CHAPTER 4

# ENVIRONMENTAL ASSESSMENT AND PHYSIOGRAPHIC SETTINGS

## 4.1 Sediment textural analysis of tidal flats, saltmarshes, mangrove swamps, saltpans, sea beaches, sand bars and sand dunes

Sundarban region has developed from the vast sediment load carried and deposited by the Ganga-Brahmaputra river systems. The soil here is fertile and has very good moisture carrying capacity. The general composition of soil is more towards silty clay. However, this region has many geomorphic settings, like tidal flats, saltmarshes, mangrove swamps, saltpans, sea beaches, sand bars and sand dunes. Soil texture varies considerably in between these settings. The tidal flats are more rich in clay and are saturated with moisture, while in the saltmarshes and saltpans have very high salinity levels in the soil, which results in a coarseness in the texture of the soil when dried. However, the saltmarshes are seldom dried, unlike the saltpans in the non-monsoon periods. The mangrove swamps have high organic content in the soil, which results in a smoother texture. The compositions of sea beaches, sand bars and sand dunes are primarily of sand, while the grain size varies between these three settings. In general, the sand in the sea beaches have the smallest grain size from undergo continuous wave action. The sand bars get inundated approximately twice daily from high tides. The tidal waves smoothen the sand particles there, and hence the sand in these sand bars also have relatively small grain size, but larger than the sea beaches. On the other hand, the sand dunes are rarely inundated due to higher elevation, and due to this near absence of the friction force from the waves, the sand dunes have higher grain size among the three. The soil in the sea beach also has higher moisture content compared to the sand bars and the sand dunes. The sand bars have higher moisture content compared to the sand dunes but lower than the sea beaches. This variation in the moisture content also plays an important role in the difference in the cohesiveness of the soil in these geomorphic settings. The textural properties of soil like moisture carrying capacity, cohesiveness and composition of sand, silt and clay are one of the leading factors in determining the characteristics of the ecology that would thrive there.

Soil texture is determined by the moisture content and the percentages of sand, silt and clay. In Figure 4.1, the moisture content and the percentages of sand, silt and clay in soil from different geomorphic settings observed in the study area are presented for the years 2018 ans 2019. It can be seen that moisture content is high in soil from tidal flats, while it is low in saltpans. The low moisture content in saltpans point to the evaporative environment present there. The soil

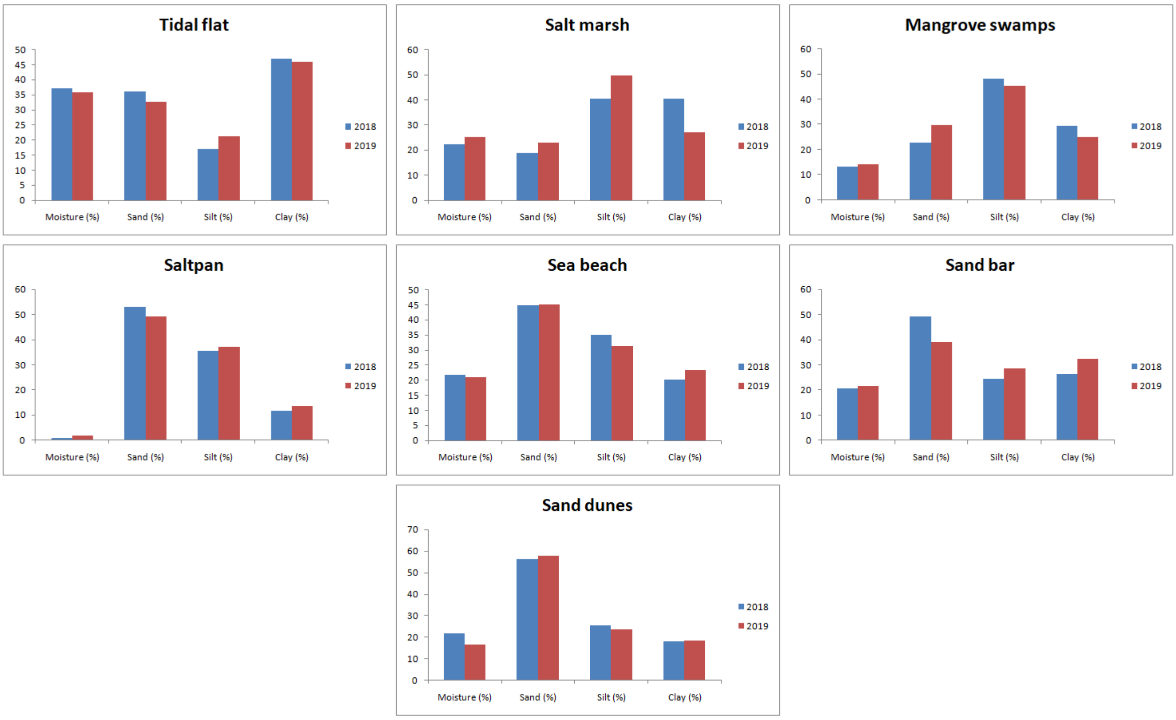


Figure 4.1: Bar plots of moisture percentage and sand, silt and clay percentages in various geomorphic settings

from tidal flats have high clay content, while soil from salt marshes and mangrove swamps is dominant in silt content. The sand content is dominant in the soil from saltpans, sea beaches, sand bars and sand dunes. Also, over the two years, significant changes in the components are not visible.

Saltpans are particularly notable formations because of their role in hindering mangrove propagation. In Figure 4.2, the map of the moisture content distribution in two chosen saltpans with one from each island is depicted. The notable variation in the moisture content in different regions of the saltpans are clearly reflected in these maps. In both the maps, the saltpan is divided in six zones based on the value of the moisture content. It is observed that in the saltpan chosen in the Henry's island, the moisture content is highest in the north-eastern part, and it decreases towards the south-western part. On the other hand, in the saltpan chosen in the Patibania island, the moisture content is highest in the eastern part and it decreases towards the western part.

In Plate 4.1, the stratigraphical view of soil at a lithopit in a saline blank is depicted. Up to a depth of 12 cm, the root zone can be observed. There are desiccation cracks visible in this region. Due to evaporation of saline water, the salinity level is highest in this region, which

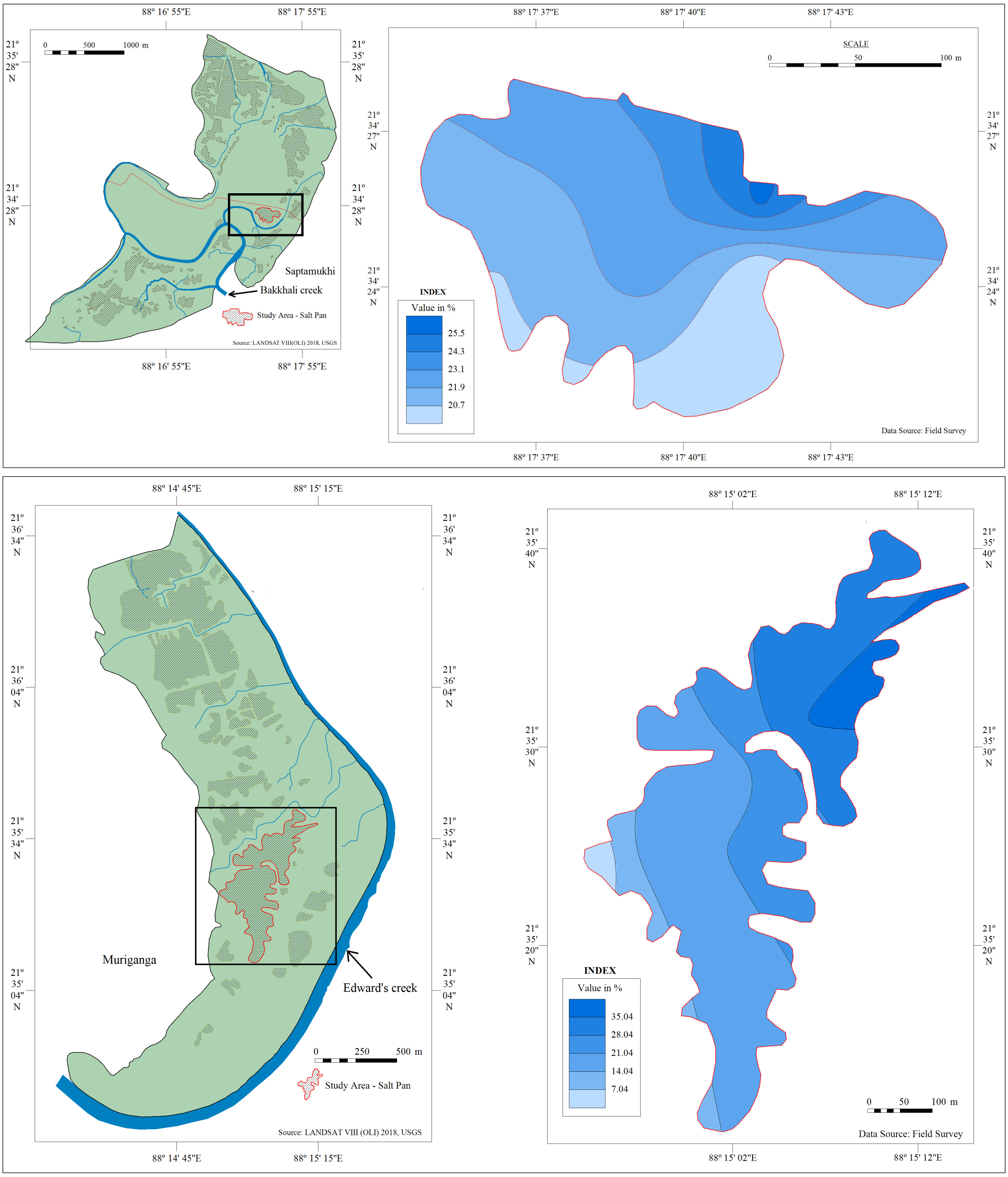


Figure 4.2: Moisture content zones in two chosen saltpans in the Henry's island (top row) and the Patibania island (bottom row) respectively.

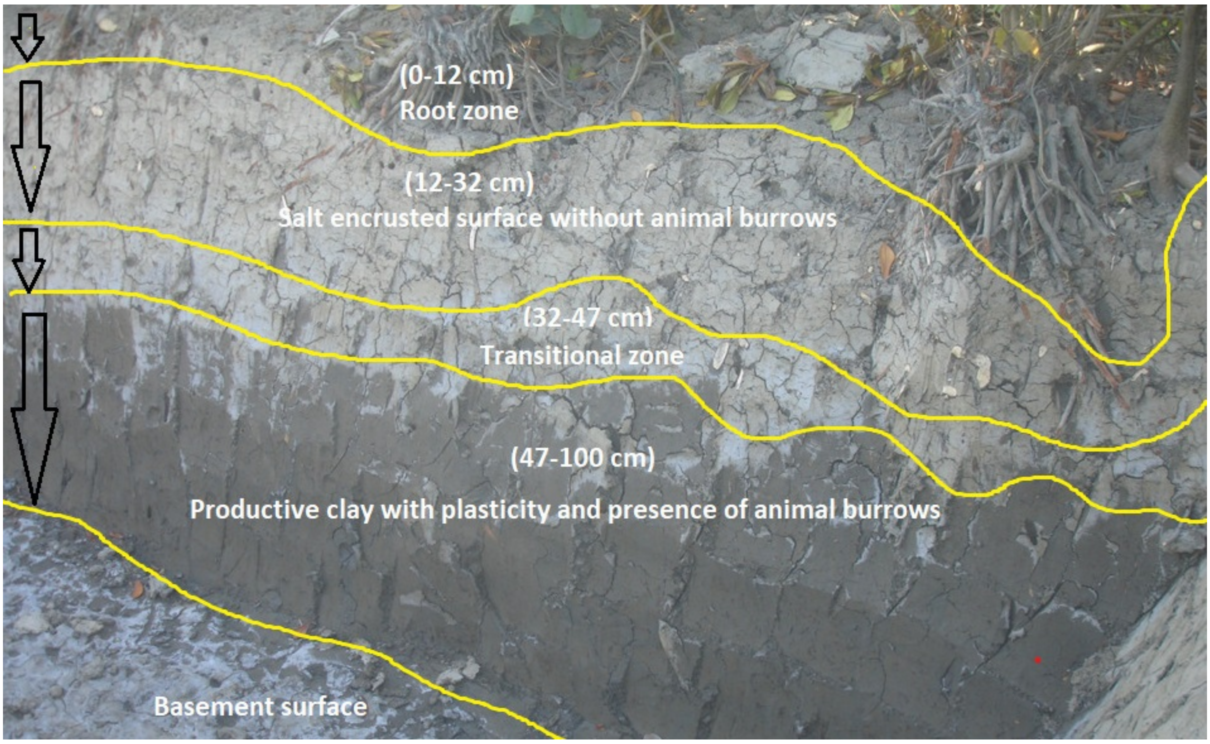


Plate 4.1: Stratigraphical view of soil in a saline blank.

has made the soil infertile. Beyond this layer a the depth of 12–32 cm, there is salt encrusted surface, where the salinity is at similar level like the upper layer. Due to this high salinity level and associated corrosive environment, this layer is unsuitable for the dwelling of soil-burrowing animals. Thus, no such burrows was observed in this layer. Deeper than this layer, at the depth of 32–47 cm, there is a transitional zone, where the salinity level starts to decrease. Next, at the depth of 47–100 cm, there is a relatively thick layer of plastic clay. This layer is relatively productive and fertile. Animal burrows were observed in this layer. Below this layer of clay, there is a basement surface of fertile sediment. The salt buildup on the surface cannot reach this layer.

