moderate vegetation density, regions with low vegetation density, creeks, aquacultural ponds, fish drying platforms, overwash fan lobes, tidal flats with planated mudbanks, tidal flat with planted vegetation, tanks, settlements, artificial ponds, sand dunes, layer of sand aprons on sea face, saltpans, salt flats with thin vegetation cover, mangrove swamps and mangrove restoration tract.

From the identified geomorphic settings in Figure 2.6, it can be clearly seen that much of the terrain of the Henry's island is profoundly reworked by human activities. Also, especially the coastal parts of the island manifestly convey that the Henry's island is being actively shaped by waves and tidal processes. The regions with dense vegetation, moderate vegetation density and low vegetation density have distinct geomorphic features and soil characteristics which made them amenable to support the respective densities of vegetation. The vegetation in turn affects the geomorphic and soil characteristics of those regions through biological debris, mangrove root action and presence or absence of canopy cover formed by the vegetation. The creeks supply saline tidal water to the inland areas of the island. The largest creek flowing through the middle part and joining the sea near the central part of the island forming a wide mouth is the Bakkhali creek. The aquacultural ponds are the sites of the principal human activity carried out in the island in terms of land and water usage. These ponds occupy most of the central part of the island. The fish drying platforms are chosen areas in the seashore based on their elevation, slope, distance to the sea and tidal action. These areas are cleared of other features to make them suitably for drying and processing the catch of fish brought by sea trawlers. Most of the fish drying platforms are located in the northern coast of the island, and only a narrow area in the eastern seashore is utilized as fish drying platforms. Areas with relatively high elevation are chosen as fish drying platforms to protect the captured fish stock from spoilage and loss caused by to waves and tides. The overwash fan lobes are relatively small sediment deposits in the eastern part of the island formed by the actions of spring tides and storm surges. Along the entire coast of the island from the north to the east and to the south, wide tidal flats can be found with planated mudbanks formed by tidal action. In the inner parts of the island also, tidal flats have formed. However, in these tidal flats, tidal action are relatively weak and cannot erase the vegetation. Owing to this, plantation of vegetation is carried out here to prevent erosion and with the aim of land reclamation. A few water bodies are found in the island which are distinct from the aquacultural ponds, and these are denoted as tanks in the map. These water bodies in the inland areas of the island serve as water storage spaces. The human settlements in the island are located in a small patch in the southern tip of the island. The settlements alter the geomorphic settings of the area on which they stand through anthropogenic actions. A few artificial tanks are located close to the settlements, which serve as a water source for utilized by the settlements. The sand dunes are mostly located in the southern coast of the island. The relatively high elevations of the sand dunes serve as a barrier to wave and tidal actions, as described in Section 2.1. The narrow fish drying platform in the eastern coast is also a sand dune by make-up, however these are now utilized as fish drying platforms, and required changes to their terrain are made for this purpose. At the eastern and the southern edges of the island, there is a sand apron on the sea face. This geomorphic unit is formed by wave and tidal action through the interplay of sediment deposition and coastal erosion. Many areas inland have witnessed salt build-up in the soil due to elevation layout and evaporation of saline tidal water. Saltpans have formed in some of these areas. The soil in these areas have very high salinity inimical to the growth of vegetation. In the rest of the areas with comparatively less soil salinity, salt flats have formed, but which can support a thin vegetation cover composed to high-salinity tolerant mangrove species. The saltpans are spread over parts of the island not utilized for human activities. However, there are two clusters of saltpans in the island, one in the south-western section and the other in the eastern part of the island. A significant part of the northern and the north-eastern regions of the island is constituted of salt flats with thin vegetation cover. Some smaller salt flats are also found in the central and the south-western parts of the island. Swampy areas occupied by mangroves are found in the central, eastern and northern parts of the island. In some portions of the island, especially in the eastern part behind the wide tidal flats and fish drying platforms, mangrove restoration tracts are developed to prevent soil erosion and offer protection from storm devastation to the inland establishments.

In the Patibania island, 11 geomorphic setting are identified, which are depicted in Figure 2.7. The geomorphic settings in the Patibania island are regions with high, moderate and low mangrove densities, creeks, beach ridge, salt marsh, saline blanks, sand flats, overwash deposits and sand spit. The regions with dense mangroves differ in their geomorphic set-up from the regions with moderate and low mangrove densities, and similar dissimilarities exist between the geomorphic characteristics of the regions with moderate and low mangrove densities. Several creeks serve as the transportation route of the saline water influx during high tides in the island. However, the largest of the creeks is the Edward’s creek, which flows along the north-eastern, the eastern, the south-eastern and then the southern edge of the island, forming the boundary of the island in these directions. The beach ridge platform is spread along the north-western shore of the island and then along a narrow patch of the western boundary. Recall from Section 2.1 that this feature has relatively higher elevation compared to the rest of the island. The salt

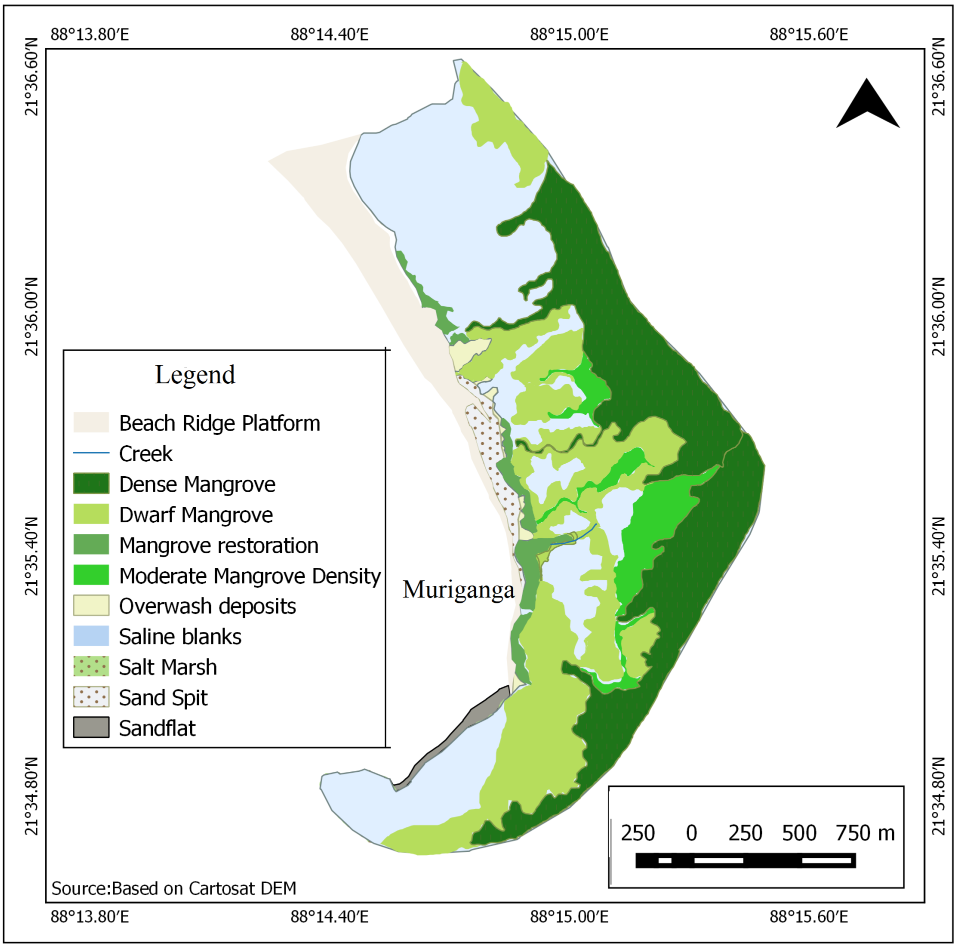


Figure 2.7: Map of geomorphic settings in the Patibania island, 2019.

marsh has formed along the western side of the island where it undergoes daily tidal inundation. Majority of the northern part of the island and significant parts of the central and the southern regions of the island are occupied by saltpans. The sandflat has formed in the western shore of the southern part of the island. The sand spit has formed in the western beach of the central part. The overwash deposit is relatively small, and formed in the western part of the middle north region of the island behind the beach ridge.

From the above descriptions, it can be seen that the arrangement of the geomorphic units and their characteristics are very different between the Henry's island and the Patibania island. The coastal configuration and fresh water influx and its utilization are also different in the two islands.

There are several reasons for the differences in the geomorphic settings of the two islands. One obvious cause is anthropogenic influence. There are organized aquacultural activities in the Henry's island apart from it being a popular tourist spot. But the Patibania island is a designated reserve forest. The economic and other activities carried out by humans have a significant role in shaping the topographic features of the Henry's island. Another important cause is the location and configuration along with the surrounding features of the two islands. The Henry's island is spread in the east-west direction directly in front of the sea, which makes much of the island go through the full brunt of the diurnal tidal actions along with the unceasing wave actions. Consequently, the Henry's island has an expansive sea beach anchored by relatively high sand dunes and overwash lobes behind it. The regions in the Henry's island adjacent to the seashore are almost completely devoid of any vegetation from the waves and tidal actions. On the other hand, the Patibania island is spread in the north-south direction with a protruding section in the southern part. This configuration shields the Patibania island up to a degree from the full forces of tidal action. The devastation caused by the storm surges is also thus experienced differently in the two islands.

It is found that the densest mangroves in the Patibania island also lie in the farthest region from the sea. The vegetation in the Henry's island in the north-western side adjacent to the creek is also relatively dense compared to other parts of the island, which is next to the creek separating it from the larger landmass. However, the density and the spread of mangroves in the Henry's island are also much smaller compared to the Patibania island, which can be attributed to the human activity in the Henry's island.

2.3 Ecosystem functions of the geomorphic settings

In this section, the effects and functions of the various geomorphic units in the local ecosystem of the two islands are described.

In the Henry's island, majority of the geomorphic settings are shaped by anthropogenic influence. Among the naturally formed settings, the coastal features including the tidal flat with planated mudbanks and the sand apron on the sea face are prominent. The tidal flat is formed by both sediment deposition and coastal erosion. The coastal erosion by tidal waves expose the lower clay layers, which through subsequent erosion form a bank of mud. But with further erosion, the mudbanks have been planated and formed the boundary of the tidal flat region. This region is submerged with each high tide. The saline water of the tides makes the soil saturated with water and have high salt content. It is very difficult for any plant species to survive in this environment because the water-saturated mud cannot provide a strong enough foundation for the roots that would enable the plant to withstand the tidal waves. The tidal wave energy itself harms other parts of the plants.

From the identified geomorphic settings, it can be clearly seen that much of the terrain of the Henry's island is profoundly reworked by human activities. Also, especially the coastal parts of the island manifestly convey that the Henry's island is being actively shaped by waves and tidal processes. The regions with dense vegetation, moderate vegetation density and low vegetation density have distinct geomorphic features and soil characteristics which made them amenable to support the respective densities of vegetation. The vegetation in turn affects the geomorphic and soil characteristics of those regions through biological debris, mangrove root action and presence or absence of canopy cover formed by the vegetation. The creeks supply saline tidal water to the inland areas of the island. The largest creek flowing through the middle part and joining the sea near the central part of the island forming a wide mouth is the Bakkhali creek. The aquacultural ponds are the sites of the principal human activity carried out in the island in terms of land and water usage. These ponds occupy most of the central part of the island. The fish drying platforms are chosen areas in the seashore based on their elevation, slope, distance to the sea and tidal action. These areas are cleared of other features to make them suitably for drying and processing the catch of fish brought by sea trawlers. Most of the fish drying platforms are located in the northern coast of the island, and only a narrow area in the eastern seashore is utilized as fish drying platforms. Areas with relatively high elevation are chosen as fish drying platforms to protect the captured fish stock from spoilage and loss caused by to waves and tides. The overwash fan lobes are relatively small sediment deposits in the eastern part of the island formed by the actions of spring tides and storm surges. Along the entire coast of the island from the north to the east and to the south, wide tidal flats can be found with planated mudbanks formed by tidal action. In the inner parts of the island also, tidal flats have formed. However, in these tidal flats, tidal action are relatively weak and cannot erase the vegetation. Owing to this, plantation of vegetation is carried out here to prevent erosion and with the aim of land reclamation. A few water bodies are found in the island which are distinct from the aquacultural ponds, and these are denoted as tanks in the map. These water bodies in the inland areas of the island serve as water storage spaces. The human settlements in the island are located in a small patch in the southern tip of the island. The settlements alter the geomorphic settings of the area on which they stand through anthropogenic actions. A few artificial tanks are located close to the settlements, which serve as a water source for utilized by the settlements. The sand dunes are mostly located in the southern coast of the island. The relatively high elevations of the sand dunes serve as a barrier to wave and tidal actions, as described in Section 2.1. The narrow fish drying platform in the eastern coast is also a sand dune by make-up, however these are now utilized as fish drying platforms, and required changes to their terrain are made for this purpose. At the eastern and the southern edges of the island, there is a sand apron on the sea face. This geomorphic unit is formed by wave and tidal action through the interplay of sediment deposition and coastal erosion. Many areas inland have witnessed salt build-up in the soil due to elevation layout and evaporation of saline tidal water. Saltpans have formed in some of these areas. The soil in these areas have very high salinity inimical to the growth of vegetation. In the rest of the areas with comparatively less soil salinity, salt flats have formed, but which can support a thin vegetation cover composed to high-salinity tolerant mangrove species. The saltpans are spread over parts of the island not utilized for human activities. However, there are two clusters of saltpans in the island, one in the south-western section and the other in the eastern part of the island. A significant part of the northern and the north-eastern regions of the island is constituted of salt flats with thin vegetation cover. Some smaller salt flats are also found in the central and the south-western parts of the island. Swampy areas occupied by mangroves are found in the central, eastern and northern parts of the island. In some portions of the island, especially in the eastern part behind the wide tidal flats and fish drying platforms, mangrove restoration tracts are developed to prevent soil erosion and offer protection from storm devastation to the inland establishments.

Both the islands include saltpan formations. These are notable geomorphic features in their own right, but also important for their roles in salinization of soil and hindering mangrove propagation. Due to these reasons, the saltpans are accorded separate attention during the field survey. Contour planning in the saltpans and the surrounding areas were done using a total station instrument.

In Figure 2.8, the contour map of a section of a saltpan in the Henry's island is presented. In this figure, the southern part corresponds to the periphery of the saltpan and the northern part corresponds to the central area of the saltpan. It can be seen from this figure that the elevation decreases as one proceeds from the periphery to the center of the saltpan. The highest elevation in this section of the saltpan is observed to be 2.66 m at the periphery in the southern part. The lowest elevation found is 2.44 m at the central part. This indicates that the central part of the saltpan has a depression bounded by relatively higher peripheral areas. After this region

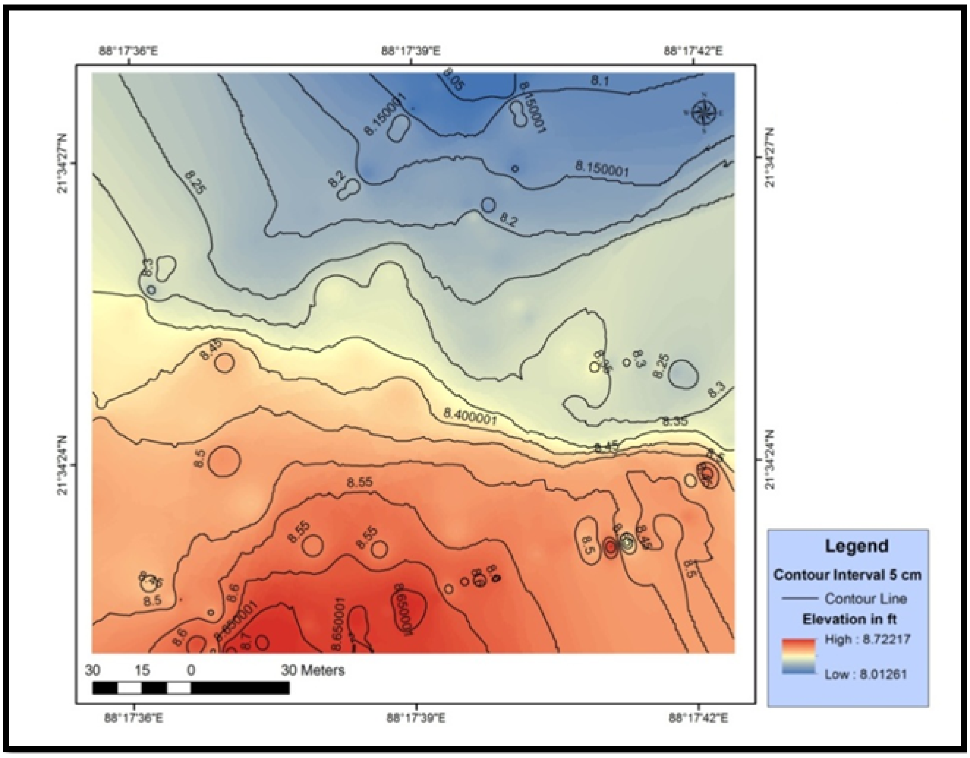


Figure 2.8: Contour map of a saltpan in the Henry's island, 2019.

gets inundated with saline water from tides or storm surges, this saucer-like topography traps the remaining saltwater for a long time and facilitates evaporative deposition of salt in the soil. Detailed discussion about these formations are provided in a later section.

In Figure 2.9, a cross sectional diagram of the Henry's island is presented with its elevation profile, the geomorphic features and the vegetation observed along the cross section. The direction of the cross section is from the west to the east. In the western end of the cross section, higher ground is observed, which has elevation 2–3 m with dense mangroves. Next to it, there is a creek with almost flat stream bed, which has elevation 2 m. On the bank of this creek, there are ditches constructed for mangrove restoration, which have the same elevation of 2 m as the creek. On the other side of the ditches, there is another creek with slightly deeper stream bed with an elevation of 1.5 m. The back dune on the bank of this creek has elevation 2–3 m, and moderately dense mangroves cover this back dune. A depression has formed between this back dune and the sand dunes farther east, which is occupied by a saltpan. Most of the saltpan is without vegetation, with its boundary having mangroves of very low density. The sand dunes have dense mangroves. Next to the sand dunes, washover lobes have salt marsh vegetation and an elevation of 2.5–3.5 m. At the eastern end of the cross section, there is sand flat devoid of any vegetation, and an elevation of 2–2.5 m.

Plate 2.3: Root systems of mangroves found in the Henry's island and the Patibania island: air breathing root (top left), pneumatophores of *Excoecaria* (top right), still root (middle left), flat root system of *Avicennia marina* (middle right), *Rhizophora* still root (bottom left), air breathing root to control soil erosion (bottom right).

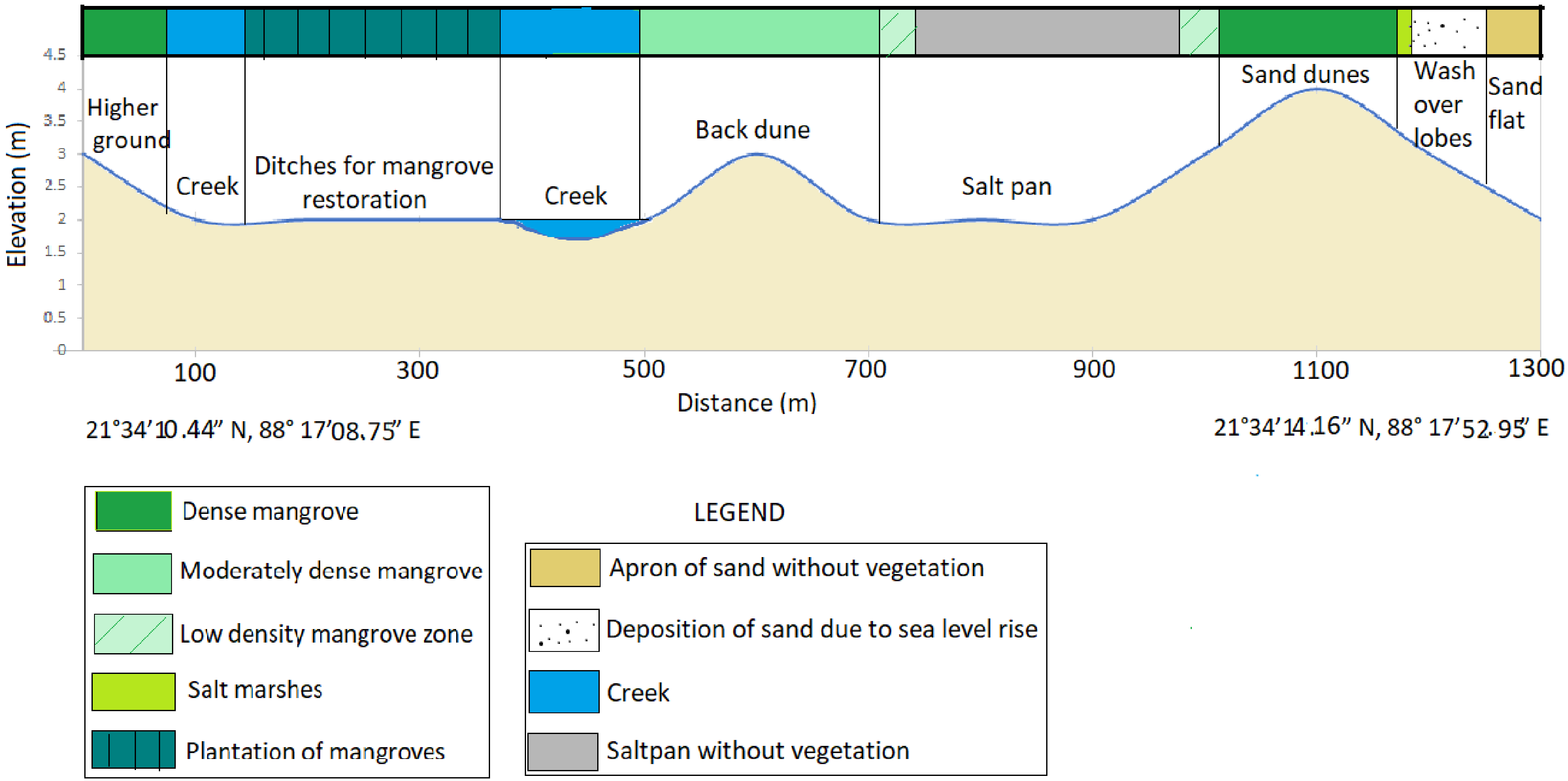


Figure 2.9: Cross sectional diagram of the Henry's island (west to east).

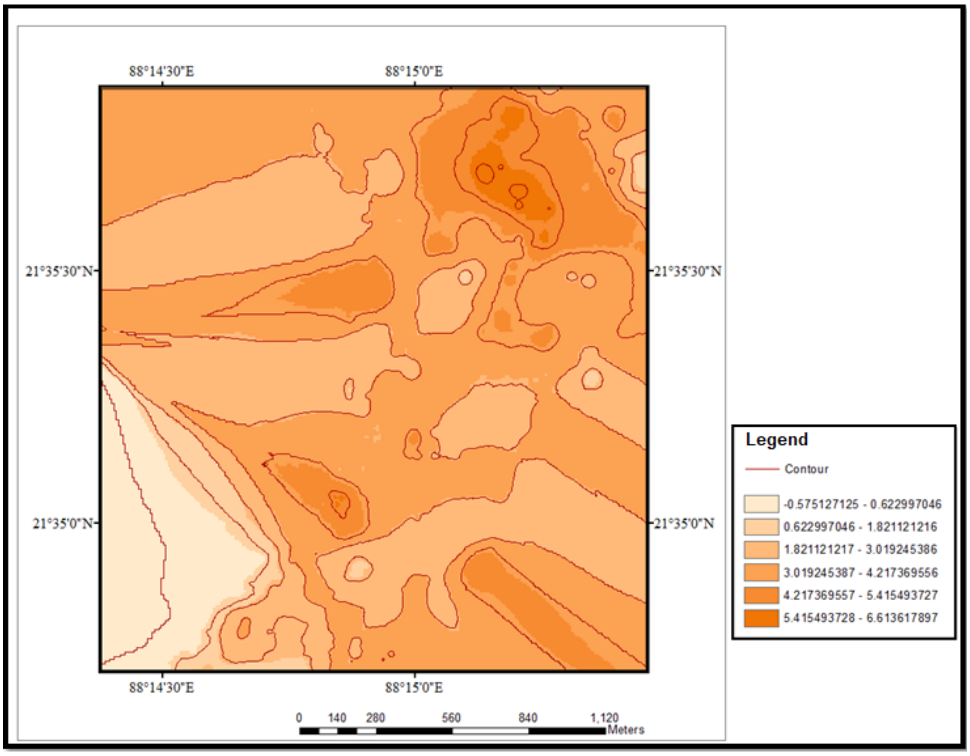


Figure 2.10: Contour planning map of saltpan, Patibania island, 2019.

In Plate 2.3, the root systems observed in the different geomorphic settings are depicted.

The contour map of a section of the Patibania island containing several saltpans is presented in Figure 2.10. The selected section presented in this figure is situated in the middle part of the Patibania island. The south-western part in this figure corresponds to the beach along the Muriganga estuary. In the eastern part of the figure, one can observe several regions having lower elevation completely surrounded by regions with higher elevation. These depressions are some of the saltpans in the Patibania island, which formed due to the same hydrological process as in the case of the Henry's island discussed above.

Saltpans are formed by hydrological processes in specific topographic settings. Climatic variations of the same hydrological processes cause conspicuous alterations in the texture and soil characteristics of a saltpan over the seasons. In Plate 2.5, the photos of a saltpan is presented during the monsoon season and in the pre-monsoon season. One can observe that the saltpan area turns into a muddy marsh during the monsoon. Due to the freshwater influx from the monsoonal rainfall, dwarf mangrove pioneer species are able to propagate there, which are the shrubs captured in the photo taken during the monsoon season. However, as monsoon ends, freshwater influx declines and the evaporative salt buildup from tidal action resumes. Consequently, those plant life able to colonize the area during the monsoon die back, and the saltpan becomes a barren surface once again.

In Figure 2.11, the schematic map of a cross section of the Patibania island taken from the west to the east is depicted. In the western end of this cross section, there is a beach ridge with a mangrove plantation and elevation 3–4 m. Next to it, the washover lobes have littoral vegetation and elevation 3–4 m. The saltpan behind the washover lobes has elevation 3–4 m. It has formed a depression between the washover lobes and higher ground and is covered in dwarf mangroves. The higher ground next to the saltpan rises to an elevation of 6 m, and has dwarf mangroves, and mangroves of very low density, low density and moderate density. Next to the higher ground, there is bank margins ridge with slightly lower elevation of 5.5 m. The bank margins ridge is covered in dense mangroves. The Edward's creek flow beside the bank margins ridge, and the stream bed of the Edward's creek has an elevation of 3 m. The two banks of the Edward's creek has bands of moderately dense mangroves. On the other bank of the Edward's creek, there is again a bank margins ridge, where afforestation of mangroves are carried out.

Plate 2.4: Geomorphic features of the Patibania island: a saltpan (left), wash over fan lobes along the sea (right).

In Plate 2.4, the photos of two geomorphic settings in the Patibania island are depicted. In the left, the photo of a saltpan is presented, and in the right of the figure, an overwash fan lobe is presented. One can notice that saltpans appear as a barren tract abruptly in an otherwise lushly vegetated area, as the larger mangrove species cannot survive the very high salinity levels found in a saltpan. The boundary of the saltpan is thinly populated by dwarf mangrove shrubs. In the photo of the overwash fan lobe in Plate 2.4, one can see that the surface is constituted of white sand and salt depositions. The region is almost devoid of vegetation, but a few mangrove pioneer species like Salicornia brachiata, Avicennia marina and Prosopis juliflora are observed, which implies that this region is in the early stage of mangrove colonization.

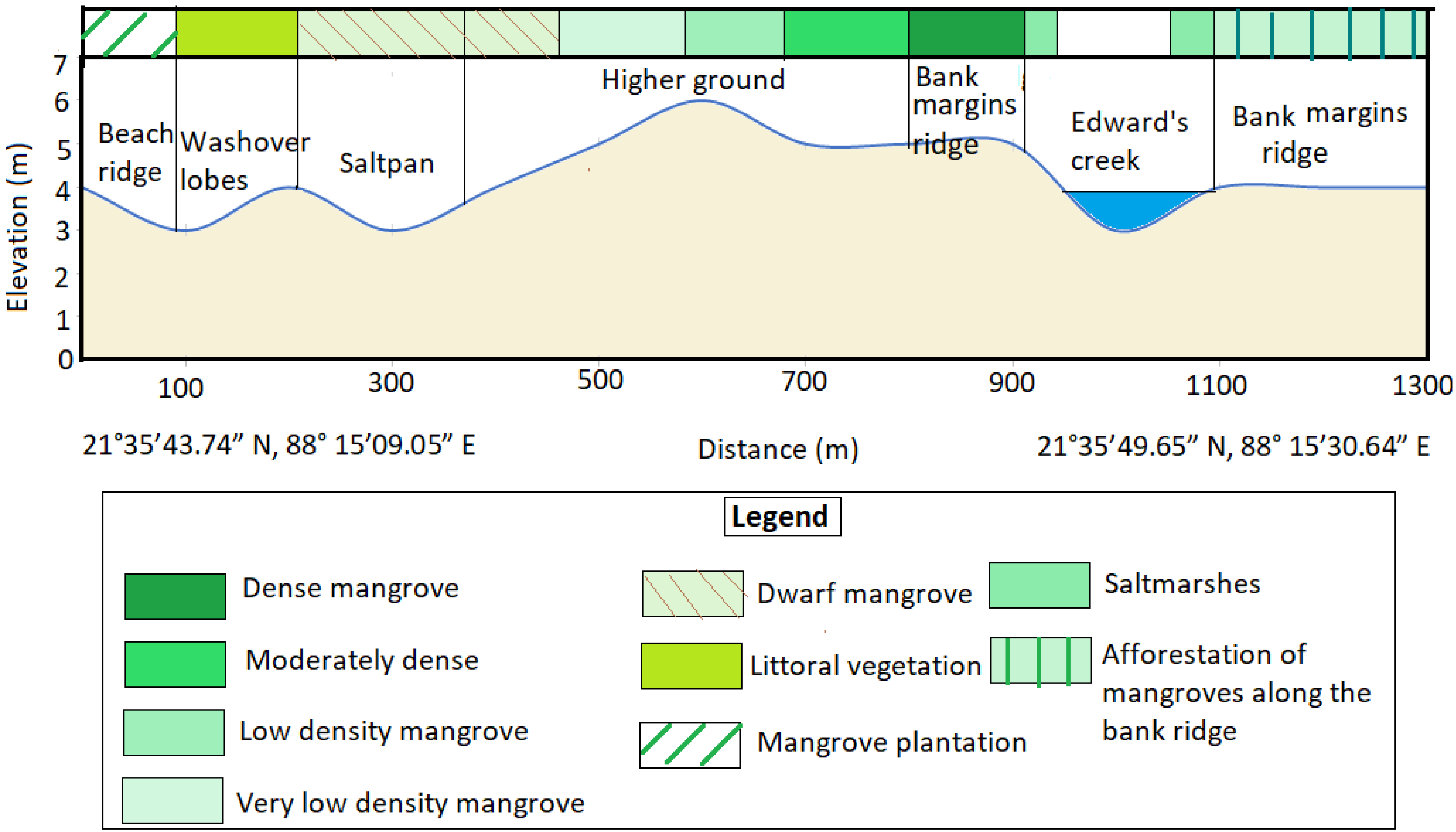


Figure 2.11: Cross sectional diagram of the Patibania island (west to east).