In Plate 4.2, soil texture in the two islands in the pre-monsoon, the monsoon and the post-monsoon season are depicted. In the pre-monsoon season, due to high temperature and associated evaporation, desiccation cracks are visible on the surface of the saltpans. In the monsoon season, the moisture content in the soil is high due to heavy rainfall, the surface is muddy. Algal encrustation of the surface occurs in this season. In the post-monsoon season, the soil moisture an nutrient content is adequate after the heavy monsoonal rainfall. The conditions are favorable for floral propagation, and most of the soil surface is is covered with fresh vegetation.

Plate 4.2: Photos of soil texture in the Henry's island in pre-monsoon (top left), monsoon (top middle) and post-monsoon (top right), and in the Patibania island in pre-monsoon (bottom left), monsoon (bottom middle) and post-monsoon (bottom right).

## 4.2 Chemical analysis of soil and water of the saltpans, salt-flats, salt ponds, tidal channels

The principal chemical properties of interest in soil are the three primary nutrients essential for thriving plant lives, which are nitrogen, phosphorus and potassium. Deficiency of any of these in soil would make the area adverse to mangrove propagation. Other chemical properties of interest of the soil in the south-western Sundarban region are pH, salinity, electrical conductivity, organic matter and organic carbon. All these properties are profoundly affected by the geomorphic settings of the area containing the soil. The pH of soil is an indication of acidity or alkalinity. In general, soil is slightly acidic, very close to neutral. However, in certain geomorphic settings, acidity in soil increases. For example, in salt marshes, due to microbe activity and related decomposition of organic matter, soil acidity is higher than normal. The salinity of soil is higher in the salt encrusted regions including saltpans, salt ponds, salt marshes, etc. The high salinity in soil often hinders mangrove and other vegetation growth. Electrical conductivity has a complex relationship with salinity levels. But it is found that an increase in salinity does not always mean an increase in electrical conductivity, and factors like moisture content and soil composition are also influential in determining the electrical conductivity of soil. The organic matter of soil is the product of partial decomposition of mangrove debris, biological wastes of

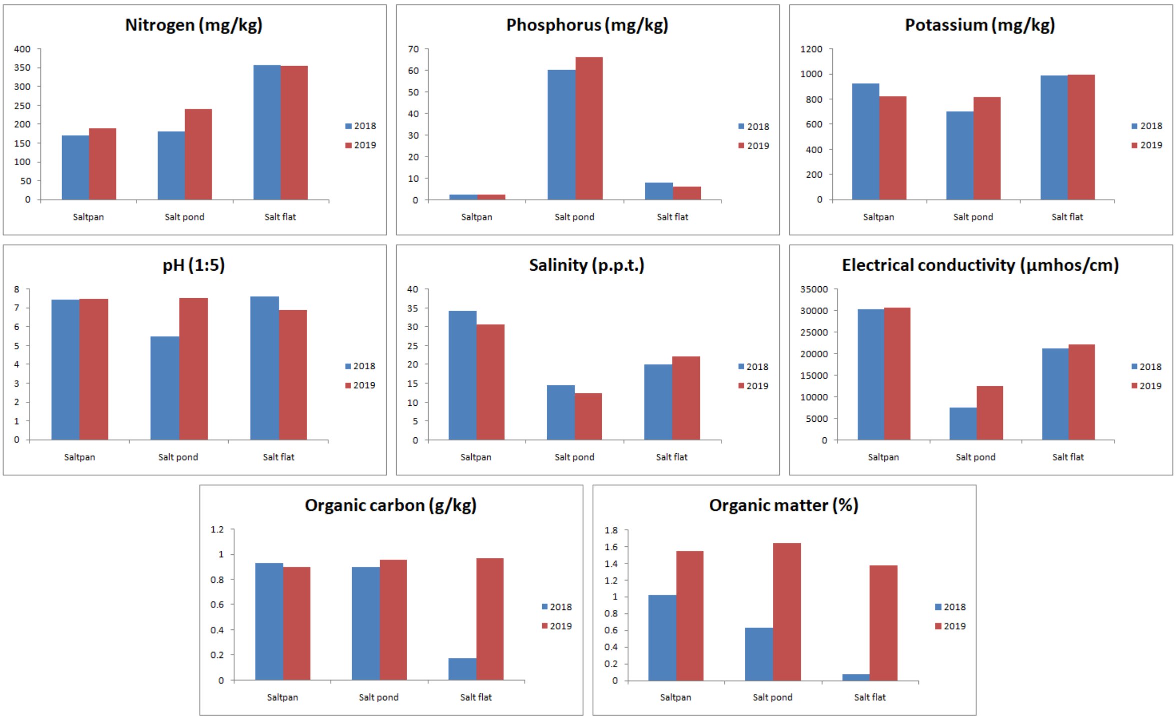


Figure 4.3: Bar plots of soil chemical components in various geomorphic settings

local animal life, and also other detritus flown in from upstream and the waves and tides. Certain geomorphic settings, like salt marshes, provide a favorable environment for the accumulation of organic matter in soil. In the mangrove regions, due to the distinct characteristics of the root propagation of the mangrove plants, an unusual amount of carbon is captured and stored in soil as organic carbon. This carbon stock is one of the most important roles of mangroves in decelerating the ongoing global warming and climate change.

In Figure 4.3, the various chemical components of soil from saltpans, salt ponds and salt flats are presented. It can be seen that nitrogen is in higher level in salt flat, phosphorus content is high in salt ponds, potassium and pH levels are similar in all three geomorphic settings, salinity and electrical conductivity is highest in saltpans. Significant variation is observed in the organic carbon level in salt flat and in the organic matter level in all three geomorphic settings.

In Table 4.1, the chemical components of water from fish pond and salt pit are presented. In can be seen that water from salt pit has vastly higher levels of chloride, salinity and electrical conductivity.

The chemical properties also vary between various regions of a saltpan. In Figure 4.4, the salinity level in the different regions of two chosen saltpans are presented. One saltpan chosen from each of the islands. One can see from this map that the salinity level varies considerably

Table 4.1: Chemical components of water

| Chemical components | Location | |
|---|---|---|
| | Fish pond | Salt pit |
| pH | 6.95 | 7.3 |
| Chloride (mg/l as Cl) | 1599.5 | 10996.6 |
| Salinity (p.p.m.) | 2889.6 | 19865.9 |
| Electrical conductivity ($\mu$mhos/cm) | 7320 | 51700 |
| Acidity (mg/l as $CaCO_3$) | 24 | 24 |
| Dissolved oxygen (mg/l as $O_2$) | 13.85 | 13.85 |

within the different regions of a saltpan. In Figure 4.4, the salinity levels in two chosen saltpans is depicted, with one saltpan from each of the islands. Each of the saltpans are divided in seven zones based on the salinity level. It is observed that in case of the saltpan in the Henry's island, the salinity level is highest in the northern part of the saltpan. In the saltpan in the Patibania island, the salinity level is maximum in the center of the saltpan, and it decreases as one moves away from the center. The organic matter level in the different parts of the two chosen saltpans are depicted in Figure 4.4. Here, each of the saltpans is divided in six zones based on the the level of the organic matter. It is observed that the organic matter level is highest in the eastern parts of both the saltpans, and it decreases towards the west.

## 4.3 Chemical analysis of soil chemicals in saline blanks

Soil samples were collected from three saline blanks in the Henry's island and one location in the Patibania island at different times over several years. Because of the significant effect of the monsoon on the soil characteristics in the mangroves, the time points are divided in the three seasons of the pre-monsoon, the monsoon and the post-monsoon. From one of the saline blanks, which will be called saline blank 1 (S1 in short), soil samples were collected in the pre-monsoon, the monsoon and the post-monsoon seasons. From the other two saline blanks in the Henry's island, which will be called saline blank 2 and saline blank 3 (S2 and S3 in short, respectively), and from the location in the Patibania island (Pa in short), soil samples were only collected during the pre-monsoon season. Each soil sample was chemically analyzed, and the

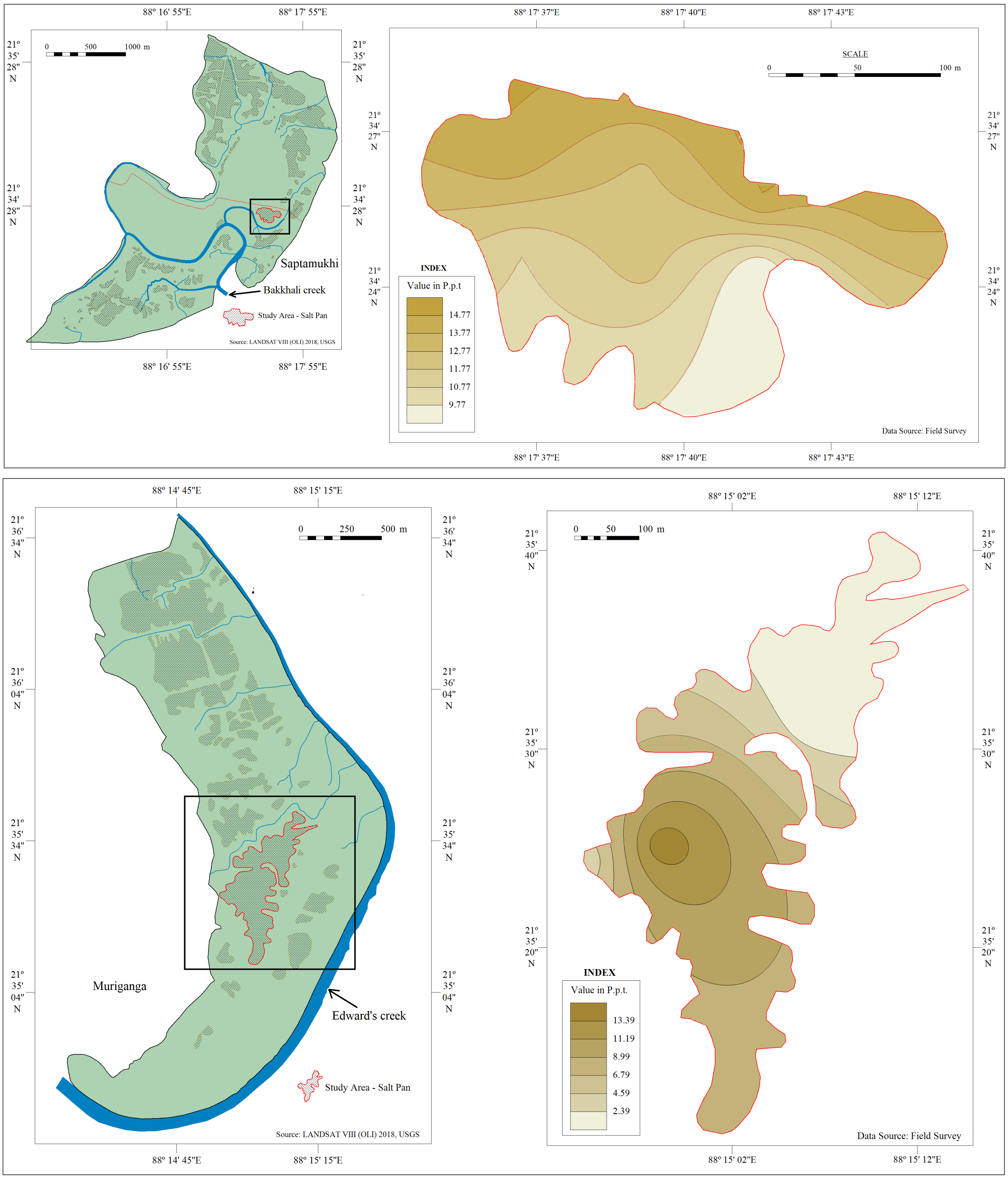


Figure 4.4: Maps of salinity in two chosen saltpans in the Henry's island (top row) and the Patibania island (bottom row) respectively.