A large tidal range, low-sloping coastline and high sediment influx constitute a favorable environment for the formation of tidal flats (Murray et al., 2019). Tidal flats generally develop in macro tidal estuaries with the tidal amplitude exceeding 4 m. Wave exposure, tidal range and slope are the key factors for the growth of tidal flats (Dyer et al., 2000). The ecosystem in a tidal flat varies with its elevation. In the upper, the middle and the lower tidal flats, the characteristics of the vegetation are distinct.

Plate 2.5: A saltpan in the Henry's island in monsoon (left) and pre-monsoon (right).

Plate 2.6: Beach ridge environment in Patibania island.

The different mangrove species identified in the two islands are mentioned in Table 2.1.

Table 2.1: Description of the mangrove species observed

Species name	Local name
Rhizophora apiculata Blume	Bhora Garjan
Rhizophora mucronata Lamk	Khamu Garjan
Bruguera gymnorrhiza Lamk	Kakra

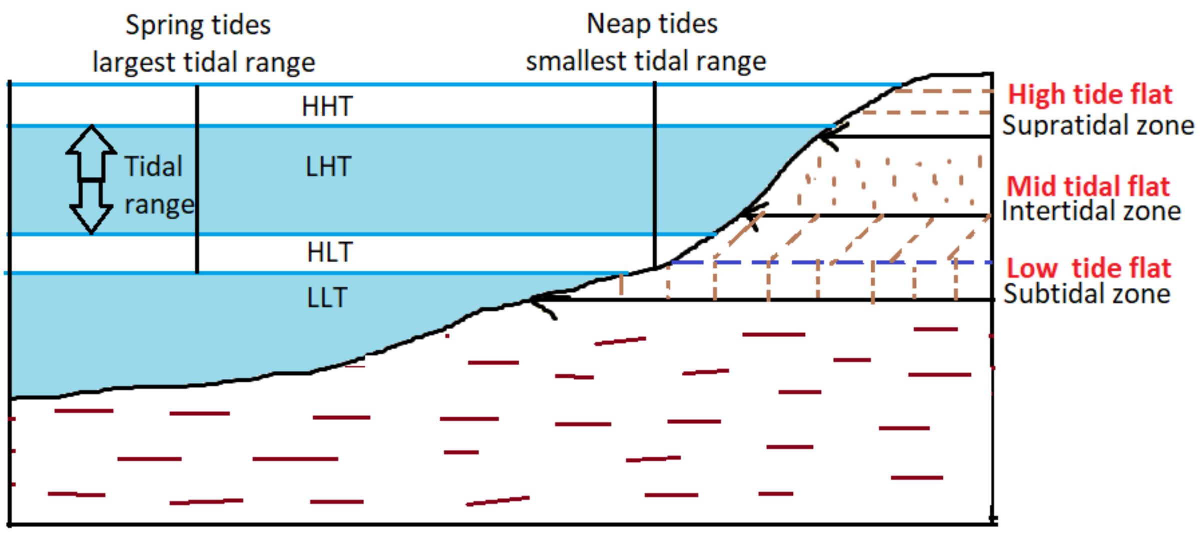
Bruguera sexangula Poir	Kakra
Ceriops decandra (Griff) Ding Hou	Jhamti Goran
Avicennia alba Blume	Kal ban/bain/bani
Avicennia officinalis L.	Jat ban/bain/bani
Avicennia marina	Peyara ban/bain/bani
Sonneratia apetala Buch. Ham.	Keora
Lumnitzera racemosa Willd.	Kripa, Kripal
Nypa fruticans Thunb.	Golpata
Nypa fruticans Thunb.	Golpata
Xylocarpus granatum Koenig	Dhundul
Xylocarpus mekongensis Pierre	Pasur
Aegiceras corniculatum (L.) Blanco	Khalsi
Excoecaria agallocha L.	Gneo, Gneoa
Aegialitis rotundifolia Roxb.	Tora
Heritiera fomes Buch. Hamilton	Sundari
Acanthus ilicifolius L.	Harkoch
Hibiscus tortuosus Roxb.	Ban Kapas
Dalbergia spinosa Roxb.	Chulia Kanta
Derris scandens Benth.	Noa Lata
Phoenix paludosa Roxb.	Hental
Terminalia catappa L.	Kat Badam
Suaeda nudiflora Moq.	Gire Sak
Salicornia brachiata Roxb.	Nona Sak
Crinum defixum Kar-Gawl.	Sukh Darshan
Cryptocoryne ciliata (Roxb.) Fisch.	Kerali
Porterasia coarctata (Roxb.) Takeoka	Dhani Ghas
Myriostachya wightiana Hook. f.	Nalai
Aeluropus lagopoides (L.) Trin.	Nona Durba
Opunita dillenii Haw.	Nag Phana
Ipomoea pes-caprae (L.) Sweet	Chagal Kuri

2.4 Tidal flat settings

Tidal flats are significant geomorphic features of south-western Sundarban, often found along the seashores, creekbanks and riverbanks. Tidal flats require an adequate supply of fine grained sediment for their formation (Gao, 2019), which is available in Sundarban from the sediment load of the Ganga–Brahmaputra river system. Lying in the intertidal zone, the tidal flats alternately undergo emergence at low tide and submergence at high tide (Rogers and Woodroffe, 2015) during each tidal cycle, approximately twice daily. The tidal inundation assists in the continuing formation of the tidal flats and shaping their geomorphic features. Tidal flats are principally constituted of mud formed from silty clay saturated with water. Sediment accretion and coastal erosion both influence the formation of tidal flats. Based on the distance from the water level, a tidal flat can be further divided in three parts: low tidal flat, middle tidal flat and high tidal flat (Semeniuk, 2018). The low tidal flat generally remains underwater to be exposed rarely. It is almost devoid of vegetation. The upper parts of the middle tidal flat generally has mangroves in the Sundarban. The upper tidal flat is rarely inundated, and may have salt encrusted surface (Semeniuk, 2018). In Figure 2.12, the geomorphic settings of a tidal flat is presented in a schematic diagram. High tidal energy is witnessed in the middle tidal flat. On the other hand, the high tidal flat has relatively low energy. The low tidal flat generally lies below the crest of the tidal waves, and experience low tidal energy. Due to the variation of the tidal energy, the sediment composition in the three zones are also different. The form of the sediment in the high tidal flat is muddy or silty clay, while the middle tidal flat is covered in fine sands. The low tidal flat generally lying below the water line has silty sand.

Plate 2.7: Tidal flats in Bakkhali coastal stretch.

The tidal flat settings in the Henry's island and the Patibania island are notable and atypical.



Vertical zone	Energy variation	Sediment types
High tidal flat	Low energy	Muddy or silty clay
Mid tidal flat	High energy	Fine sands
Low tidal flat	Moderate energy	Silty sand

Figure 2.12: Tidal flat settings of an estuary.

The Henry's island has an open coastal configuration with the seashore lying perpendicular to the tidal direction. On the other hand, the coast of the Patibania island lies parallel to the tidal currents with its southern protrusion providing a degree of protection to its coast from high energy waves. This dichotomy of configuration indicates that the coast of the Henry's island witnesses higher energy wave action compared to the Patibania island. Though tidal flats are more likely to form in the presence of lower energy tidal waves (Masselink and Short, 1993), it is found that it is the Henry's island which has an extensive tidal flat while the Patibania island has almost none.

The apparent discrepancy in the formation of tidal flats in the Henry's island and the Patibania island can be explained by the enormous sediment load in the waters of Sundarban. In the presence of such a surplus sediment budget coupled with large tidal ranges, the higher energy tidal waves crashing on the southern and eastern seashores of the Henry's island actually cause net deposition of sediment and thus aid in the formation of the wide tidal flats. The very low coastal slopes of the Henry's island also help in the development of the tidal flats. In the case of the Patibania island, the sediment rich tidal waves pass along as longshore currents causing relatively lower levels of sediment deposition, which have not caused the formation of tidal flats.

The tidal flats in the exposed southern and the eastern coasts of the Henry's island are barriered in the back by relatively high sand dunes. A particularly large and extensive tidal flat is seen along the eastern part of the Kiran beach in the Henry's island. Along with the open-coast tidal flats (Fan, 2012) in these regions, tidal flats are also seen in the relatively sheltered mouth of the Bakkhali creek. Here, the tidal flats are formed due to the more usual lower-energy tidal action in sheltered areas along with high sediment load, the asymmetry of flood currents and ebb currents and a low slope.

The newly formed tidal flats in the Henry's island are nutrient rich zones favorable for the growth of mangroves. In Plate 2.7, a photo of a tidal flat in the Bakkkhali coastal stretch in the southern seashore of the Henry's island is presented. Several mangrove pioneer species are observed thriving there. Mangrove plantations are also carried out along these regions owing to the nutrient availability.

While the longshore drift of sediments in the Patibania island has not resulted in the formation of tidal flats, it caused the development of other geomorphic features. The shoreline of the Patibania island contains sand spits, sandflats, and a long beach ridge platform, all of which are the outcomes of the deposition of sediments by longshore currents.

Two creeks, one from each island, are selected for closer inspection of the tidal flats on their banks. From the Henry's island, the Bakkhali creek is selected, and from the Patibania island, the Edward's creek is selected. These two creeks are the largest creeks in the respective islands, and influence the geomorphic settings and the ecosystem functioning in the respective islands. In Plate 2.8, the locations of the Bakkhali creek and the Edward's creek are depicted.

Plate 2.8: Locations of the Bakkhali creek in the Henry's island and the Edward's creek in the Patibania island.

In Figure 2.13, the schematic diagrams of the cross profiles of the Bakkhali creek and the Edward's creek are presented. The cross sections are taken from the west to the east. It can be seen that tidal flats have formed on the eastern banks of both the creeks. The tidal flat region on

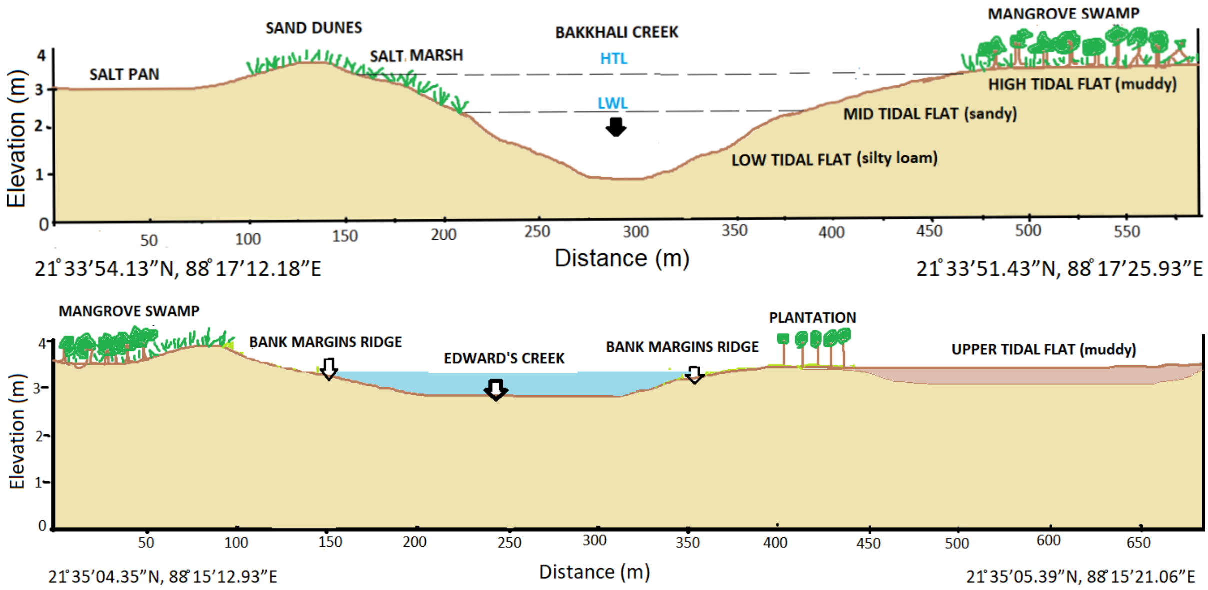


Figure 2.13: Schematic diagrams of cross profiles of the banks of the Bakkhali creek and the Edward's creek.

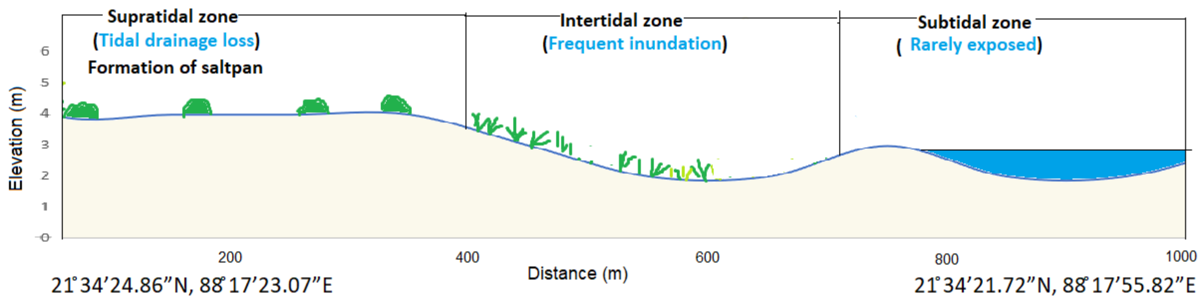


Figure 2.14: Schematic diagram of a cross profile of the tidal zones in the Henry's island.

the bank of the Bakkhali creek is more extensive and has more prominent elevation difference between the low, mid and high tidal flats. The soil characteristics of the low tidal flat is silty loam, while the soil is sandy in the mid-tidal flat and muddy in the high tidal flat. On the middle tidal flat of the Edward's creek, plantation of mangroves is established. The other bank of the Edward's creek has a comparatively steep bank margins ridge, beyond which there is a mangrove swamp.