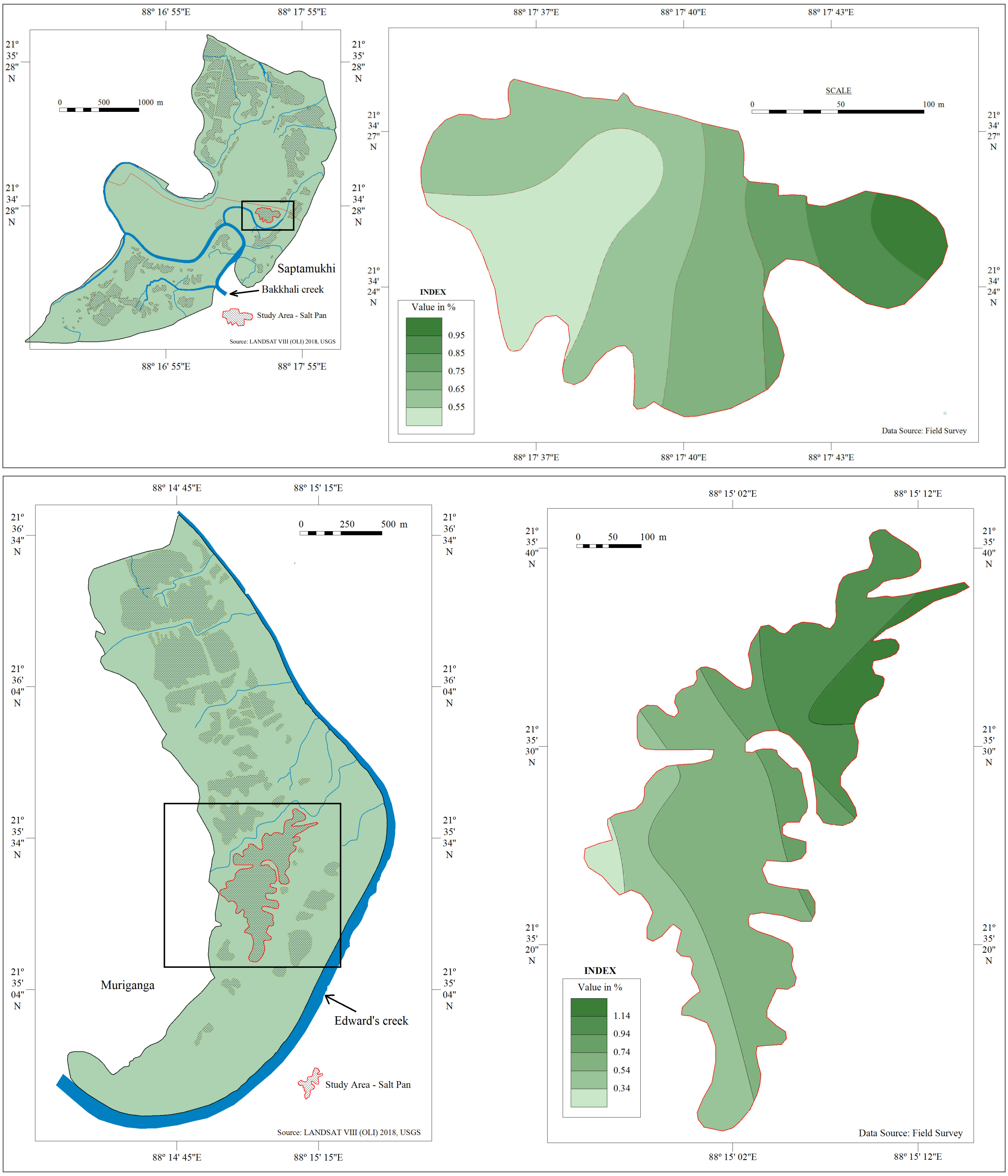


Figure 4.5: Maps of organic matter in the Henry's island (top row) and the Patibania island (bottom row) respectively.

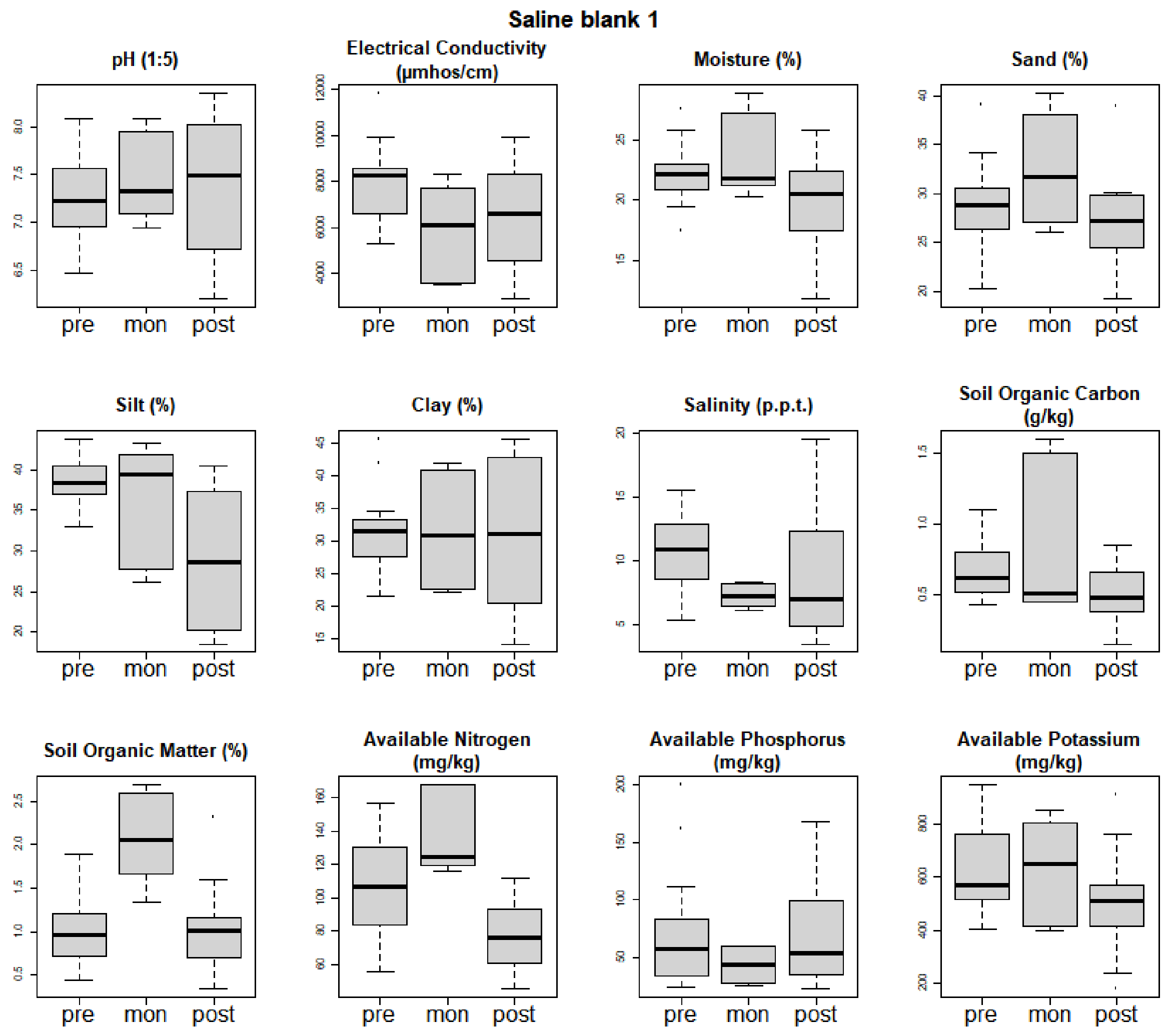


Figure 4.6: Comparative boxplots across seasons for the soil variables in saline blank 1 (pre: pre-monsoon, mon: monsoon, post: post-monsoon).

quantities of the following twelve variables were measured: soil pH, electrical conductivity, the percentages of moisture, sand, silt and clay, the salinity, the soil organic carbon and the soil organic matter, the available nitrogen, phosphorus and potassium. In Table 4.2, the means and the standard deviations of the soil variables in saline blank 1 are presented over the three seasons, and in Table 4.3, the means and standard deviations of the soil variables in saline blanks 1, 2, 3 and Patibania in pre-monsoon are presented.

Comparative boxplots are used to analyze these data. The boxplot provides information about the center, the spread and the skewness of the sample as well as the presence of outliers. In Figure 4.6, comparative boxplots are constructed across the three seasons for the data from saline blank 1. The boxplots clearly reflect the change in the median levels of the soil variables

Table 4.2: Means and standard deviations of soil variables in saline blank 1.

| Variable | Statistic | pre-monsoon | monsoon | post-monsoon |
|---|---|---|---|---|
| pH (1:5) | mean | 7.28 | 7.45 | 7.38 |
| | s.d. | 0.48 | 0.47 | 0.74 |
| Electrical Conductivity ($\mu$mhos/cm) | mean | 7909.38 | 5895.00 | 6552.08 |
| | s.d. | 1730.64 | 2108.88 | 2352.01 |
| Moisture (%) | mean | 22.20 | 23.55 | 19.53 |
| | s.d. | 2.45 | 3.59 | 4.08 |
| Sand (%) | mean | 28.68 | 32.43 | 27.31 |
| | s.d. | 4.67 | 5.75 | 4.87 |
| Silt (%) | mean | 38.49 | 36.33 | 29.09 |
| | s.d. | 2.97 | 7.40 | 8.64 |
| Clay (%) | mean | 31.41 | 31.52 | 31.20 |
| | s.d. | 6.09 | 8.52 | 11.97 |
| Salinity (p.p.t.) | mean | 10.66 | 7.24 | 8.58 |
| | s.d. | 3.25 | 0.93 | 5.21 |
| Soil Organic Carbon (g/kg) | mean | 0.69 | 0.84 | 0.51 |
| | s.d. | 0.20 | 0.56 | 0.21 |
| Soil Organic Matter (%) | mean | 1.00 | 2.07 | 1.05 |
| | s.d. | 0.41 | 0.55 | 0.51 |
| Available Nitrogen (mg/kg) | mean | 108.01 | 136.58 | 76.71 |
| | s.d. | 28.36 | 24.53 | 21.12 |
| Available Phosphorus (mg/kg) | mean | 69.39 | 43.42 | 74.39 |
| | s.d. | 50.64 | 14.98 | 51.08 |
| Available Potassium (mg/kg) | mean | 615.94 | 627.50 | 505.68 |
| | s.d. | 154.20 | 211.80 | 198.37 |

Table 4.3: Means and standard deviations of soil variables in saline blanks 1, 2, 3 and Patibania in pre-monsoon.

| Variable | Statistic | S1 | S2 | S3 | Pa |
|---|---|---|---|---|---|
| pH (1:5) | mean | 7.28 | 7.16 | 6.81 | 7.37 |
| | s.d. | 0.48 | 1.27 | 0.93 | 0.86 |
| Electrical Conductivity ($\mu$mhos/cm) | mean | 7909.38 | 6460.83 | 13531.25 | 11851.82 |
| | s.d. | 1730.64 | 2821.90 | 9457.60 | 9084.83 |
| Moisture (%) | mean | 22.20 | 22.76 | 9.84 | 16.48 |
| | s.d. | 2.45 | 7.26 | 8.24 | 7.01 |
| Sand (%) | mean | 28.68 | 30.88 | 37.83 | 50.23 |
| | s.d. | 4.67 | 6.44 | 9.76 | 26.22 |
| Silt (%) | mean | 38.49 | 34.35 | 36.84 | 38.31 |
| | s.d. | 2.97 | 10.53 | 6.34 | 6.99 |
| Clay (%) | mean | 31.41 | 34.44 | 22.04 | 21.09 |
| | s.d. | 6.09 | 9.65 | 8.50 | 10.51 |
| Salinity (p.p.t.) | mean | 10.66 | 7.15 | 14.06 | 12.85 |
| | s.d. | 3.25 | 3.74 | 9.53 | 6.90 |
| Soil Organic Carbon (g/kg) | mean | 0.69 | 0.47 | 0.44 | 0.91 |
| | s.d. | 0.20 | 0.23 | 0.28 | 1.00 |
| Soil Organic Matter (%) | mean | 1.00 | 0.72 | 0.67 | 1.12 |
| | s.d. | 0.41 | 0.36 | 0.41 | 0.42 |
| Available Nitrogen (mg/kg) | mean | 108.01 | 219.72 | 222.07 | 88.97 |
| | s.d. | 28.36 | 50.39 | 111.83 | 39.00 |
| Available Phosphorus (mg/kg) | mean | 69.39 | 40.94 | 10.67 | 48.21 |
| | s.d. | 50.64 | 23.40 | 11.24 | 35.19 |
| Available Potassium (mg/kg) | mean | 615.94 | 708.50 | 685.04 | 571.64 |
| | s.d. | 154.20 | 85.18 | 341.88 | 231.49 |

over the seasons. They also convey the changes in the dispersion and the skewness of the variables. The dispersion of the soil pH increases from pre-monsoon to post-monsoon through monsoon as reflected in the interquartile spreads in the respective boxplots, and its median level also rises gradually. The electrical conductivity is lower in monsoon than in pre-monsoon or post-monsoon, while the moisture content is positively skewed in the monsoon. Sand and silt levels rise in the monsoon, while the median levels of clay in the samples remain almost unchanged over the seasons. The dispersions of the sand, the silt and the clay contents vary over the seasons noticeably. The dispersion in soil salinity is lowest in the monsoon, and its median level at the monsoon is lower than that in the pre-monsoon. The soil organic carbon distribution is very positively skewed in the monsoon. Soil organic matter and available nitrogen levels rise considerably in the monsoon, and the available nitrogen distribution is also positively skewed in the monsoon. The available phosphorus level is lower in the monsoon than the pre-monsoon and the post-monsoon. Available potassium level is higher in the monsoon and its dispersion is also higher in that season.

Since data were collected in all the four locations in the pre-monsoon season, comparative boxplots are used to analyze them across the locations in Figure 4.7. It can be observed that the saline blanks in the Henry's island are not homogeneous among themselves, as the distributions of the soil variables there show considerable variation across the saline blanks. The level of soil pH is marginally higher in Patibania than the other locations. Electrical conductivity is lower in the saline blanks S1 and S2 than the other two, with considerably lower dispersion. Moisture content is lowest in S3, and its dispersion also varies across the locations. The dispersion of the sand content also varies considerably across the locations. The median silt content level is lowest in S2 with a positively skewed distribution, while the median clay content level is highest in S2 with a negatively skewed distribution. Salinity is also lowest in S2. The soil organic carbon level has a few outliers in the data from Patibania. Both soil organic carbon and soil organic matter is marginally lowest in S3. Available nitrogen is highest in S2, though the distribution of the available nitrogen in S3 is more dispersed and is positively skewed. Available phosphorus is lowest in S3, with lowest dispersion. However, available potassium level is highest in S3, with the highest dispersion.

Boxplots only provide limited information about the shape of the underlying distribution, and cannot provide any information about multi-modality. For this reason, the same datasets are analyzed using their estimated densities. The densities are estimated using Gaussian kernels. In

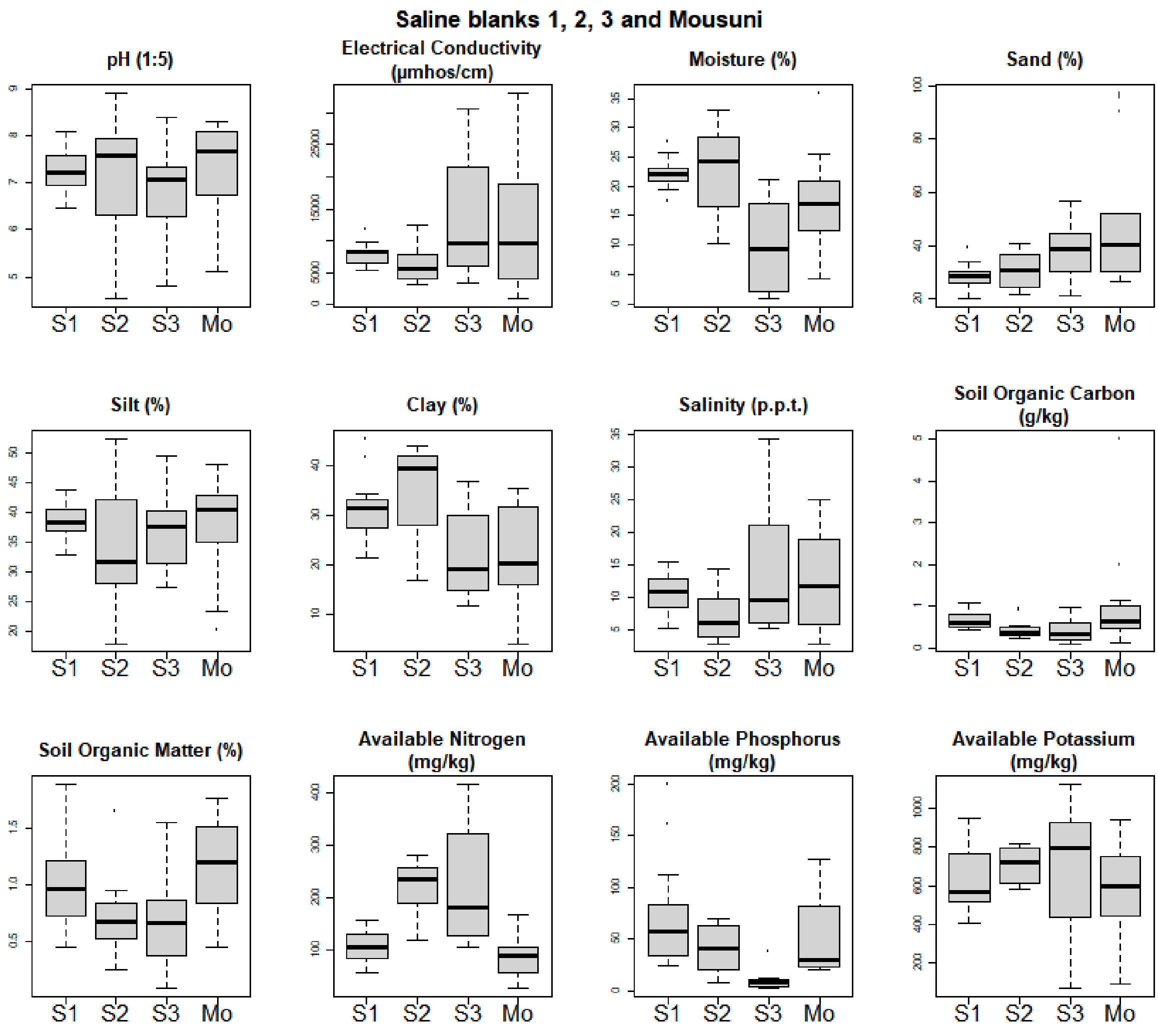


Figure 4.7: Comparative boxplots across locations for the soil variables in pre-monsoon.

Figure 4.8, the estimated densities are plotted of the soil variables across the seasons in saline blank 1. It can be observed that the soil pH distributions during pre-monsoon and monsoon are very similar, while that corresponding to post-monsoon is flatter. The electrical conductivity distributions are similar for monsoon and post-monsoon, though that corresponding to monsoon is bimodal. The moisture content distributions have different shapes and resulting skewness across the seasons, and that corresponding to pre-monsoon is has lower spread. The distributions corresponding to sand, silt and clay contents exhibit noticeable evidences of multi-modality. The shape of the salinity distributions change over the seasons, and the salinity distribution for monsoon has very low dispersion. The soil organic carbon and the soil organic matter distributions for pre-monsoon and post-monsoon are similar, however, the distributions for monsoon are different than them. The available nitrogen and available potassium distributions

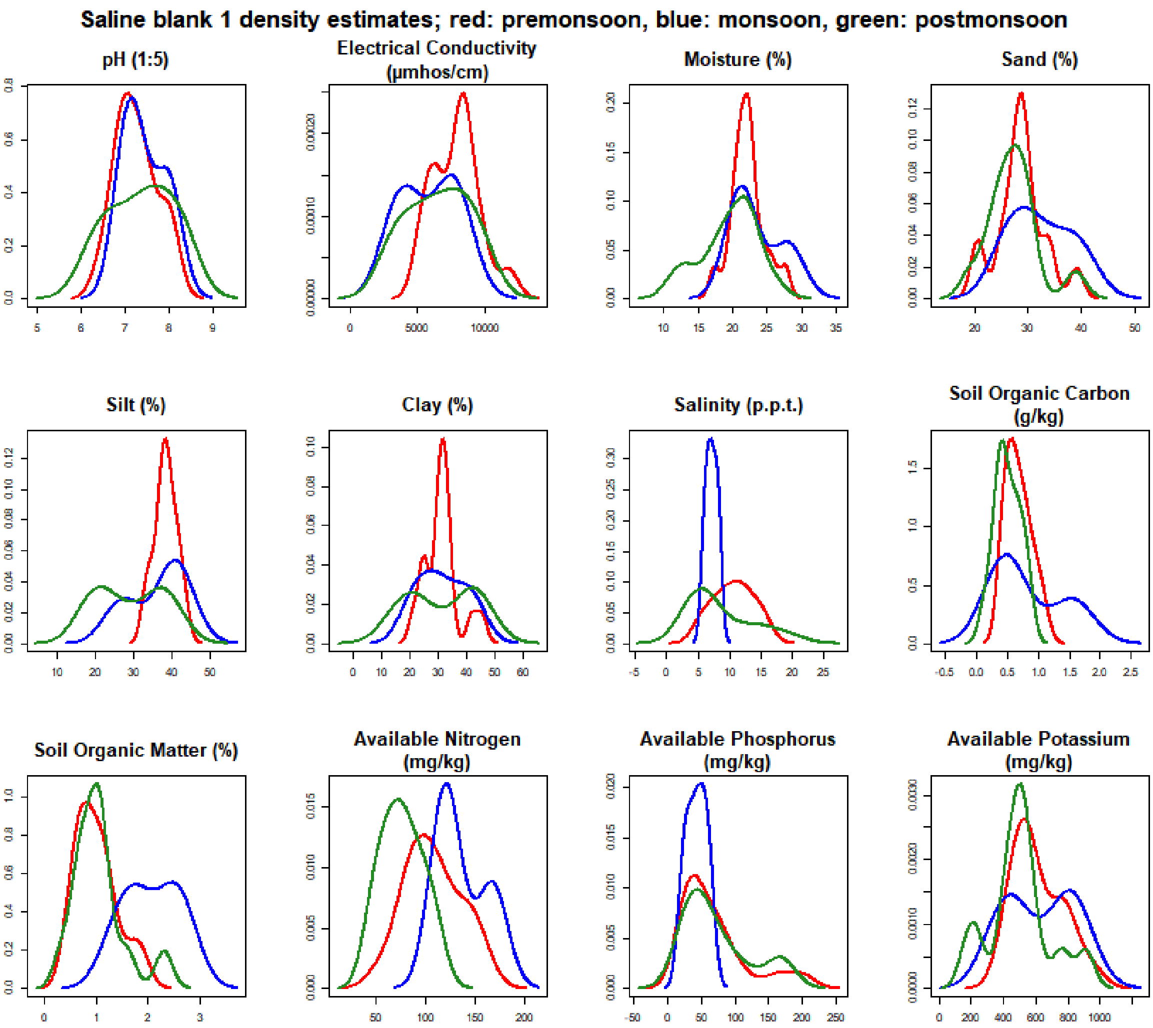


Figure 4.8: Estimated densities across seasons for the soil variables in saline blank 1.

are very different across the seasons. The available nitrogen distribution for monsoon exhibit multi-modality. The available potassium distributions for monsoon and post-monsoon also exhibit multi-modality. The available phosphorus distributions for pre-monsoon and post-monsoon are very similar, but that corresponding to monsoon is different and exhibits lower spread.