The different tidal zones in the Henry's island and the Patibania island are presented in Figure 2.14 and Figure 2.15, respectively, which depict two cross sections of the respective islands. The subtidal zone lies under the mean low tide level, and is rarely exposed. On the other hand, the elevation of the supratidal zone is higher than the average high tide level, which means this zone is rarely inundated by tidal water. The intertidal zone is inundated, partially or fully, during each high tide. Consequently, the moisture content of the soil in this region is high,

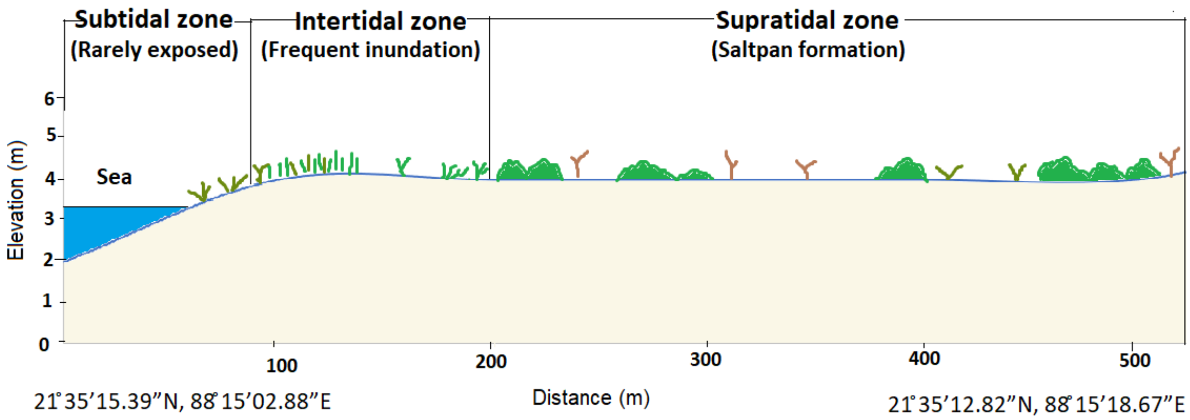


Figure 2.15: Schematic diagram of a cross profile of the tidal zones in the Patibania island.

which makes this region suitable for the growth of mangroves. In the subtidal zone, salt marsh vegetation is observed, and its density decreases as one proceeds away from the water level. On the other hand, the supratidal zone suffers from tidal drainage loss and resultant decline in water availability. Due to the deficiency of water in the supratidal zone, salinity rises in the soil. Progressive buildup of salinity in the soil of the supratidal zone has caused a concentration of saltpans in this zone of the islands. Dwarf mangroves which can withstand very high salinity levels are observed in the supratidal zone.

2.5 Saltmarsh vegetation and biogeography

Saltmarshes, which develop on the upper tidal flat, possess a distinct geomorphic character in the coastal belt. Saltmarshes lead in the process of coastal morphodynamic change in various aspects. Saltmarshes can be divided into high and low salt marshes on the basis of elevation and plant zonation (Adam, 1993). Low saltmarshes are found along the seaward margin and high saltmarshes are found in the hinterland. Soft muddy strata in an estuary and low energy coastlines are the favorable places for the growth of saltmarshes. Grasses, herbs, flowering plants and shrubs dominate saltmarshes.

Saltmarshes prefer to grow in a region where the concentration of sediments are high, and they can become a productive ecosystem. Saltmarshes have the capacity to sequester carbon from atmosphere and conserve it in the soil. So, saltmarshes act as a carbon sink in the ecosystem as well as a buffer of the coastal belt. In Chmura and Hung (2004), it was observed that salt marshes sequester carbon at an average rate of 210 g/m^2/year and globally store at least 430 Tg

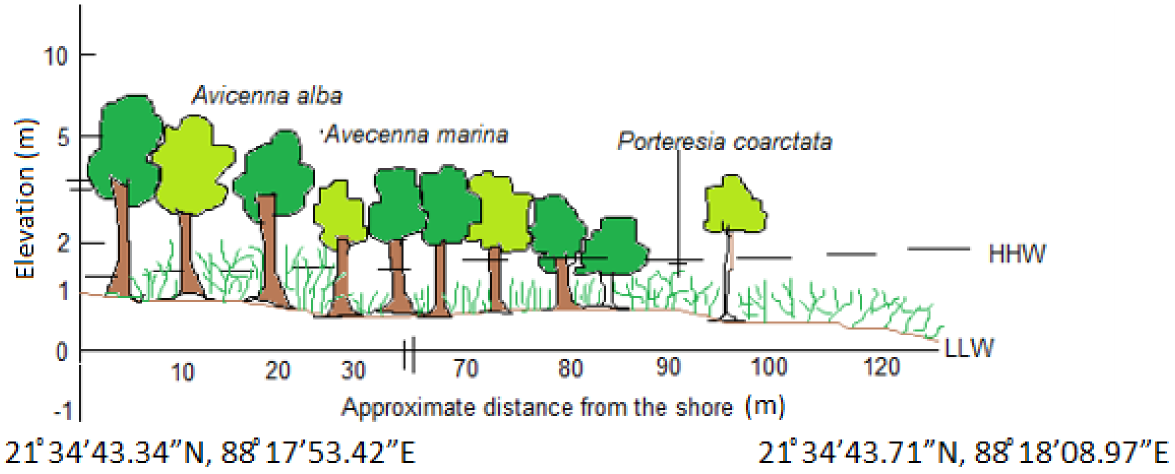


Figure 2.16: Distribution of saltmarsh vegetation along the coastal tract.

of carbon in the upper 50 cm of marsh soils. Saltmarshes carry out the highest level of carbon sequestration among the ecosystems in a coastal belt.

The reasons behind such huge conservation of carbon in the saltmarshes include the fact that saltmarshes conserve carbon with direct vertical accretion, the decay of organic carbon is low due to anoxic condition and finally the release of methane in atmosphere is low from saltmarshes (Mcleod et al., 2011). In terms of ecosystem services, they provide a number of functions to the community. Saltmarshes have high ability for adaptation to withstand multiple stressors. They can survive in extremely saline soil, brackish water, as well as in coastal flooding.

Biogeography of the saltmarshes is also interesting. Two types of saltmarshes are seen in the tidal flats. One type is called halophytes and another one is called glycophytes. Halophytes are grown in lower tidal flat areas which are prone to frequent inundations and extreme salinity. On the other hand, glycophyetes are seen on the upper tidal marsh areas. (Plate 2.9).

In Figure 2.16, a cross section of the Patibania island is presented, which depicts the vegetation succession from the lower low water (LLW) level towards the higher high water (HHW) level. It can be seen that next to the LLW line, saltmarsh vegetation is prominent. The mangrove density increases as one moves away from the LLW line towards the HHW line.

Halophytes and glycophyetes have different salt tolerant level that's why their location of growth also different. Halophytes commonly colonize low and mid elevation saltmarshes, while the upper marsh may be colonized by both halophytes and glycophytes. When the elevation of saltmarshes increases, the availability of saline water to the lower saltmarshes decreases. Soil salinity is determined by frequent inundation of low lying areas. Higher salt marshes witness low frequency of tidal inundation. However, the salinity of the soil also changes under the effects of coastal flooding and groundwater depletion. In a coastal area, balance between brackish water and fresh water is governed by rainfall and tidal water. In a lean season, extreme evaporation rate and evapotranspiration rate increase the soil salinity and leads to hypersaline condition. This situation leads to the formation of salt flats. High soil salinity may result in reduced water uptake and damage cell membranes – causing increased cell permeability and loss of nutrients to the soil (Alongi, 2002). Salinity of soil in the hypersaline patches affect the nutrients of the saltmarshes. Development of saltmarshes largely depend on low energy coast, tidal flat configuration and gently sloping bedrock.

Saltmarshes are considered as young in origin, which developed during the time when sea level has been close to its present level. The biogrography of saltmarshes are governed by the interplay of geomorphic processes, biological processes and human interference (Masselink et al., 2014). Diversities of saltmarshes are observed in different latitudes and climates. In tropical region saltmarsh diversity is less due to salinity of soil. Distribution of saltmarshes is extensive in tropical coast, and the vegetation is considered as pioneer community at seaward regions where true mangroves cannot exist. Generally, saltmarsh species increases its numbers with the increasing elevation. Low marshes have the capacity to adapt themselves in extreme soil salinity and high temperature. Whereas high marshes have narrow tolerance level to the environmental adversities. Spatial zonation of saltmarsh distribution is completely different in different estuarine systems. *Salicornia* monocultures and *Suaeda maritima* are found in the saltmarshes in the Patbania island and the Henry's island.

Plate 2.9: Saltmarsh vegetation along the Muriganga estuary.

In Plate 2.9, the saltmarsh on the bank of the Edward's creek is depicted. Saltmarshes are visible on both the banks of the Edward's creek. But the density of saltmarsh vegetation decreases with increasing elevation.

2.6 The role of sedimentation and saltmarsh maintenance

Development and growth of saltmarshes are determined by tidal regime, sediment supply, energy of the shore and sea level rise. Elevation of tidal flat is controlled by the sediment accumulation through tidal prism and vegetation. A saltmarsh survives in that tidal flat which is higher in elevation and suitable for its existence. Growth of saltmarshes is controlled by the internal factors of previously growing saltmarshes in that tidal flat. Ongoing tidal flows help in accumulation of sediments and provide organic matter. Rapidly growing saltmarshes can trap sediments and organic materials. Saltmarshes have strong relationship between sediment supply and distances of sources of sediments. There is a inversely proportional relationship between sediment accumulation and hydroperiod (Masselink et al., 2014). Hydroperiod refers to the period of inundation, and it depends on tidal range and surface elevation. The role of low saltmarshes in accumulation of sediment is more significant because its hydroperiod is greater then the high saltmarshes. Rate of sedimentation at lower marshes is high because of frequent tides which brings sediments and these sediments are deposited in the region with low elevation before it reaches the salt marshes with higher elevation. Pethick (1981) coined this process as a 'negative loop' because due to sedimentation, height of the tidal flats and salt marshes increases which indirectly decreases the hydroperiod. This in turn influences the subsequent rate of sedimentation. Sediments on which saltmarshes are grown are brought down by tidal water. These sediments transport minerogenic and organic materials to the saltmarsh, which are allochthonous sediment. Also, the salt-marsh plants themselves can supply organic material, which is called as autochthonous sediment.

The sources of the sediments are coastal shoreline eroded materials and erosion of lower tidal flats. Salt marshes accept huge amount of marine sediments because of its location at the open coast, sometimes they receive huge amount of sediment influx through the storm surge, which can create significant change to the coastal morphodynamics. For example, super cyclone Aila, which occurred in 2009, and Amphan, which arrived in 2020, greatly influenced the saltmarshes on the coastal belt of south-western Sundarban along with significant ecological consequences on the ecosystem services. Sediment deposition, sediment erosion, sediment compaction, soil shrinkage, root decomposition, root growth, soil swelling, and lateral folding of the marsh root mat are the impacts of storm surges in Henry's and Patibania island.

In Figure 2.17, the sediment accumulation state and the biogeography of the saltmarsh along the Bakkhali creek is depicted on a cross section along with the elevation profile, geomorphic

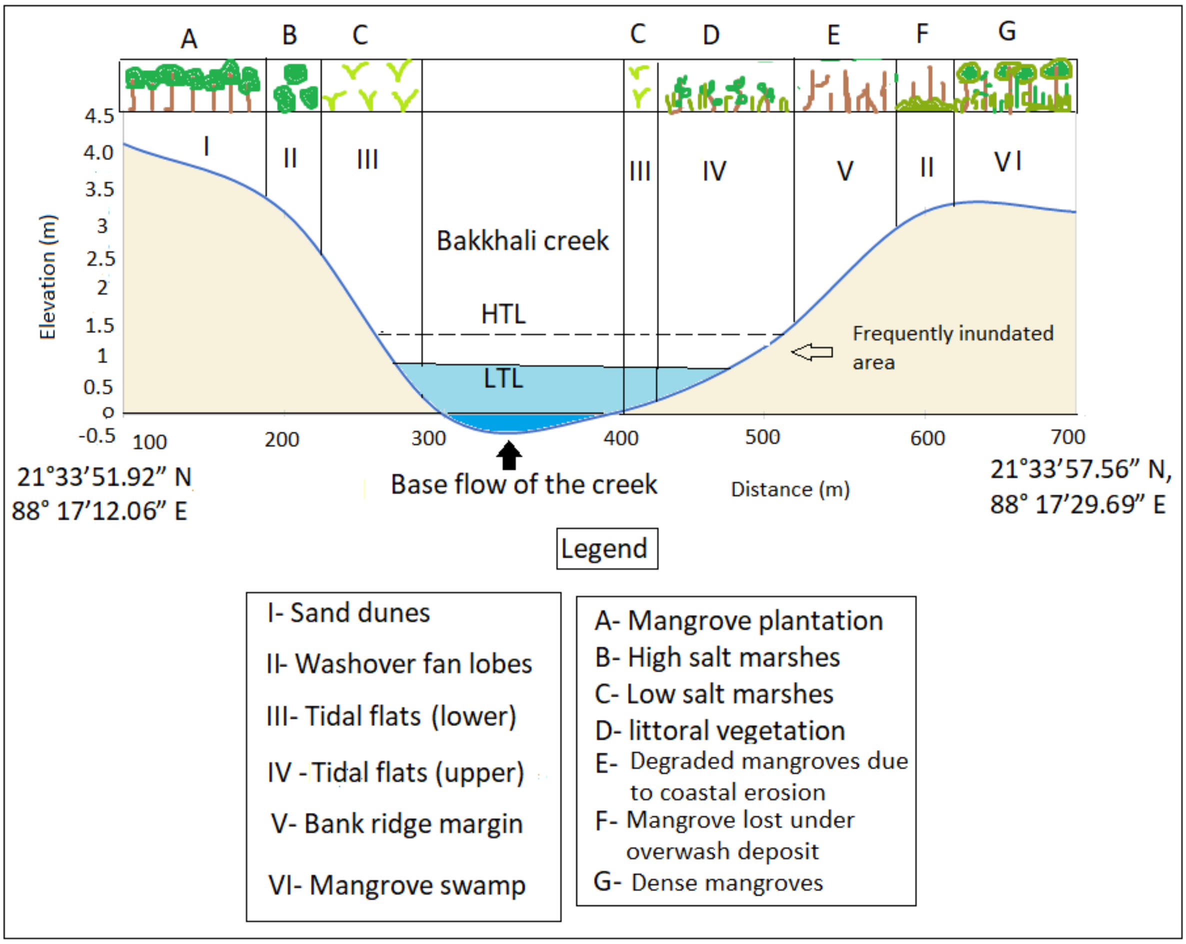


Figure 2.17: Sediment accumulation and biogeography of saltmarsh along the Bakkhali creek.

settings and vegetation. The direction of the cross section is from the west to the east. In the cross section, high saltmarshes can be observed on the overwash fan lobes, which are rarely inundated. Low saltmarshes are noted on lower tidal flats. Littoral vegetation is found on upper tidal flats. The schematic diagram of the cross section also depicts the change in vegetation characteristics with elevation. On the sand dunes, mangrove plantation is observed. In eroded areas of the coast, degraded mangroves are noted. Next to the degraded mangroves, remains of mangroves lost under overwash deposits are observed. Beyond the overwash fan lobes, mangrove swamp with dense mangroves is observed.