Next, in Figure 4.9, the estimated densities for the data from the four locations collected in pre-monsoon are plotted. It is observed that almost always, the four estimated densities corresponding to a soil variable are of completely different shapes. The multi-modalities are also more pronounced. Perhaps the only case, where a pair of densities are similar, is in electrical conductivity, where the densities corresponding to S3 and Patibania are very similar.

From the estimated densities, both across the seasons and across the locations, it can be

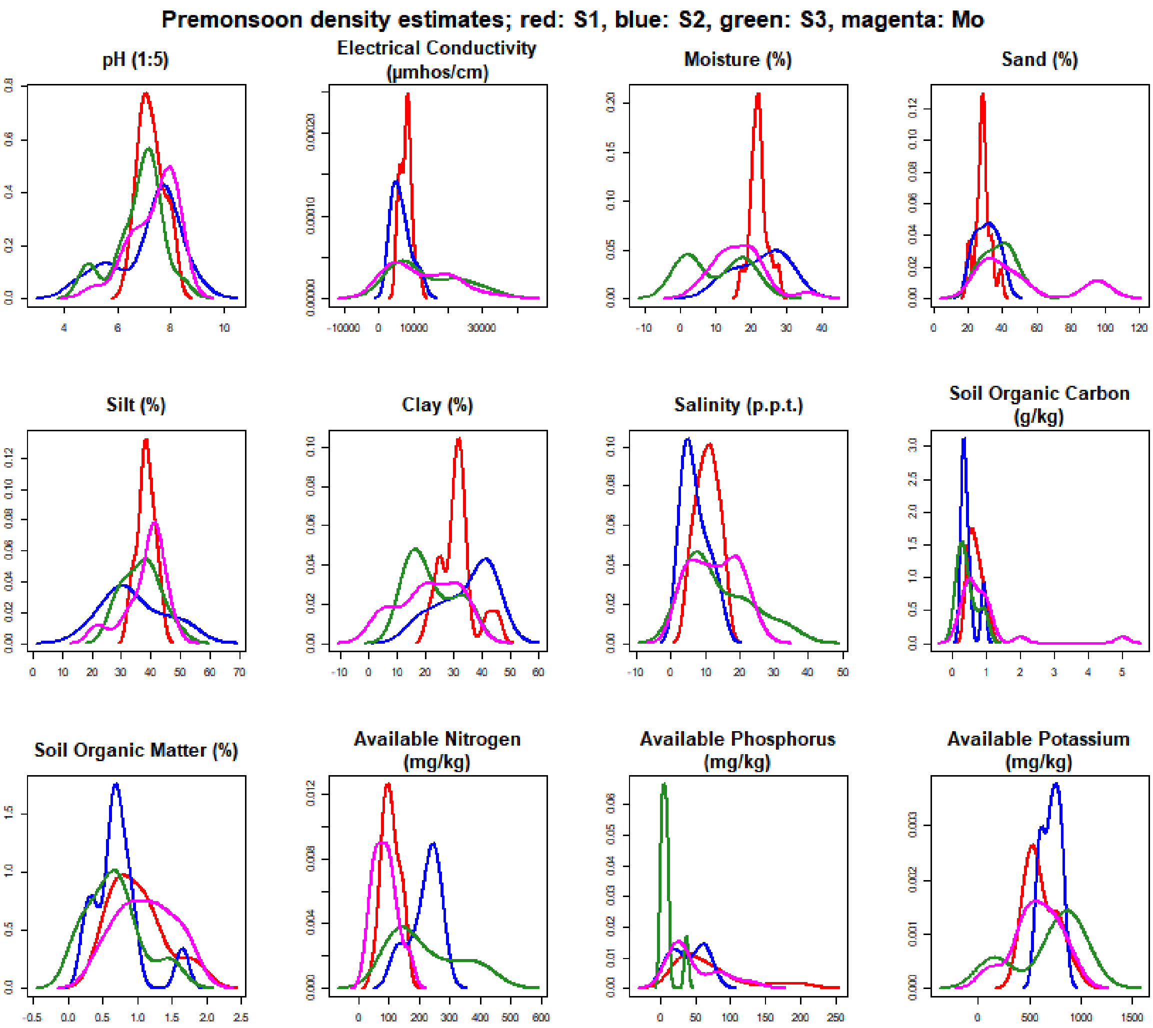


Figure 4.9: Estimated densities across locations for the soil variables in pre-monsoon.

noticed that almost always, one or more of the densities corresponding to a soil variable deviate from Gaussianity. This observation is of consequence in our subsequent analysis.

The boxplots and the density plots provide visual indication of differences among the groups. However, to ascertain whether the differences are statistically significant or not, analysis of variance (ANOVA) are carried out in the datasets. The ANOVA tests whether there is a statistically significant difference among the means of the classes. A small p-value for the ANOVA test implies statistically significant difference among the group means. For example, if the p-value of the ANOVA test is smaller than 5%, one can state that there is a statistically significant difference among the group-means at 5% level. One can also consider other levels, e.g., 1%, to reject a null hypothesis (the ANOVA null hypothesis is that all the group-means are identical, so rejecting the null hypothesis means stating that there is a statistically significant difference among the group-means). However, it is a convention to only consider either 5% level or 1% level. The ANOVA procedure assumes that the observations follow normal distributions with equal variance (homoscedasticity). These two assumptions, i.e., that the observations are normally distributed and homogeneity of variances, may not hold in practice. To check whether the assumptions are satisfied in the concerned data, the Shapiro-Wilk test of normality (Shapiro and Wilk, 1965; Royston, 1982b,a, 1995) and Levene's test for homogeneity of variance across groups (Levene, 1960) are used. A small p-value of the Shapiro-Wilk test indicates towards the non-normality of the data, while a small p-value of Levene's test points toward the heterogeneity of variances among the groups (heteroscedasticity). If the p-value of the Shapiro-Wilk test is smaller than 5%, it implies that there is a statistically significant evidence of non-normality of the distributions of the groups at 5% level. If the p-value of the Levene's test is smaller than 5%, it can be stated that the distributions of the groups are heteroscedastic in nature at 5% level. Under non-normality or heteroscedasticity, the ANOVA procedure does not work satisfactorily to discern the difference among the group means. In that case, the Kruskal-Wallis test (Kruskal and Wallis, 1952) may be used. This test checks whether the underlying distributions of all the groups are the same. A small p-value indicates that the distributions of the groups are different. So, a p-value of the Kruskal-Wallis test smaller than 5% implies that there is a statistically significant difference among the underlying distributions of the groups at 5% level. The Kruskal-Wallis testing procedure only requires the independence of the observations for its validity, which is far weaker requirement than the ANOVA procedure. In particular, it does not require normality of the underlying distributions of the groups nor homoscedasticity. However, if the data actually satisfy normality and homoscedasticity, then the ANOVA procedure is more powerful than the Kruskal-Wallis test. In Table 4.4, the p-values of the ANOVA test, the Shapiro-Wilk test of normality, Levene's test for homogeneity of variance and the Kruskal-Wallis test are presented for the data from saline blank 1, where the groups correspond to the three seasons.

In case the ANOVA or the Kruskal-Wallis test yields a small p-value lower than a certain level, which indicates a statistically significant difference among the group-means or the distributions of the groups, respectively, one may be interested exactly which pairs of group-means or which pairs of group-distributions have a statistically significant difference. For this, the Tukey honest significant differences test, which is also known as Tukey's range test (Tukey, 1949) to compare the group-means, and the pairwise Wilcoxon rank sum test (Wilcoxon, 1945) along with the Benjamini-Hochberg procedure to adjust p-values for multiple testing (Benjamini and

Table 4.4: P-values of ANOVA related tests on soil variables in saline blank 1.

| Variable | ANOVA | Shapiro-Wilk | Levene | Kruskal-Wallis |
|---|---|---|---|---|
| pH (1:5) | 0.79 | 0.57 | 0.16 | 0.7 |
| Electrical Conductivity ($\mu$mhos/cm) | 0.08 | 0.58 | 0.31 | 0.1 |
| Moisture (%) | 0.04 | 0.87 | 0.26 | 0.19 |
| Sand (%) | 0.13 | 0.44 | 0.67 | 0.18 |
| Silt (%) | 0 | 0.39 | 0 | 0.01 |
| Clay (%) | 1 | 0.23 | 0 | 0.97 |
| Salinity (p.p.t.) | 0.14 | 0.11 | 0.07 | 0.05 |
| Soil Organic Carbon (g/kg) | 0.08 | 0.05 | 0.14 | 0.14 |
| Soil Organic Matter (%) | 0 | 0.17 | 0.58 | 0 |
| Available Nitrogen (mg/kg) | 0 | 0.26 | 0.61 | 0 |
| Available Phosphorus (mg/kg) | 0.41 | 0 | 0.33 | 0.59 |
| Available Potassium (mg/kg) | 0.23 | 0.65 | 0.43 | 0.27 |

Hochberg, 1995) are used to compare the pairs of the distributions of the groups. If the p-value of the Tukey honest significant differences test for a particular pair of group-means is small, it indicates that the particular pair of group-means are statistically different. For example, if the p-value of the Tukey honest significant differences test is less than 5%, it can be stated that there is a statistically significant difference between the two group-means at 5% level. Similarly, if the p-value of the pairwise Wilcoxon rank sum test for a particular pair of groups is less than 5%, one can state that there is a statistically significant difference between the distributions of the two groups at 5% level. In Table 4.5, the p-values of the Tukey honest significant differences tests for the data from saline blank 1 are presented, with the groups corresponding to the three seasons pre-monsoon, monsoon and post-monsoon. In Table 4.6, the p-values of the pairwise Wilcoxon rank sum tests on the soil variables in saline blank 1 are presented, again with the groups corresponding to the three seasons.

Next, in Table 4.7, the p-values of the ANOVA test, the Shapiro-Wilk test of normality, Levene's test for homogeneity of variance and the Kruskal-Wallis test for the soil variables from saline blanks 1, 2, 3 and Patibania are presented for the pre-monsoon season. In Table 4.8, the p-values of the Tukey honest significant differences tests for the soil variables from saline blanks 1, 2, 3 and Patibania are presented for the pre-monsoon season. In Table 4.9, the p-values of the pairwise Wilcoxon rank sum tests on the soil variables from saline blanks 1, 2, 3 and Patibania are presented for the same pre-monsoon season.

Next, the pairwise association of the soil variables are analyzed. For this, the Pearson product-moment correlation coefficient and its associated test of significance is used to check if the correlation is statistically significant or not.