2.7 Evolution of saltpan formation

Saltpans and salt flats are produced by morphological dynamics of the swamps and extension of dry periods in the regions. The spatial and temporal distributions of saltpans and salt flats

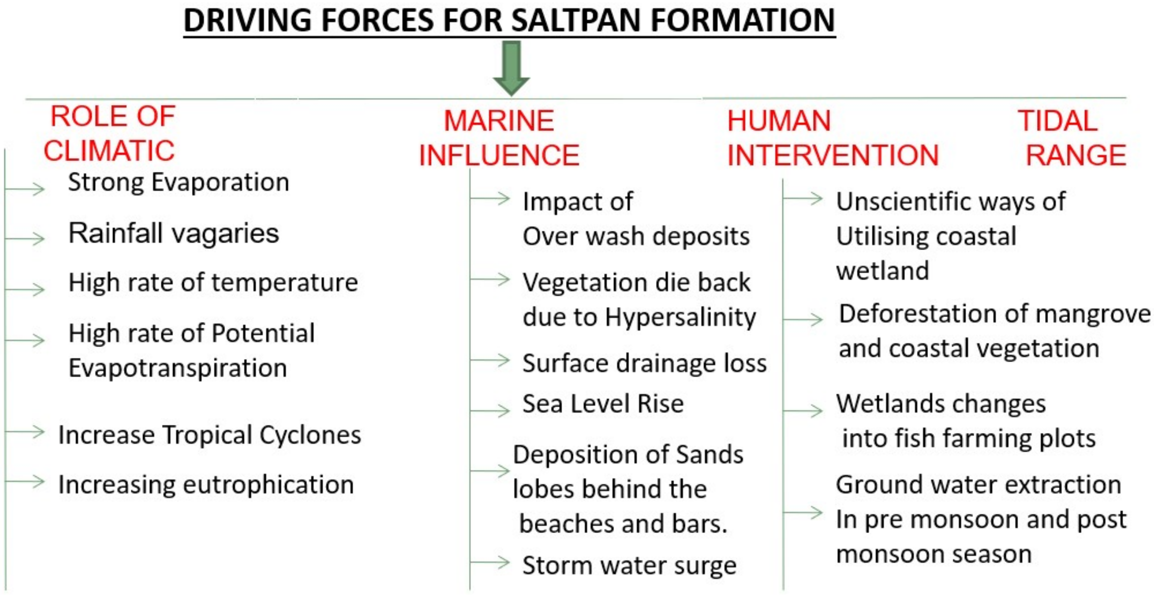


Figure 2.18: Factors affecting saltpan distribution within islands.

are related with the maturity of mangrove swamps. Evolution of saltpan in the South western Sundarban specially in Henry's and Patibania island is controlled by several factors, which are general topography of the islands, hydrological characters, extreme climatic variation, sea level rise, frequent cyclones, tidal drainage loss, lack of freshwater influx and blocking of creeks due to siltation.

Saltpans develop in the tidal swamps of abandoned delta, where the input of fresh water is nil in the non-monsoonal seasons. The rapid evaporation of water between two high tides has led to the formation of salt encrusted area in the landward zone (Paul, 1998). The seepage channels carries huge silts from inner parts of the islands by the scouring process caused by ebb tides. This tends to lower the interior of the flood plains and gradually form pan areas and enlarge them (Figure 2.18). Saltpans are evolved from the primary salt encrusted area that are small shallow depressions and some of which form as residual unvegetated areas within a developing mangrove swamp while others (often long and narrow) are the result of the blocking of part of a tidal creek by slumping banks and siltation (Plate 2.10). Development and growth of the saltpans are mostly seen after Aila in Henry's and Patibania islands. Though the presence of these saline patches were seen prior to Aila but those have increased their area after 2009 mainly due the cyclonic impact of Aila. Prolonged time of saltwater accumulation within depressions of islands influence the growth of saline patches within mangrove swamps. Development of saltpan have been observed in six stages in different parts of islands. Some

Plate 2.10: Location of mature saltpan in Henry's island (left) and saltpans in Patibania island (right).

saltpans are in primary stage, some are in secondary stage and few are in mature stage. Mature saltpans have unique hydro-geomorphic characteristics. Location of saltpans in the two study areas have been identified with repeated field survey and from Cartosat 2A DEM (Figure 2.19). Seasonal observation implies that in pre-monsoon season desiccation cracks retard the growth of mangroves, whereas in monsoon season algal encrustations and standing pool of water influence eutrophication process. In this season nutrient availability slightly increased so mollusks are seen on the top layer of saltpans (Plate 2.11). Salt tolerant species are seen in the central part and towards fringe areas species richness gets higher in the mature saltpans of the Henry's island. These kinds of hypersaline patches are significant geomorphic features of Sundarban islands. It has the great impact on mangrove degradation in Sundarban. Patibania has also pronounced features of saltpans.There is another kinds of vegetation succession is seen along with saltpan development.

There are certain processes of saltpan formation from literature reviews and field survey. They are the following:

- Wide areas of the upper marsh are liable to flood only in equinoctial tides and in storm surge which expose top soil under hypersaline condition by prolonged evaporation and salt encrustation. Halophytic plants disappear from here such areas are called saline 'blanks'(Paul, 1999).
- Saltpans are also developed in the linear depressions of abandoned creeks, swales between point bars,smaller pools of the supratidal flat and even in the elongated chutes of channel bank.
- Saltpans are mostly influenced by monsoonal fresh water.It is replaced by herbaceous patches of Sesuviumprotulacastrum, Salicorniabrachiata and salt marsh grasses.

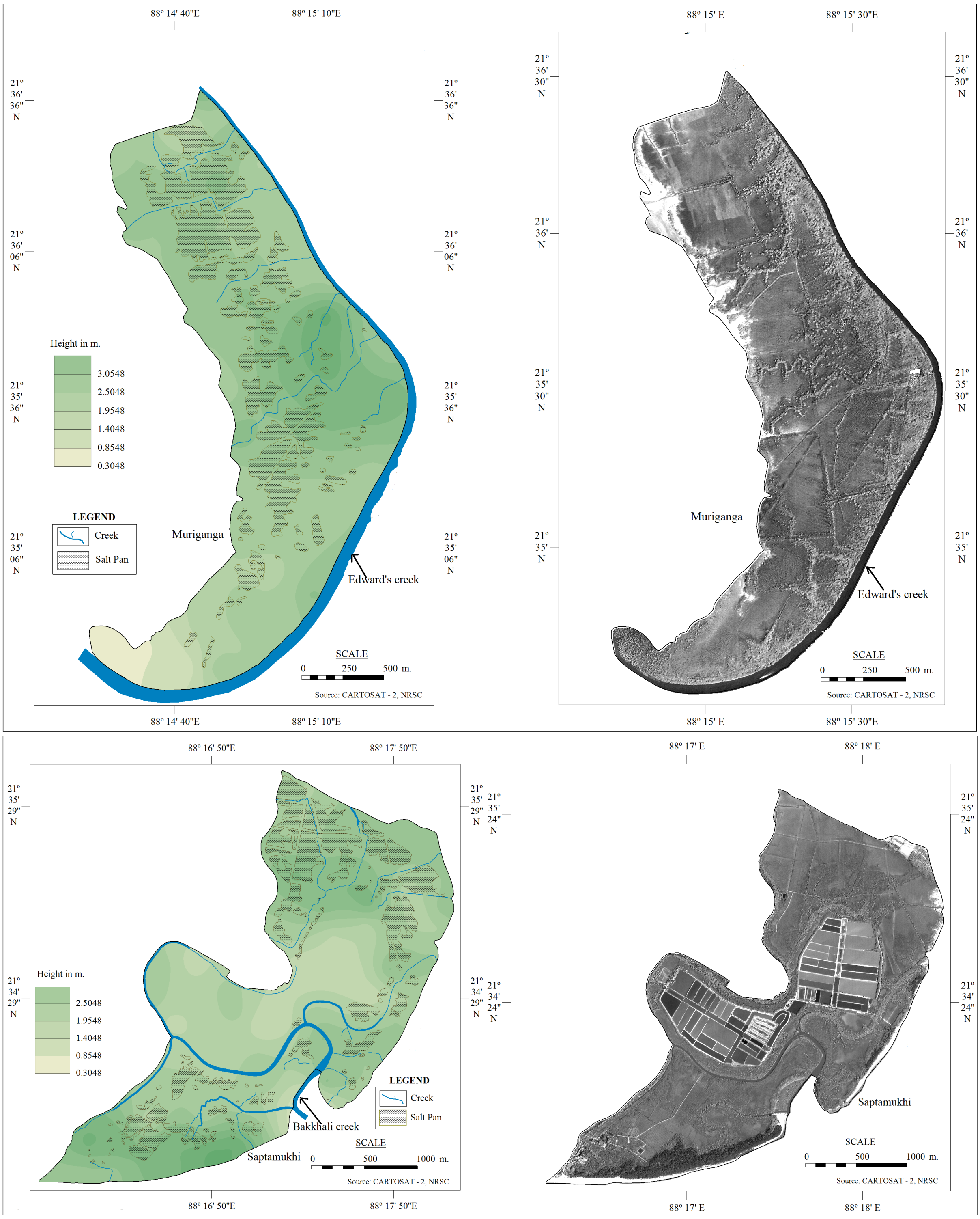


Figure 2.19: Identification of saltpans in the Patibania island (top) and the Henry's island (bottom) based on Cartosat 2A DEM (2019).

- There are few places of tidal flood plains where their initial swamp surface were left unvegetated and the high spring tide water lay in this embryo pools evaporated to produce highly saline conditions in which no plant can survive.

Development of saline patches within islands have certain stages of growth system.

In the first stage depressions in the surface acts as a primary cause for the development of saltpans.High storm surge inundates the total island area. The depressions in the topography helps to accumulate salt water for prolonged time.

In the second stage, hydrology of the coastal system plays important role. All the tidal creeks of the low lying areas become chocked due to frequent inundation process of tidal activity.Siltation and slumping of the banks hampers the fresh water influx into the island, which eventually maintained the hydrological balance between fresh water and salt water.Due to this level of salinity remains higher in the islands pockets .

In the third stage climate, mainly high evaporation rate and lack of monsoonal rainfall becomes the integral factors for the development of saline patches. In the presence of extreme temperate and high evaporation rate, water gets evaporated remains the salt on the surface. This is how primary saltpans are produced.

In the fourth stage, these primary saltpans widens its area and sometimes it remains without vegetation, or retard the growth of vegetation due to extreme salt encrustrations. This is the mature stage of saltpans.Thus these saltpatches or hypersaline pathches create bald pathches within mangrove swampy zone.

In the fifth stage if there occurs any high storm surge or cyclones its broaden the area of the saline patches ,and it also changes its shape too.Like circular to semicircular, rectangular. They are given different name for example saltpond, salt flats, saline blanks etc.Their soil characters, mangrove characteristics also changes during pre-monsoon to monsoon and in post-monsoon seasons.

In the mature stage or final stage of saltpan, it is seen the unique succession level of mangroves with different characters.Some times it is seen high salt tolerant species of mangroves in the central prt of the saltpans,or sometimes stunted growth of mangrove species in the centre,and sometimes devoid of vegetation in the central part.It is observed from the field study that central part of the saltpans have maximum salinity then the peripheral region ,So richness of the mangrove species are maximum in the periphery. Level of organic matter is high in peripheral part of saltpans.

Plate 2.11: GPS profile of a saltpan, with the locations of a long profile and three cross profiles depicted.

Naturally occurring this kind of saltpan changes its character if there is any high rainfall occur.That fresh water minimize the effect of hypersalinity and helps to grow mangroves by upgrading the soil character.Immense deposition of salt on the upper part of the soil ,make this layer infertile .whereas lower stratais high plasticity and animal burrows indicates the fertility of the soil. Another factor which trigger the growth of saltpans within mangrove zones are pore water salinity.If the pore water salinity increases vegetation die back occurs.Not only that high level of pore water salinity retard the growth of mangroves and regenaration process too. In Plate 2.11, the GPS profile of a saltpan is presented. The locations of a long profile and three cross profiles are depicted in the satellite map. It can be seen that the saltpan developed in a dense mangrove zone. Within the saltpan, due to very high salinity, only a meager vegetation is present. The central part of the saltpan is almost barren. In Figure 2.20, the long profile and the cross profiles are presented, with the zones of vegetation being marked over the profiles. In Plate 2.12, the GPS profiles of two other saltpans are presented, which also developed in a dense mangrove zone. The saltpans form bald patches in an otherwise densely vegetated area. It is observed that wherever the saltpans emerge, the vegetation suffers from the very high salinity levels in the soil.

From Figure 2.19, it is clear that in the Henry's island most of the saltpans are concentrated

Plate 2.12: GPS profiles of two saltpans.

where the elevation is low and experience frequent tidal inundation along the coastline adjacent areas. In the Patibania island, most of the saltpans are concentrated at the middle part of the islands due to small pockets of depression and prolonged time accumulation of salt water.These patches are also developed beside the coastal stretch western part of the island.