Let $(X_1, Y_1), \ldots, (X_n, Y_n)$ be the paired sample, and let $\bar{X} = n^{-1} \sum_{i=1}^{n} X_i$ and $\bar{Y} = n^{-1} \sum_{i=1}^{n} Y_i$. The Pearson product-moment correlation coefficient is defined as

$$\rho_{X,Y} = \frac{\sum_{i=1}^{n} \left(X_i - \bar{X}\right) \left(Y_i - \bar{Y}\right)}{\sqrt{\sum_{i=1}^{n} \left(X_i - \bar{X}\right)^2} \sqrt{\sum_{i=1}^{n} \left(Y_i - \bar{Y}\right)^2}}.$$

The Pearson product-moment correlation coefficient lies between 1 and $-1$, and it measures the strength of linear association between the variables. The Pearson correlation is 1 when there is a perfect positive linear association between $X_i$'s and $Y_i$'s, i.e., $Y_i = a + bX_i$ for all $i$, where $b$ is a positive number and $a$ is any number. On the other hand, the Pearson correlation is $-1$ when there is a perfect negative linear association between $X_i$'s and $Y_i$'s, i.e., $Y_i = a - bX_i$ for all $i$, where $b$ is a positive number and $a$ is any number like before. If the p-value of the

Table 4.5: P-values of Tukey honest significant differences tests on soil variables in saline blank 1 (pre: pre-monsoon, mon: monsoon, post: post-monsoon).

| Variable | mon - pre | post - pre | post - mon |
|---|---|---|---|
| pH (1:5) | 0.8 | 0.89 | 0.97 |
| Electrical Conductivity ($\mu$mhos/cm) | 0.11 | 0.2 | 0.8 |
| Moisture (%) | 0.67 | 0.1 | 0.05 |
| Sand (%) | 0.26 | 0.75 | 0.11 |
| Silt (%) | 0.76 | 0 | 0.07 |
| Clay (%) | 1 | 1 | 1 |
| Salinity (p.p.t.) | 0.17 | 0.35 | 0.77 |
| Soil Organic Carbon (g/kg) | 0.53 | 0.28 | 0.08 |
| Soil Organic Matter (%) | 0 | 0.97 | 0 |
| Available Nitrogen (mg/kg) | 0.06 | 0.01 | 0 |
| Available Phosphorus (mg/kg) | 0.49 | 0.96 | 0.4 |
| Available Potassium (mg/kg) | 0.99 | 0.26 | 0.38 |

Table 4.6: P-values of pairwise Wilcoxon rank sum tests on soil variables in saline blank 1 (pre: pre-monsoon, mon: monsoon, post: post-monsoon).

| Variable | mon, pre | post, pre | post, mon |
|---|---|---|---|
| pH (1:5) | 0.84 | 0.84 | 0.89 |
| Electrical Conductivity ($\mu$mhos/cm) | 0.12 | 0.23 | 0.62 |
| Moisture (%) | 0.8 | 0.3 | 0.32 |
| Sand (%) | 0.37 | 0.37 | 0.23 |
| Silt (%) | 1 | 0.01 | 0.1 |
| Clay (%) | 1 | 1 | 1 |
| Salinity (p.p.t.) | 0.05 | 0.13 | 0.89 |
| Soil Organic Carbon (g/kg) | 0.8 | 0.15 | 0.42 |
| Soil Organic Matter (%) | 0 | 1 | 0.01 |
| Available Nitrogen (mg/kg) | 0.04 | 0.01 | 0 |
| Available Phosphorus (mg/kg) | 0.74 | 0.85 | 0.74 |
| Available Potassium (mg/kg) | 0.97 | 0.27 | 0.83 |

Table 4.7: P-values of ANOVA related tests on soil variables in saline blanks 1, 2, 3 and Patibania in pre-monsoon.

| Variable | ANOVA | Shapiro-Wilk | Levene | Kruskal-Wallis |
|---|---|---|---|---|
| pH (1:5) | 0.28 | 0 | 0.29 | 0.18 |
| Electrical Conductivity ($\mu$mhos/cm) | 0.03 | 0.01 | 0 | 0.16 |
| Moisture (%) | 0 | 0.45 | 0 | 0 |
| Sand (%) | 0 | 0 | 0 | 0 |
| Silt (%) | 0.37 | 0.29 | 0.03 | 0.27 |
| Clay (%) | 0 | 0.07 | 0.14 | 0 |
| Salinity (p.p.t.) | 0.04 | 0.02 | 0.01 | 0.07 |
| Soil Organic Carbon (g/kg) | 0.08 | 0 | 0.18 | 0 |
| Soil Organic Matter (%) | 0 | 0.07 | 0.67 | 0 |
| Available Nitrogen (mg/kg) | 0 | 0.01 | 0 | 0 |
| Available Phosphorus (mg/kg) | 0 | 0 | 0.03 | 0 |
| Available Potassium (mg/kg) | 0.3 | 0.01 | 0.01 | 0.11 |

Table 4.8: P-values of Tukey Honest Significant Differences tests on soil variables in saline blanks 1, 2, 3 and Patibania in pre-monsoon.

| Variable | S2 - S1 | S3 - S1 | Pa - S1 | S3 - S2 | Pa - S2 | Pa - S3 |
|---|---|---|---|---|---|---|
| pH (1:5) | 0.99 | 0.46 | 0.99 | 0.74 | 0.91 | 0.23 |
| Electrical Conductivity ($\mu$mhos/cm) | 0.95 | 0.13 | 0.35 | 0.06 | 0.17 | 0.89 |
| Moisture (%) | 1 | 0 | 0.05 | 0 | 0.05 | 0.02 |
| Sand (%) | 0.99 | 0.4 | 0 | 0.68 | 0.01 | 0.11 |
| Silt (%) | 0.41 | 0.91 | 1 | 0.78 | 0.39 | 0.92 |
| Clay (%) | 0.81 | 0.02 | 0 | 0 | 0 | 0.99 |
| Salinity (p.p.t.) | 0.5 | 0.47 | 0.74 | 0.04 | 0.08 | 0.94 |
| Soil Organic Carbon (g/kg) | 0.79 | 0.67 | 0.68 | 1 | 0.19 | 0.1 |
| Soil Organic Matter (%) | 0.26 | 0.09 | 0.83 | 0.99 | 0.04 | 0.01 |
| Available Nitrogen (mg/kg) | 0 | 0 | 0.81 | 1 | 0 | 0 |
| Available Phosphorus (mg/kg) | 0.14 | 0 | 0.24 | 0.1 | 0.93 | 0.01 |
| Available Potassium (mg/kg) | 0.72 | 0.83 | 0.94 | 0.99 | 0.36 | 0.45 |

Table 4.9: P-values of Pairwise Wilcoxon Rank Sum Tests on soil variables in saline blanks 1, 2, 3 and Patibania in pre-monsoon.

| Variable | S2, S1 | S3, S1 | S3, S2 | Pa, S1 | Pa, S2 | Pa, S3 |
|---|---|---|---|---|---|---|
| pH (1:5) | 0.58 | 0.4 | 0.4 | 0.5 | 0.58 | 0.29 |
| Electrical Conductivity ($\mu$mhos/cm) | 0.15 | 0.43 | 0.15 | 0.65 | 0.43 | 0.43 |
| Moisture (%) | 0.53 | 0 | 0 | 0 | 0.03 | 0.03 |
| Sand (%) | 0.34 | 0.01 | 0.09 | 0 | 0.03 | 0.35 |
| Silt (%) | 0.43 | 0.43 | 0.47 | 0.43 | 0.43 | 0.43 |
| Clay (%) | 0.42 | 0.01 | 0.01 | 0.01 | 0.01 | 0.95 |
| Salinity (p.p.t.) | 0.07 | 0.93 | 0.07 | 0.62 | 0.07 | 0.8 |
| Soil Organic Carbon (g/kg) | 0.02 | 0.02 | 0.58 | 0.96 | 0.04 | 0.03 |
| Soil Organic Matter (%) | 0.09 | 0.04 | 0.66 | 0.39 | 0.03 | 0.02 |
| Available Nitrogen (mg/kg) | 0 | 0 | 0.63 | 0.09 | 0 | 0 |
| Available Phosphorus (mg/kg) | 0.16 | 0 | 0 | 0.09 | 0.6 | 0 |
| Available Potassium (mg/kg) | 0.2 | 0.2 | 0.38 | 0.58 | 0.2 | 0.2 |

test of significance of the Pearson correlation is less than 5%, it can be stated that the Pearson correlation is statistically significantly different from zero at 5% level.

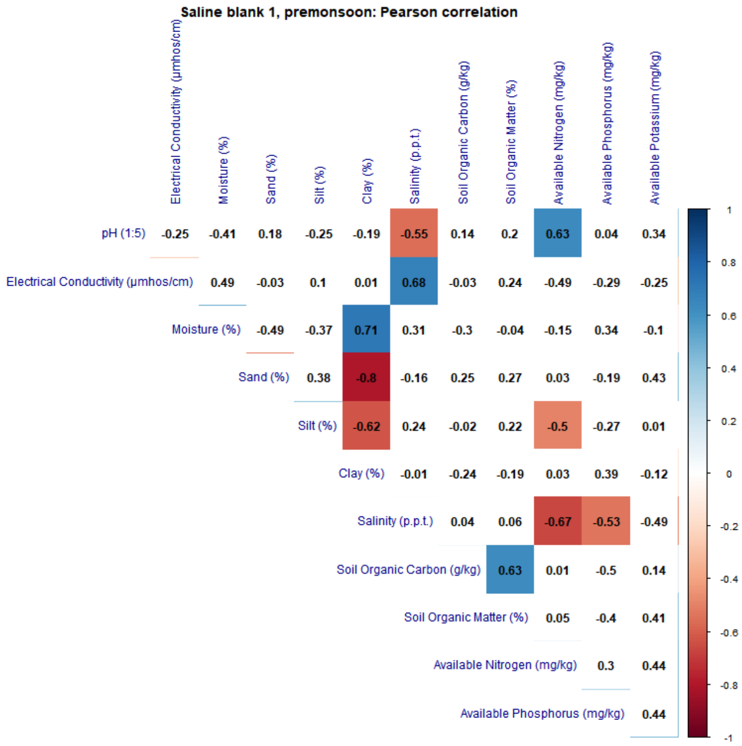


Figure 4.10: Pearson correlation plot of soil variables at saline blank 1 in pre-monsoon.

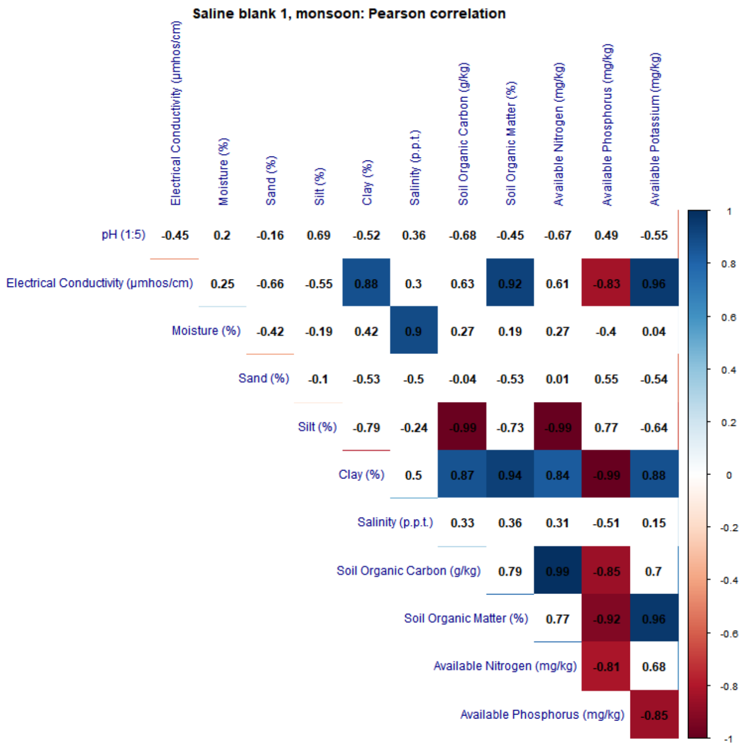


Figure 4.11: Pearson correlation plot of soil variables at saline blank 1 in monsoon.

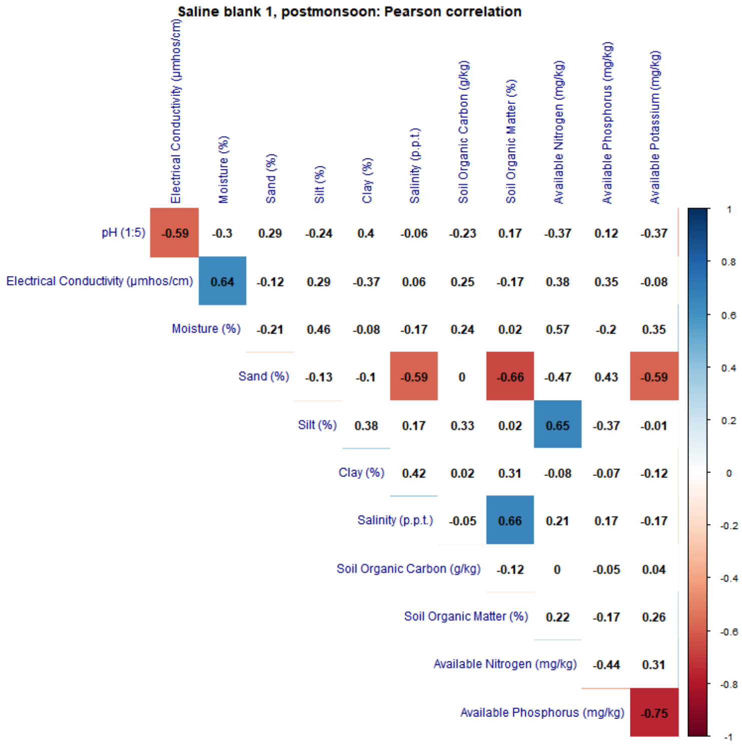


Figure 4.12: Pearson correlation plot of soil variables at saline blank 1 in post-monsoon.

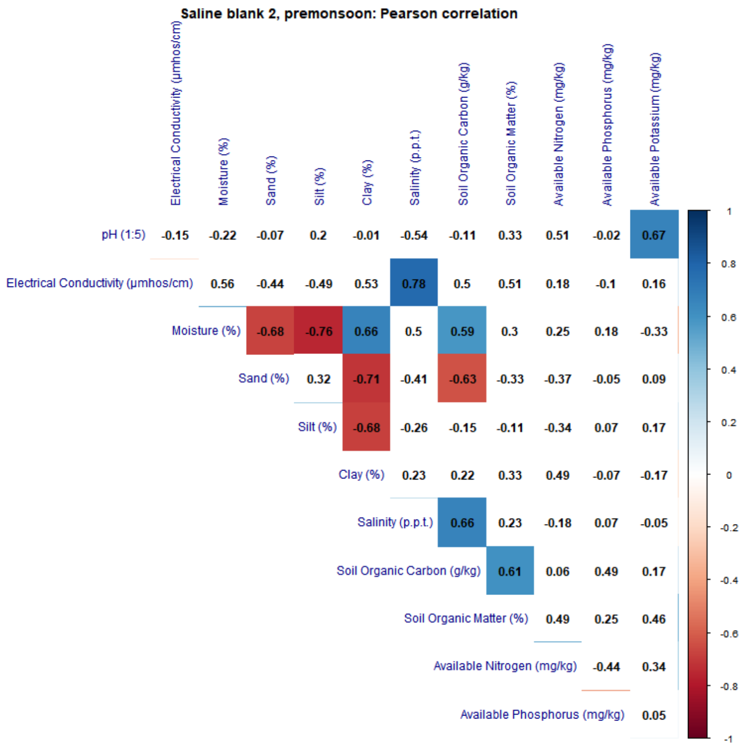


Figure 4.13: Pearson correlation plot of soil variables at saline blank 2 in pre-monsoon.

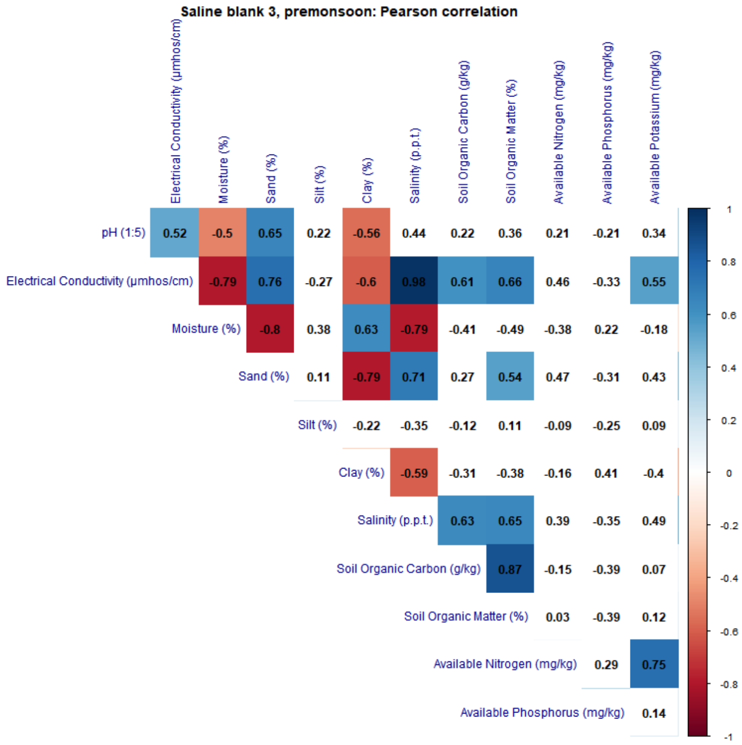

Figure 4.14: Pearson correlation plot of soil variables at saline blank 3 in pre-monsoon.

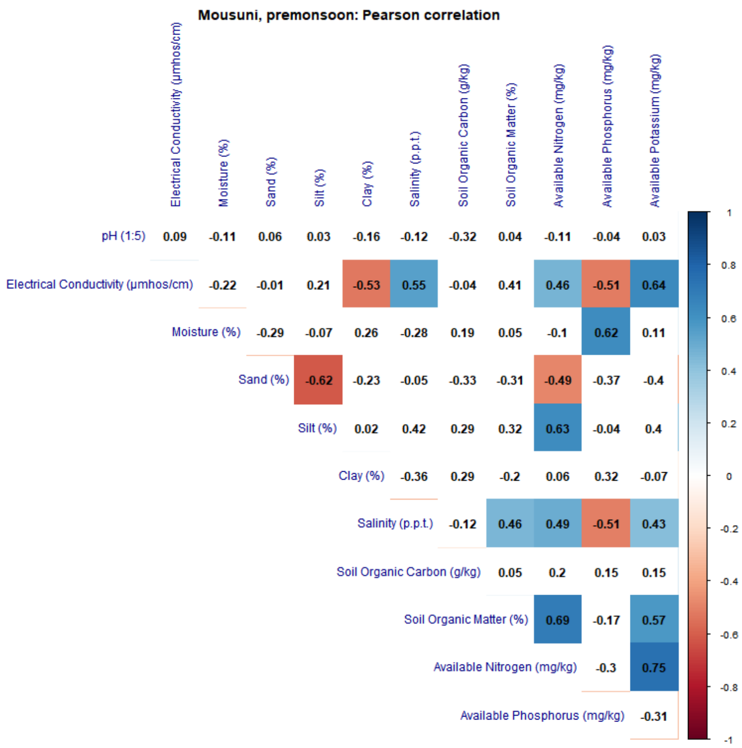

Figure 4.15: Pearson correlation plot of soil variables at Patibania in pre-monsoon.

In Figure 4.10, the Pearson correlation plot of the soil variables from saline blank 1 in pre-monsoon is presented. The correlation values, which are found to be statistically significantly different from 0, have a background color of either blue (for positive correlation) or red (for negative correlation). In Figure 4.11, the Pearson correlation plot of the soil variables from saline blank 1 in monsoon is presented, with the statistically significant correlation values having colored background. In Figure 4.12, the Pearson correlation plot of the soil variables from saline blank 1 in post-monsoon is presented. In Figure 4.13, the Pearson correlation plot of the soil variables from saline blank 2 in pre-monsoon is presented. In Figure 4.14, the Pearson correlation plot of the soil variables from saline blank 3 in pre-monsoon is presented. In Figure 4.15, the Pearson correlation plot of the soil variables from the Patibania island in pre-monsoon is presented.

## 4.4 Variation in growth and diversity of mangroves

The mangrove plants in general thrive in the presence of higher than normal levels of salinity in soil and tidal inundation. However, there is a lot of variation among the mangrove species themselves with regard to their most favorable salinity level, extent of inundation, soil composition, etc. Some species thrive in the oligohaline zone (low salinity), some in the mesohaline zone (moderate salinity) while some other in polyhaline zone (high salinity) (Rahman and Islam, 2015; Kamruzzaman et al., 2017). The soil cohesiveness is also influential in supporting the bigger mangrove trees while also allowing the roots to propagate freely. The different physiographic settings play a paramount role in determining the most appropriate mangrove species that would thrive the best.

Mangrove succession is prominently observed in tidal flats. These zones are in active formation phase, and the soil there is not well-consolidated. In this soil, certain algae form biological productive colonies, which help in consolidating the soil (Naskar, 1999). The lower portions of the tidal flats, that undergo daily tidal inundation, mangrove grasses like *Porteresia coarctata* proliferate and form grass meadow (Naskar, 1999). This meadow in turn traps sediments along with floating mangrove seeds and seedlings, providing a favorable habitat for further mangrove proliferation. Along the elevation in a tidal flat and then the supra tidal zone, a clear succession of mangrove species can be observed. In the upper intertidal zone, bigger mangrove plants proliferate to form ridge forests.

In the two islands under study, a diverse set of geomorphic features are observed. Though there are significant overlap in the species growing in the different geomorphic settings, some

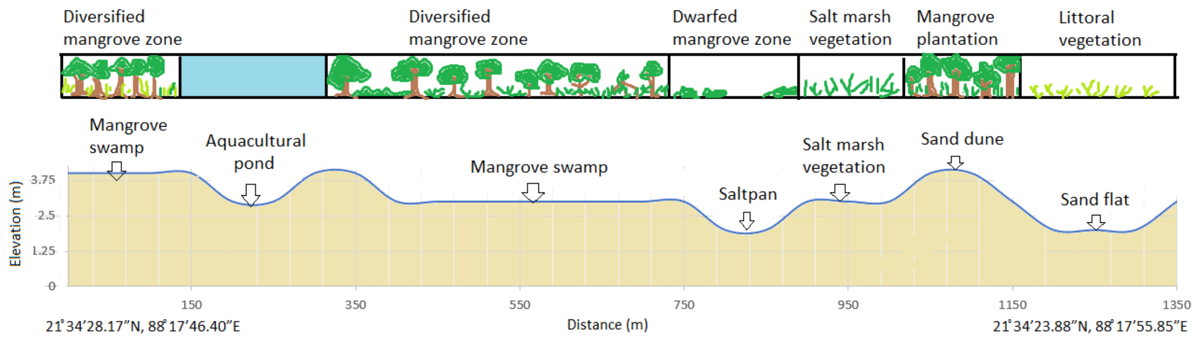


Figure 4.16: The mangrove zones in the Henry's island from the western boundary to the eastern boundary.

clearly distinguishable characters are observed in the local ecology of the geomorphic settings.

In the Henry's island, in the littoral zone next to the sea, which witness continuous wave and tidal actions, aquatic or semi-aquatic vegetation is observed. These plants are mostly herbaceous in nature, which enables them to weather the wave energy befalling them. However, in parts of this zone, where elevation is relatively higher and above the high tide mark, artificial plantation is developed, because the relatively higher elevation makes the young plants less likely to be swept away by the waves. For this artificial plantation however, woody plants are selected, which have strong and relatively wide stems, and exhibits luxuriant foliage. In parts of the seashore, there are tidal flats, which also have several sections based on their elevation, upper tidal flats, middle tidal flats and lower tidal flats. And vegetation characteristics are also different in the three zones of the tidal flats as described before. In the areas inland just behind the littoral zone, the effects of tidal drainage loss are visible. The tidal drainage loss results in less water influx, and higher levels of salinity builds up in the soil due to evaporation. In these conditions, salt marshes have formed, and the vegetation there exhibits stunted growth due to higher salinity levels and less freshwater availability. In the supratidal zones in these areas, saltpans have formed from the high salt buildup in the surface soil. Several creeks meander deep inland in the Henry's island, carrying water there. In the areas of the island next to these active creeks, true mangroves were observed. The creek water increases the water availability in those areas, helping the development of true mangroves. Some such areas inland of the island exhibit dense mangrove zones.

In Figure 4.16, the elevation profile of a cross section of the Henry Island along with the mangrove zones are presented. The sand flat on the seashore and the sand dune just behind it lie in the littoral zone. The salt marsh region has lower elevation. Further lower is the elevation of the saltpan areas. Next, mangrove swamp areas have developed with water influx from the creeks.

Though mangroves are halophytic plants, the very high salinity levels in the saltpan areas are intolerable to almost all mangrove species, which results in almost barren patches in otherwise vegetated regions. However, as the salinity level varies from the center to the outward regions of a saltpan, considerable variation of mangrove vegetation is observed with the variation in the salinity levels in a relatively small area. In Figure 4.17, the vegetation map of a saltpan in the Henry's island is presented.