To analyze the physiography of the saltpans and their topographical characters, cross profiles are drawn with the help of Dumpy level survey. The four cross profiles in Figure 2.20 are drawn in east–west and north–south directions to demonstrate the relationship between vegetation succession and elevation in a saltpan region. The characteristics of the vegetation in and around a saltpan varies prominently, and in the saltpan over which the cross profiles are drawn, the vegetation is spatially divided in six zones. In the central part (zone I), dwarf mangroves are observed, which include *Salicornia*, *Aegiceras* and *Excoecaria*. The dwarf mangroves can tolerate very high levels salinity. However, their growth has been retarded due to the hypersaline conditions prevalent in the saltpan area. The density of vegetation increases as one moves away from the central part. There is a depression in the central part. This depression helps trap both saline water during storm surges and freshwater during rainfall. The amount of rainfall trapped is however very small compared to the trapped saline water. The low intensity of monsoonal rainfall and delayed arrival of monsoon affects the amount of rainfall. In Section 5.1, the declining nature of rainfall is demonstrated using trend analysis. Due to the declining rainfall,

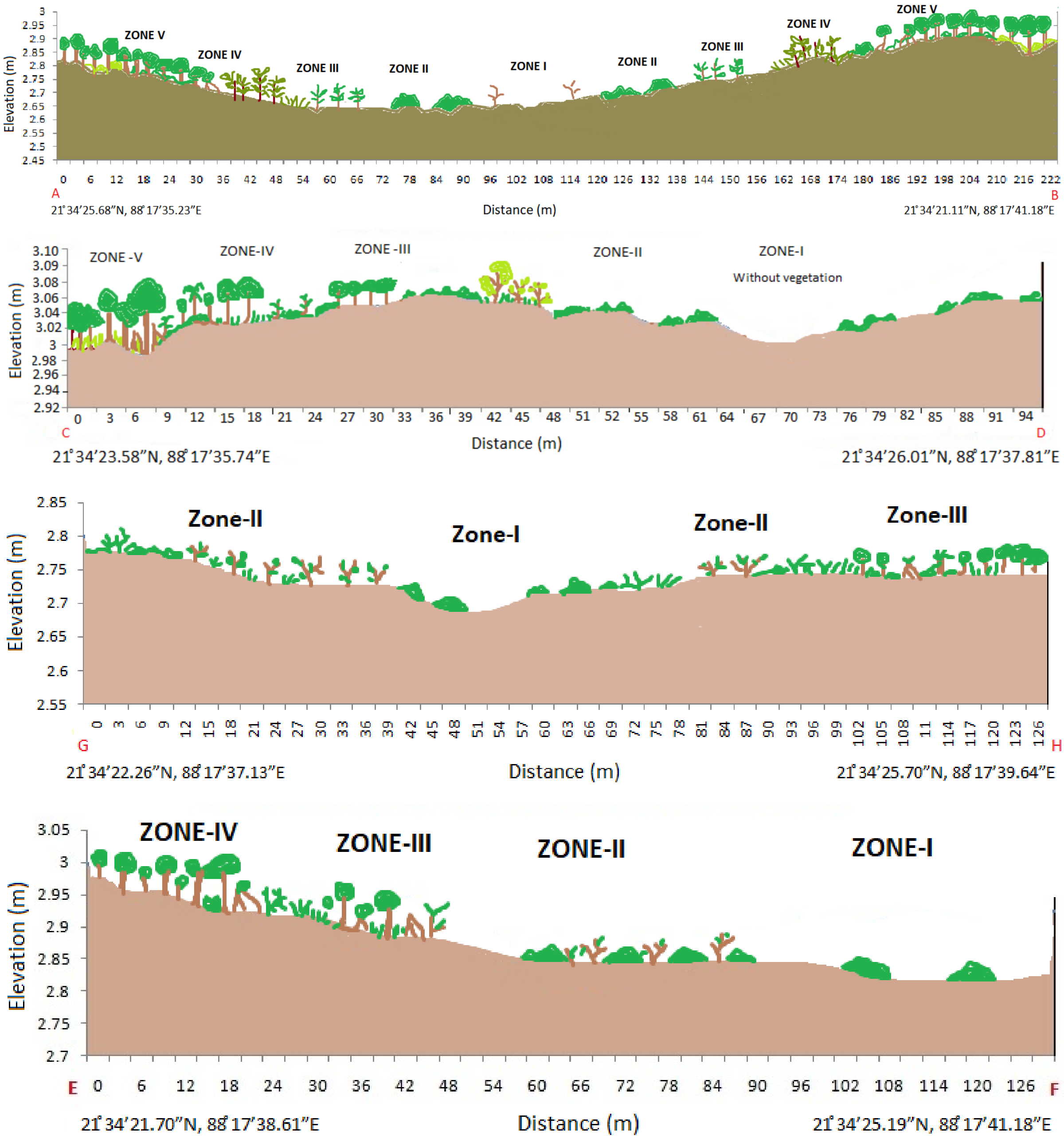


Figure 2.20: A–B (first from top): east-west oriented cross profile; C–D, E–F and G–H: north-south oriented cross profiles in a saltpan.

there is change in the vegetation succession. Mangroves adapt themselves with the changing climate through physiological changes. The increasing salinity from the evaporation of the saline water causes the expansion of the saltpan over time. At the lower parts of this depression, the trapped water remains for a longer time due to the lower elevation. This variation of water inundation among the different parts of the saltpan causes differences in the soil character of these regions. With the changing soil character, the vegetation also changes in the different

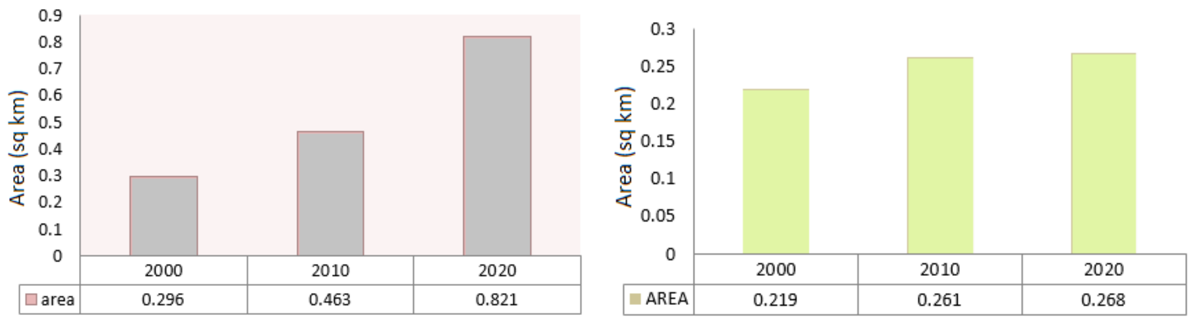


Figure 2.21: Changing area of saltpans presented through bar graphs for the Henry's island (left) and the Patibania island (right).

parts of a saltpan.

Area of the saltpans changes in last two decades (Figure 2.21). The spatial distribution of saltpans also changed over the same time frame, which is reflected in the maps of saltpans in the two islands in the years 2000, 2010 and 2020 presented in Figure 2.24 and Figure 2.25. Frequent cyclones at the Bay of Bengal and its impact on low lying areas of Sundarban inundate the coastal tract. Decline of monsoonal rainfall which causes lack of freshwater favored the growth of salt patches and negatively affect mangrove regeneration process. It is identified that the area of saltpans have increased mainly after Aila which hit Sundarban in 2009. The storm surge height was more than 2.5 m, which inundated the region for a long time. The prolonged inundation helped in the growth and development of new saltpans in this region. In both the islands, increased rate of salt patches indicates a vigorous stress on the mangrove community and ecosystems.

2.8 Geomorphic settings of estuaries and tidal channels

Evolution of any geomorphic setting in any coastal environment such as in estuaries, deltas are controlled by sediment supply, sea level and other physical processes. This section describes the geomorphic settings of estuaries and tidal channels because they are closely associated.

Estuaries are the route by which sediment is transported from rivers to the sea (Dyer, 1995). The dimension and distribution of materials of tidal inlets are controlled by volume and tidal flow, sediment supply and wave energy. Mouth of every estuary is enclosed with sandy barrier that is controlled by salt water prism. Estuaries provide huge nutrients to the coastal ecosystems. On the other hand, tidal creeks interrupt longshore transport of sediments, supply of sands to

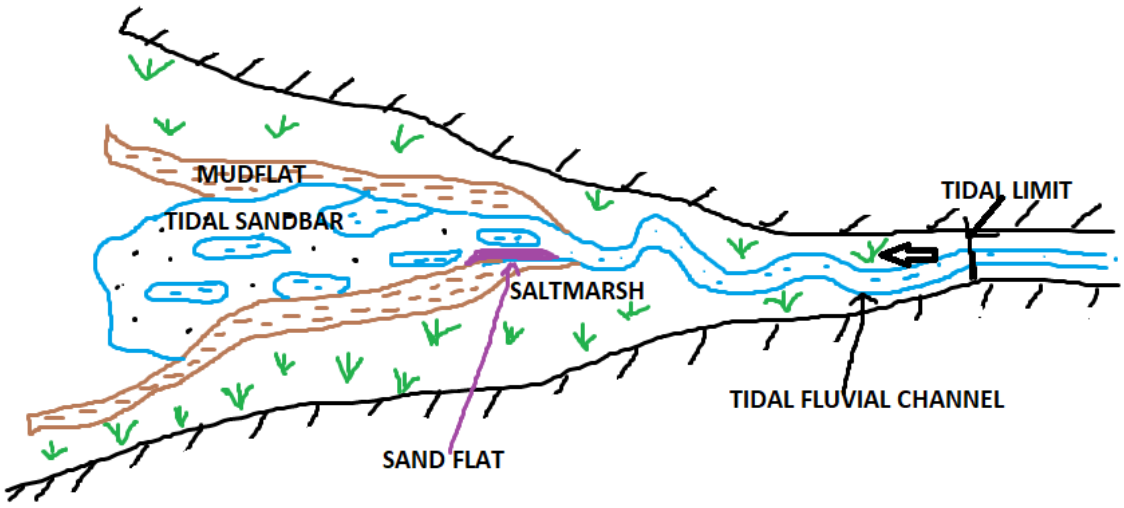


Figure 2.22: Geomorphic of tide dominated estuary.

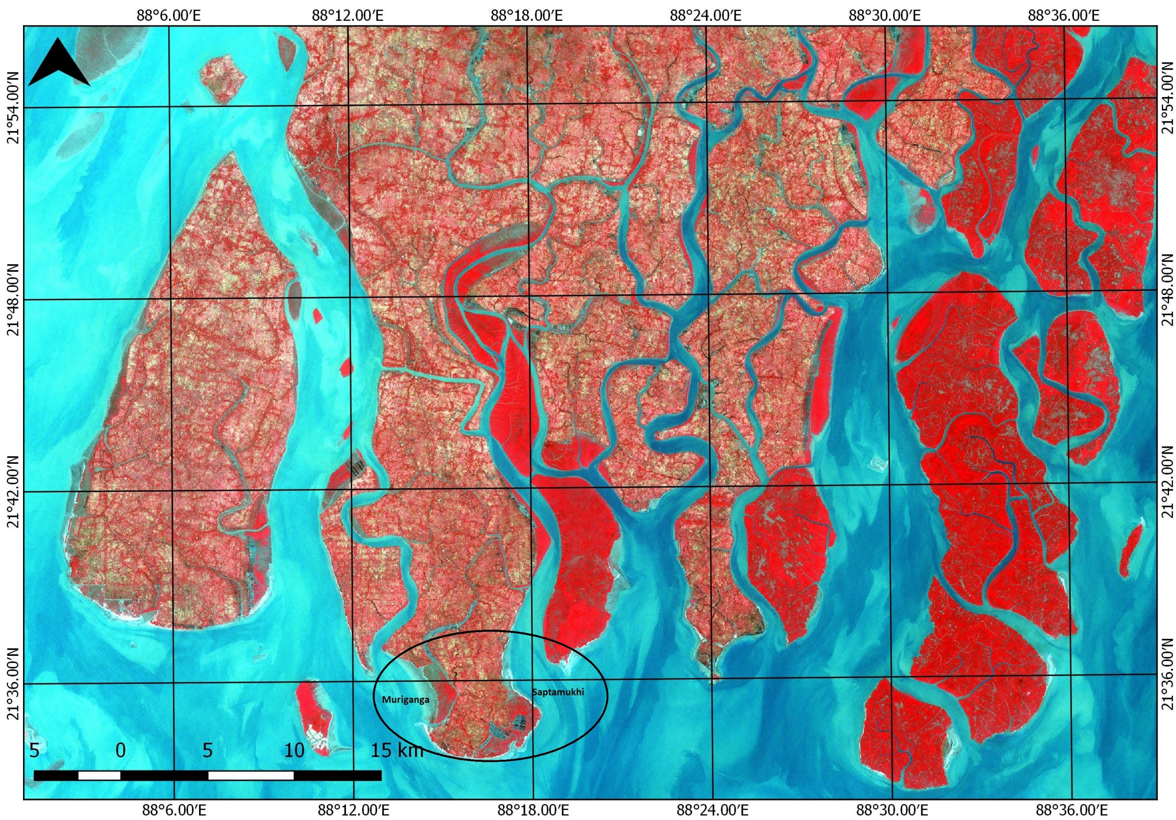


Figure 2.23: Location of Muriganga and Saptamukhi estuaries within Hooghly estuary in south-western Sundarban.

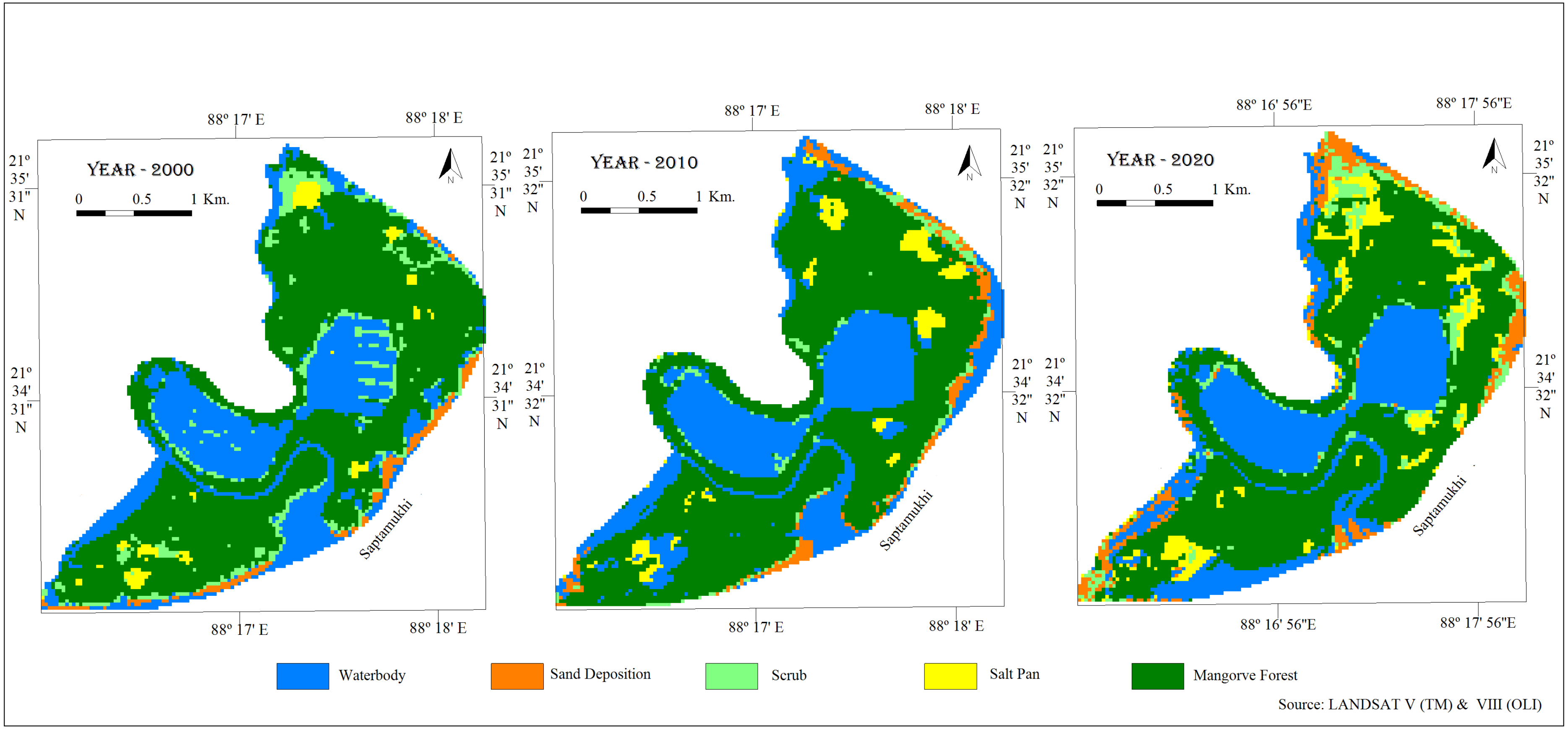


Figure 2.24: Changing area of saltpans within Henry's island.

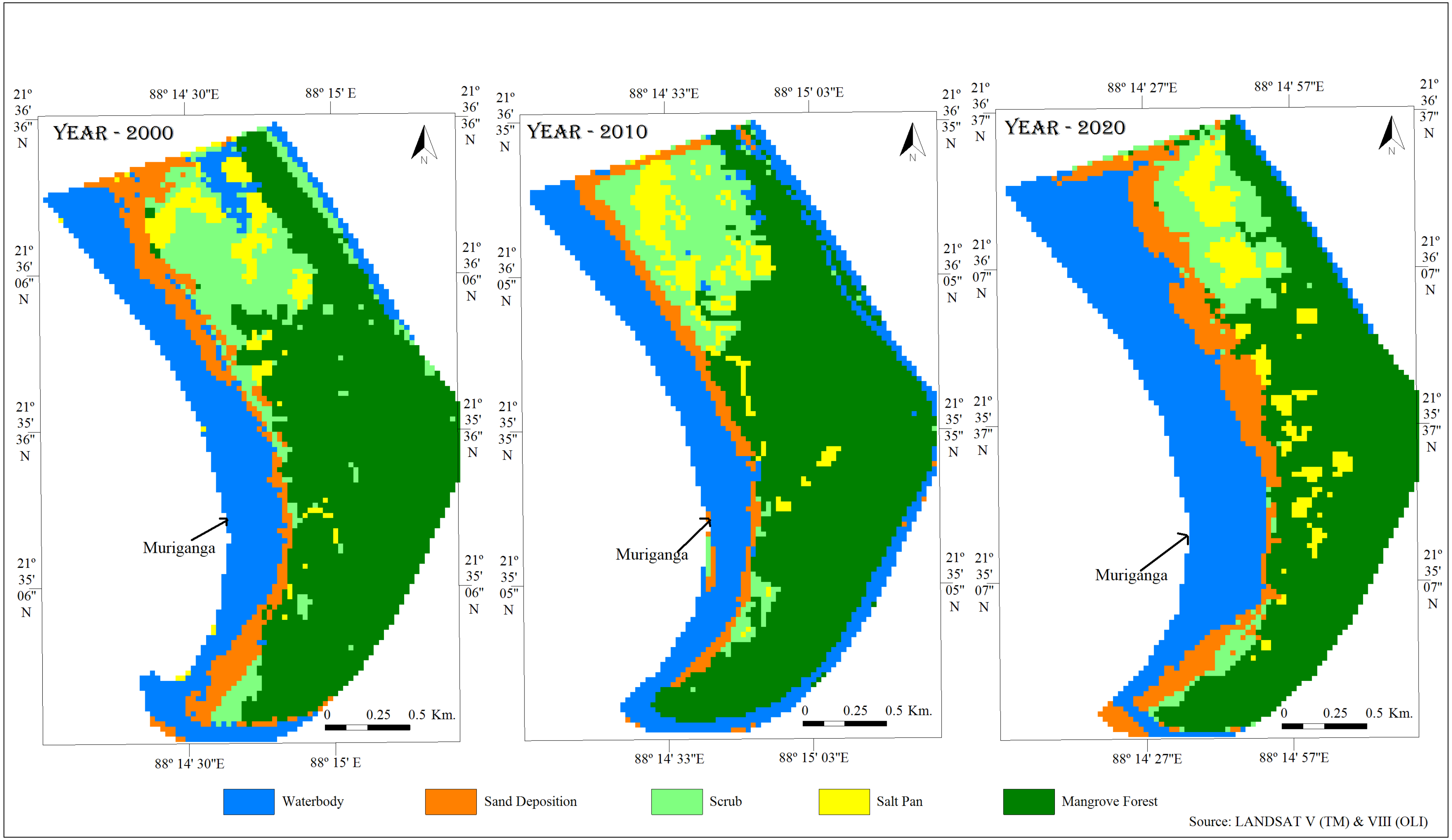


Figure 2.25: Changing area of saltpans within Patibania island.

the downdrift beaches, erosional and depositional process of tidal shoreline. The magnitude of shoreline changes is the consequence of tidal inlet processes. Hooghly estuary is a macro-tidal estuary, where the height of the tides exceeds the wave energy at the mouth of the estuary. Due to funnel shape mouth, strong tidal currents of flood tides amplified up due to convergence. In Figure 2.22, a schematic diagram of the geomorphology of a tide dominated estuary is presented, which includes features like sand flat, mudflat, tidal sandbar, saltmarsh, tidal fluvial channel and alluvial valley.

Sinuous and meandering pattern of channels are the common characteristics of Sundarban estuary. Huge tidal rush hits the exposed bank. Geomorphically, Sundarban have several physiographic settings. Convex inner part of the estuarine banks are relatively protected from tidal rush. So, formation of tidal mudflats, swamp development is common features of the estuarine environment. Sandy coastal plains and low lying islands are exposed in south western Sundarban which face severe erosion (Paul, 2002). Freshwater discharge of the two mixes with saltwater which is carried out into the estuarine reaches by tides. The Henry's island and the Patibania island are situated at the Saptamukhi and the Muriganga estuaries (Figure 2.23). Saptamukhi and Muriganga both are contradicting in nature. Their estuarine characters are also different. Saptamukhi is no more active now in terms of fresh water discharge. It is fully dominated by tide waters though a little amount of freshwater comes down into their lower courses through the inter connecting channels like Ichhamati–Raimangal–Bidya rivers. Muriganga river has direct access of fresh water but both the rivers are active due to tidal flow. Tidal flow erodes the exposed mud bank of Saptamukhi and Muriganga so the bank erosion is a major problem of these two islands.

In terms of shape of the river has concave left bank in lower middle reaches which is exposed to erosion but Saptamukhi river has convex left bank in lower reaches therefore it experiences deposition. Long sandy coastal belt and low-lying estuarine islands are erosion-prone geomorphic units of these region. Ghosh (2018) identified five major geomorphic units of these two estuaries (Table 2.2).

Table 2.2: Showing the geomorphic units of Saptamukhi and Muriganga river estuary. (Source: modified after Ghosh (2018))

Hydro Geomorphic Unit	**Geomorphic settings**	**Extent of erosion**	**Extent of deposition**

Flat sandy coastal belt in the extreme south	2-2.6m elevation, flat and gentle sloping towards south	Entire southern part	Small patches in western part
Low lying estuarine island in the mouth reach	2.6-3.8 m elevation. Flat and gentle sloping toward marginal parts from inner part.	Entire south western part	Eastern and northern portion
Tidal flat in the middle reach estuary	2-3.9 m elevation. Flat and gentle sloping towards south western part is exposed whereas eastern part is situated in inner bank.	Almost western part	The concave sheltered eastern part.
Elevated tidal flat in the upper reach of the estuary.	3-6 m elevation. Slightly elevated and gentle sloping toward south western part is exposed.	Western marginal section	In the interior eastern portion.
Mid-channel island in the upper-middle reach of estuary	Around 2 m of height covered by mangrove swamp, inner part of estuary.	Southern part	Sheltered northern part.

Bakhali creek is extended to west-north -west direction separating the boundary line Fredrick island and Bakkhali area. The geomorphology of the Bakkhali creek and its surroundings are presented in Figure 2.26. The southern bank is characterized by significant rill channel which are cutting across the intertidal flat of the channel bank margin. This perpendicular tidal flat is colonized by saltmarsh patches with waterline colonization of true mangroves. The uppermost part of the southern bank is covered by longshore drift of sandsize sediment over the paleo-mudbank. The true mangroves habitats are located behind the sand zone. The line of the sand zone at the backshore is also fringed with planted casuarina trees and Prosopis trees. Some older plants are Excoecaria are exposed on the true line margins. The entire tidal flat is sloping

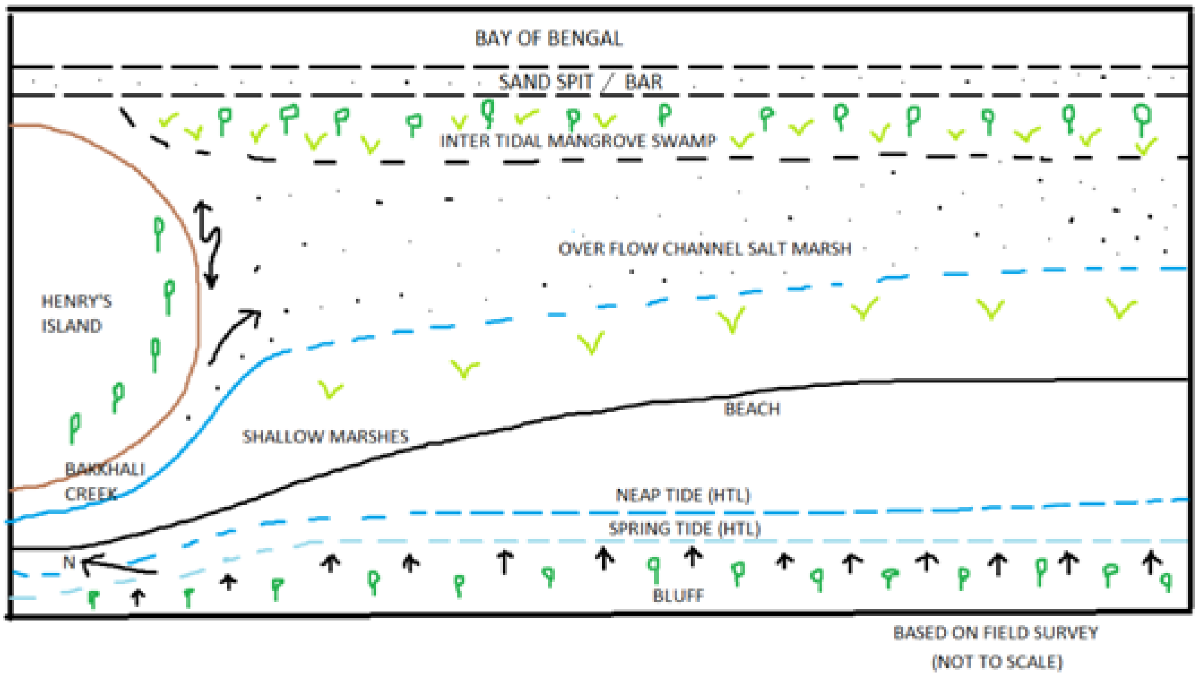


Figure 2.26: Geomorphology of the Bakkhali creek and surrounding areas.

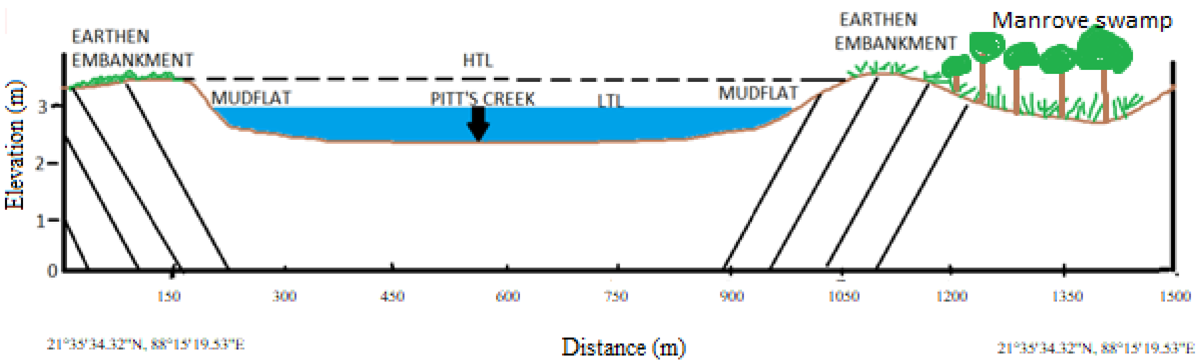


Figure 2.27: Geomorphology of the Pitts creek and surrounding areas.

towards the sub-creek at an around 5°–17° slope. The vegetation zones of tidal flat separated into 4–5 zones with colonization of salt marsh vegetation and true mangroves. Liquid muds are deposited at the lower flat of these zone perpendicularly during the high tide. Avicennia mangrove with vertical pneumatophore are the signature of active tidal zone of these area.

The northern zone of sub creek is densely colonize by mangrove thickness with *Avicennia*, *Bruguera*, *Aegicerous*, *Lumnithzera*, *Leguncularia* and *Excoecaria*. Some bare spot of the mud flats are visible within the swampy tract of the area.

Pitts creek is located in between Amarabati Spit and Sushnir Char or Patibania island. The creek is approaching towards south and south west direction into the Bay of Bengal keeping Sushnir char and Mousuni island on the left side and Amarabati spit on the right side. A cross section of the Pitts creek is presented in Figure 2.27. The creek has wide ripening zone on the both sides at mouth. The Susnir Char is thicker vegetation with mangrove trees and mangrove scrubs. The creek is significantly fringed by wider tidal flat. They have categorized into base mudflats and vegetated mud flats. The base mudflat is affected by hydrological stress of tidal inflow and outflow of saltwater movement. This type of mudflat is characterized by regular tidal inundation and regular accretion of fresh water silts at the high tides twice daily. The sloping mudflat is also affected by scour marks at different heights, those demarcate the signatures of mid tide profile. Second zone of the tidal flat is extended on the bank margins low land areas under intertidal zone. This zone is protected by earthen embankments for blocking the salt water inundation into the inner part of open lands. This particular tidal flat is colonized by saltmarsh vegetation and mangrove thickets. Several tide pools and bare patches of mudflat are also visible within the vegetated tidal flat of the creeks margin bank. Among the salt marsh vegetation, *Poteresia*, *Salicornia*, *Suaeda*, *Oryza*, saplings of *Avicennia*, *Excoecaria* are major plant species found there. The tidal range is very high in this coastal environment of Sundarban (ranging from 3.50 m to 5.50 m) in different tidal condition wide grass land and heat land are extended on the landward margin of the protected tidal flat towards the south of Pitt's creek. The Fresargunj fishing harbor is located at the Pitt's creek. Number of fishing trawlers are entering and moving out during the loading and unloading of marine fishes. This is a major fish leading station of south-western Sundarban. The fishing trawlers go to the sea for venturing the fish operations for 1 days to 14 days at a stretch in to the sea. Ecologically the ripening habitat of Pitt's creek is maintaining the appreciable status.

2.9 Geomorphic settings and ecosystem functioning of mangrove shores

Mangroves develop in tropical and subtropical shores, where tidal forces are not too high and sediment supply is considerable. Sheltered or semi-sheltered estuarine regions offer favorable conditions for the growth of mangroves. Growing in the intertidal zone of a shoreline, the mangroves undergo diurnal inundation in tidal water. To cope with the frequent inundation in saline water, mangroves evolved to have certain adaptations. The presence of mangroves in a shoreline influence the geomorphology of the shoreline in several ways, which are described below.

To support themselves on inundated muddy soil, mangroves evolved to have a dense network of roots. This network of roots are efficient sediment trappers. This web of roots further reduces the already low levels of tidal energy prevalent in the mangrove shoreline, which allows fine sediment to settle in the mangrove region. The biological litter produced by mangroves also add to the sediment supply. Through this pair of avenues, mangroves increase sediment accretion in a shoreline where they grow.

The abundant supply of organic matter and the saline condition in a mangrove shore gives rise to anoxic conditions in the soil through decomposition by bacteria. The inadequacy of oxygen however slows down decomposition. This imbalance of organic matter supply and its oxidation through decomposition increases the organic carbon content in the soil to substantial levels (Jardine and Siikamäki, 2014; Atwood et al., 2017). Abundance of organic matter also gives rise to eutrophication (Lovelock et al., 2009). This deposited organic carbon in the soil amid high rate of sedimentation and saline conditions becomes peat after a long time.

Being situated in a coastal region, mangroves have to withstand sea level rise to survive over a long period. It is observed that mangrove wetlands remain in a relative equilibrium when the sea level rise is gradual (Cahoon et al., 2006; Woodroffe et al., 2015). This rise in the sea level, the rate of sedimentation increases in the mangrove wetlands, which increases the elevation of the mangrove habitat. However, if the rise in sea level is too fast, the mangroves cannot keep pace with (Woodroffe et al., 2015). The mangroves in the shores of Sundarban is thus at risk from the ongoing and projected sea level rise. However, mangrove habitats are able creep up in the upland areas in the face of sea level rise (Woodroffe et al., 2015).

Mangrove shores also provide a degree of protection from cyclones by absorbing part of the storm energy. The interior region of a coast covered by a mangrove shoreline suffers comparatively less than an open coast. However, the mangroves themselves are damaged in face of storm surges.

The mangrove habitats in the shore serve constitute a productive ecosystem. Their special roots protect provide a protective environment with plenty of places for hiding. Due to this and the abundance of organic matter, the submerged portions of the mangrove shore are favorable hatching places for fishes and other aquatic creatures. Besides, the high rate of carbon sequestration and storing it in the soil is one of most valuable ecosystem function in the face of the ongoing global warming and climate change.

2.10 Impact of sea level change in the island

In coastal region, a local sea level rise leading to a landward motion of the coastline, or marine transgression, could be driven by land subsidence and/or sea-surface rise. A retreat of the coast,known as a marine regression, could be driven by land uplift and/or sea-surface fall (Masselink and Gehrels, 2015). A number of estimation has been made of future sea level rise has been developed, with estimates ranging from as low as 0.1 m to as high as 3.7 m by the year 2100 (Warrick and Oerlemans, 1990). This estimation shows that there will be 0.55 m rise of sea level by the year 2050 (Paul, 2002). According to Nicholls and Leatherman (1996), the sea level rise is accelerated by global warming which would cause thermal expansion of ocean water melting of mountain glaciers and melting of ice sheets (Figure 2.28).

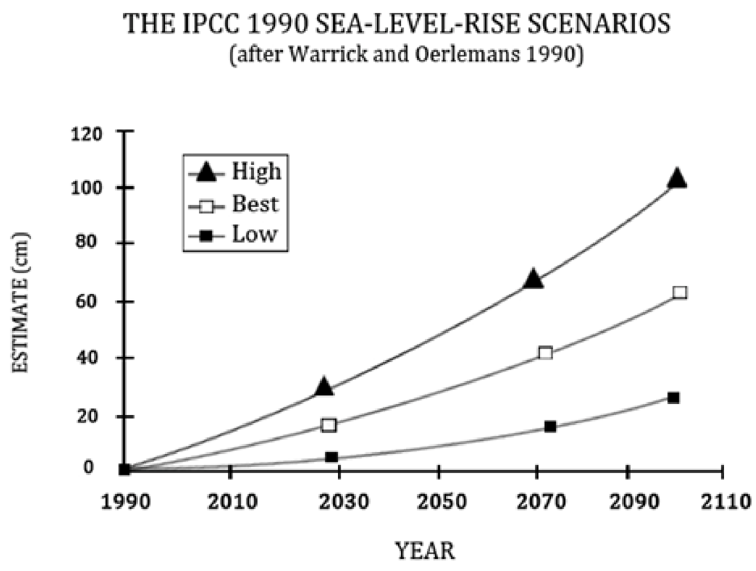


Figure 2.28: Deltaic lowland coasts of Bangladesh and West Bengal (India) under threat. The 50 cm, 1cm 2.0-2.5 m sea level rise can inundate a large part of the estuarine floodplain in Sundarban (Paul, 2002).

The coastal belt of Sundarban would largely affected by the relative change of coastline. The deltaic setting of the coast is prone to subsidence by out compaction of deltaic sediments and basement faulting of the Bengal delta. Coastal stretch of Sundarban is tectonically active zone which rise to the relative change of local sea level from time to time. Effects of sea level rise are felt by the islanders and people living at the low-lying areas. Major impacts of sea level rises are coastal wetlands loss, degradation of mangrove forest. Frequency of cyclones, coastal flooding and storm surge activities would increase the shoreline erosion, river bank erosion. Higher sea waves, repeated wave action, longshore currents displace sediments in low lying areas of coastal stretch. Due to sea level rise, saline water intrudes in the wetlands which increase coastal water table, heads of estuaries and aquifers. Coastal tracts of Sundarban is lying 2.5 and 4.8 m surface height from the mean sea level. Highest tidal amplitude rises up to 6 m where as normal tidal limit exceeds 5m limit from west to east in the coastal plain of Sundarban. Therefore, islands normally prone to inundate with or without sea level rise. Huge population pressure on the coastal islands, exploiting ground water, construction of sea walls, embankments exerts pressure on deltaic wetlands. So, the people who are living in those coastal islands are under utter risk. When the delta subsides under auto compaction of sediments, the low lands become more vulnerable to the sea level rise. The general effects of sea level rise on the coasts are:

1. Erosion of beaches and bluffs
2. Severe salt water intrusion problem into aquifers and surface waters.
3. Embankment breaching
4. Increasing chlorinity in the fresh water.
5. Frequency of flooding increased.
6. Coastal configuration changes.
7. Salt water intrusion increase salinity in drinking water.
8. Salinity of the soil increases and formation of salt patches within islands.
9. Inundation of coastal low-lying areas.
10. Coastal ecosystem affected due to sea level rise and brackish water aquaculture is growing.
11. Formation of beach ridge

Sea-level rise is one of the most important consequences of climate change and has the potential to cause significant global impacts on ecosystems and societies. Changes in relative sea level cause coastal changes by either inundating low-lying areas of land (transgression) or subaerially exposing areas of land previously flooded(regression), directly affecting shoreline erosion and accretion, and coastal stability in general. Hence, increases in sea level are likely to increase coastal erosion rates in lower elevation areas and affect sediment transport in coastal regions (Plate 2.13).

Plate 2.13: Top-left: Coastal erosion at Kiran beach, top-right: Shoreline displacement at Bakkhali sea beach, bottom-left: Landward migration of mangroves, bottom-right: Impact of overwash deposits at Bakkhali beach.

2.11 Mangrove response to sea level change

Mangroves are grown on the intertidal zone of shoreline. Sea level rise greatly influence the biological process of flora and fauna of Sundarban wetlands. A equilibrium is maintained among sea level and dynamics of mangroves in terms of water depth and accretion, erosion and vegetative stabilization, productivity and decomposition, and tidal flushing and drainage efficiency. Mangrove forest (mangals) is a unique floral community, adapted to grow, persist in coastal and estuarine regions of the tropics and sub-tropics, tolerating the environmental adversities and anthropogenic disturbances and yet renders a multitude of ecological services to the huge human habitants of the shores (Woodroffe et al. (2016), Spalding (2010), Gilman et al.

(2007), Lewis III (2005)). Mangrove hydrologically adjust themselves to a sea level change, but these adjustments depends on sedimentologic, hydrologic, biologic character (Pramanik, 2015). Excessive cyclonic events, storm surge and global climate change enhance the problem to a great extent. Surface water plays vital role in proliferation of mangrove species as it faces semi diurnal tides per day. Mangrove can withstand with salt water logging condition but they require fresh water for their growth and development. The level of salinity preferences varies with differences of mangrove species. When the sea level increases, accretion also increases and it affect on the mangrove structure of the wetlands. On the contrary if the sea level falls due to high rate of accretions, then eventually accretions also declines so there is a negative feedback operates in maintaining equilibrium condition. Sea level rise has great impact in the island modification. Sediment supply to the islands become less when there is increase in channel width of the creeks with high rate sea level change.

The persistence of mangroves implies an ability to cope with moderately high rates of relative sea-level rise (Woodroffe et al., 2016). Mangrove adapt themselves with changing sea level. Sometimes they migrate to landward if there is less sea level.Mangrove can establish themselves in higher elevation. The more landward of these mangrove sediments were able to keep pace with sea-level rise as it slowed prior to reaching present level, and the mangrove forests appear to have persisted into the 'big swamp' phase that characterized these estuarine plains (Masselink et al., 2014). Three phases of estuarine infill noticed (Woodroffe et al., 2015):

a) Transgressive phase (8000-6800 years)-during these mangroves transgress landward over terrestrial environments because of sea level rise drowned the valleys. Sediment supply could not keep pace with the rapid inundation of the landform, which create large area suitable for the formation of intertidal wetlands.

b) The big swamp phase (6800-5300 years)-this phase is accounted for stabilizing sea level. Mangrove surface was able to keep up with the decelerating rate of sea level rise. Filling of estuaries 10-15 m of mangrove muds clearly indicates that.

c) The sinuous/cuspate phase (since 5300 years BP)-In this stage transition from mangroves to grasses and sedge land vegetation just because of floodplain mature. Replace of lower intertidal species like Sonneratia to intertidal species like Rhizophora or ceriops, higher intertidal species like Avicennia and freshwater floodplain species.

There are some regions where sea level has fallen, the mangrove substrate remains left emergent.

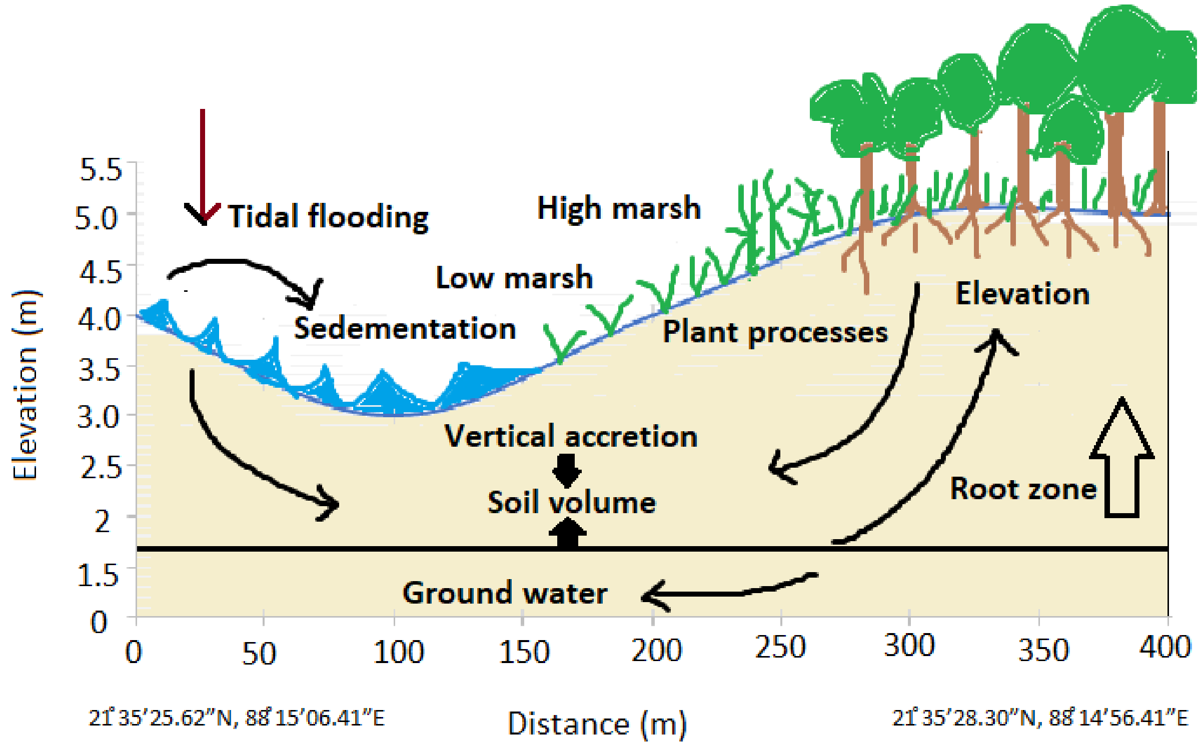


Figure 2.29: Morphodynamic feedback on sedimentation in mangrove ecosystems.

Infilling of the mangrove swamps was also associated with channel migration in estuaries and coastal plains. In trapping sediments mangrove andand the role of tide are very influencial. Normally sediments are distributed by tides, mangrove themselves contribute to accumulation of autochthonous material, these often form peats composed predominantly of root matter incorporated into the substrate.

Mangroves have the considerable resilience to fluctuations in sea level change because they can modify their environment through surface elevation change and they can move inland with successive generations. Positive surface elevation change is influenced via the inputs of autochthonous and autochthonous organic matter as well as the trapping and retention of inorganic sediments and subsurface compaction (Krauss et al., 2014). Mangrove can follow variety of mechanism in sediment trapping like slowing water velocities through aerial roots thus it arrests sediments (Furukawa and Wolanski, 1996), microbial filamentous algal mats trapping and binding sediment, accumulation of litter and woody debris.

Finally, it can be said that mangroves have adapted to past patterns of sea level change, some of which have occurred more rapidly than at rates occurring at present and in near future. Sediment accretion is a key process that contributes to mangroves keeping pace with sea level change. Apart from these mangroves can adjust to extreme environmental conditions in terms

Plate 2.14: Top: Sediment displacement of mangroves at Patibania island, bottom: Salt resilient mangroves at Kiran beach, Henry's island.

of salinity tolerance and inundation. Geomorphically adjustment with sea level is a key factor of mangroves. To adjust sea level change mangrove, involve landward extension into adjacent systems. Anticipated future rates of sea level rise are likely to have far-reaching impacts on mangrove forests as well as wetlands which are vulnerable to coastal squeeze.