Table 4.10: Geomorphology and mangrove variation in a saltpan in the Henry's island.

| Zone | Characteristics | Mangroves |
|---|---|---|
| Zone I (radius 30 m) | Bare surface with soft clay deposit | Marine cell, mangrove detritus, algal patch, animal skeleton |
| Zone II (radius 20 m) | Frequent location of salt marsh zone | Isolated patch of *Salicornia* and dry stump of *Ceriops*. |
| Zone III (radius 14 to 16 m) | Combined zone of Salicornia and ceriops in dwarfed condition. Gastropods are seen. | *Ceriops* in living condition and *Salicornia* in two colours (pinkish and greenish). |
| Zone IV (radius 10 m) | Dwarfed mangroves with dense colony and small open patches | *Aegiceras*, *Excoecaria* are in stunted condition, *Salicornia* are found. |
| Zone V (radius 15 m) | Dense mangrove fringe area with smaller trees and larger trees. | *Bruguera*, *Excoecaria*, *Avicennia*, luxuriant growth of *Phoenix*, *Heritera* and *Lumnithzera*. |

In the Patibania island, the western shore has higher elevation compared to the eastern boundary next to the Edward's creek. So, the tidal water enters in the island predominantly from the Edward's creek sweeping and inundating the eastern shore. Consequently, there is no shortage of water availability in this area, which has an bank margin ridge next to the Edward's creek, and due to the moderate salinity levels of the tidal water, the mangrove diversity and richness is maximum in this region of the island. Next inland to this diverse mangrove zone is the stunted mangrove zone, where due to relative deficiency of water and higher salinity levels in soil, the mangroves are stunted. Further inland, this zone transitions to a salt marsh zone containing salt marsh formations and associated mangroves, which have higher salinity

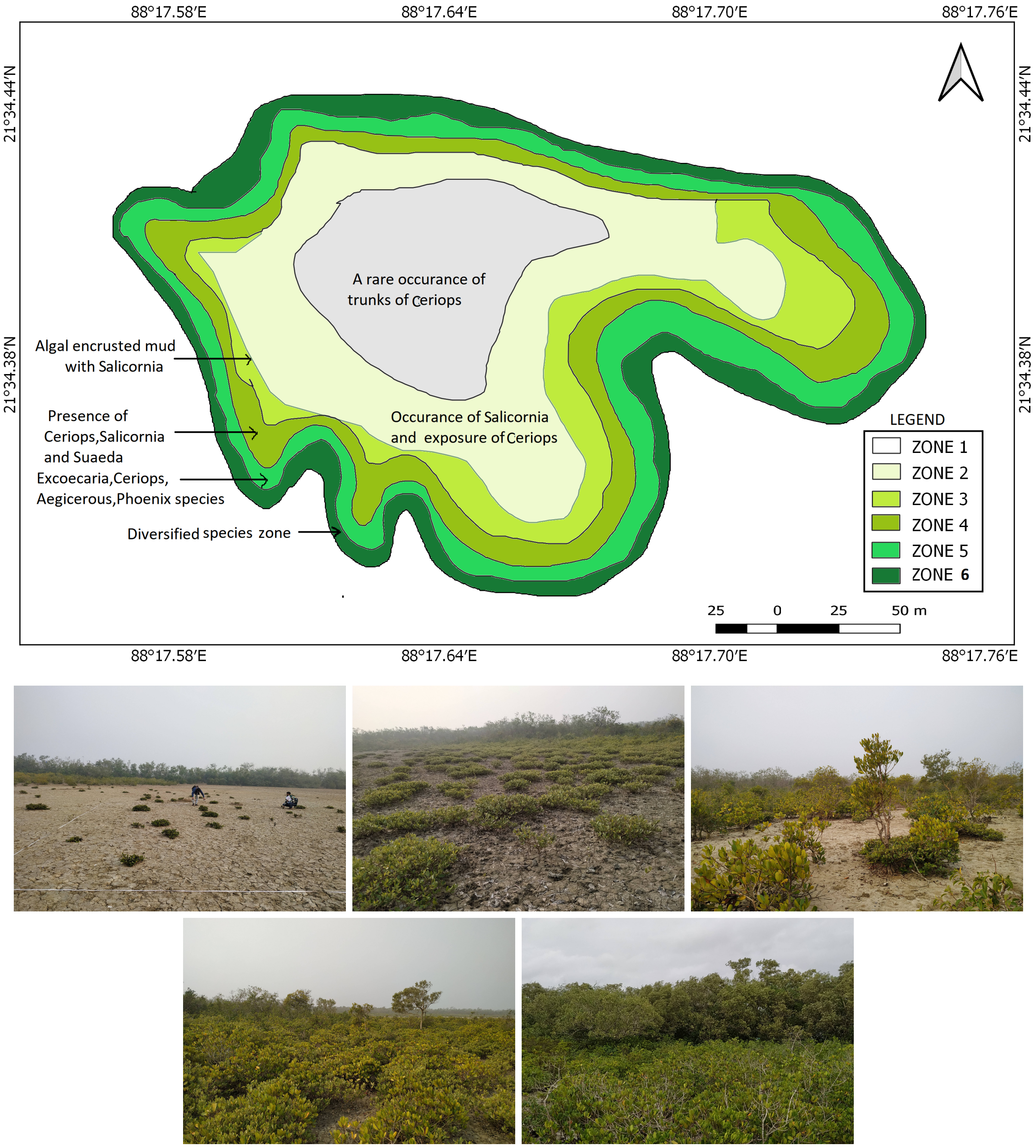


Figure 4.17: Zonation of mangroves within a saltpan in the Henry's island: zone I (lof left), zone II (top middle), zone III (top right), zone IV (bottom left) and zone V (bottom right).

tolerance but generally dwarf in nature. Between the stunted mangrove zone and the salt marsh zone however, there is a transitional zone, where the characteristics of both zones are observable. After the salt marsh zone further inland, soil salinity further increases, with numerous saline blanks. The saline blanks are nearly barren with almost no vegetation. After a transitional zone next to this saline blank zone, there is a littoral zone on the western seashore containing aquatic and semi-aquatic plants that can withstand frequent inundation. The transitional zone between the saline blank zone and the littoral zone bear plants and vegetation characteristics from both its neighboring zones. Near the seashore in some parts of the island, where tidal water influx serves a plentiful water budget. Here, some artificial plantations are developed by the forest department consisting of true mangrove species. This zone has relatively dense vegetation. In Plate 4.3, the elevation profile of a cross section of the Patibania island is

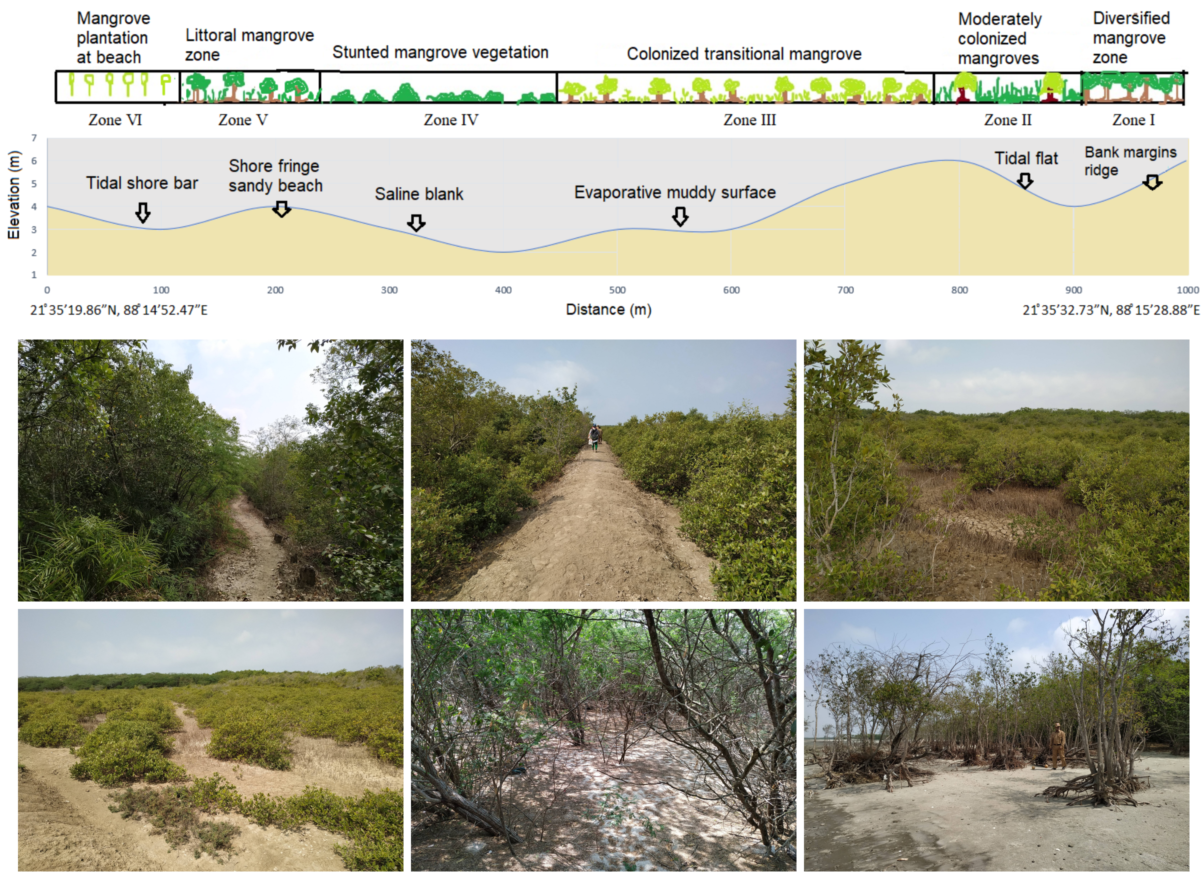


Plate 4.3: The mangrove zones in the Patibania island from the western boundary to the eastern boundary. Photos of vegetation in Zone I (top left), Zone II (top middle), Zone III (top right), Zone IV (bottom left), Zone V (bottom middle) and Zone VI (bottom right).

depicted with the mangrove characteristics in the different zones. One can observe that the tidal flat has lower elevation compared to the eastern region. However, there is a region at the end of the tidal flat with relatively higher elevation that hinders tidal water influx inland. From this water deficiency, evaporative muddy patches and then saline blanks have developed with sparse mangrove vegetation. Next, in the littoral zone in the west containing the shore fringe sandy beach region, mostly herbaceous vegetation has developed. Also in this region, some artificial plantation is carried out consisting of true mangroves. The plant species identified in these six zones are presented in Table 4.11.

Table 4.11: Mangrove species observed in the different vegetation zones in the Patibania island

| Vegetation Zone | No. of plant species | Scientific name |
|---|---|---|
| Zone 1 | 15 | Rhizophora apiculata, Bruguiera gymnorhiza, Avicennia marina, Avicennia officinalis, Avicennia alba, Ceriops tagal, Ceriops decandra, Kandelia candel, Bruguiera parviflora, Xylocarpus granatum, Sesuvium protulasastrum, Thespesia populnea, Phoenix paludosa, Salicornia brachiata, Ceriops tagal. |
| Zone 2 | 10 | Avicennia alba, Excoecaria agallocha, Ceriops decandra, Phoenix paludosa, Acacia farnesiana, Bruguiera parviflora, Salicornia brachiata, Carallia brachiata, Suaeda maritima, Ceriops tagal. |
| Zone 3 | 8 | Avicennia alba, Prosopis juliflora, Avicennia marina, Bruguiera gymnorhiza, Ceriops decandra, Avicennia officinalis, Sonneratia griffithii, Suaeda maritima. |
| Zone 4 | 7 | Salicornia brachiata, Avicennia alba, Sonneratia griffithii, Ceriops decandra, Fimbristylis ferruginea, Aegiceras corniculatum, Ceriops tagal. |
| Zone 5 | 12 | Avicennia marina, Avicennia officinalis, Avicennia alba, Excoecaria agallocha, Tamarix gallica, Salicornia brachiata, Acacia farnesiana, Ceriops decandra, Aeluropus lagopoides, Salicornia brachiata, Ipomoea pes-caprae, Sesuvium portulacastrum. |
| Zone 6 | 3 | Excoecaria agallocha, Prosopis juliflora, Tamarix gallica. |

To cope with the high salinity in the soil and pore water, the various mangrove species have developed notable abilities. One of such abilities is being able to exude the excess salt in the water brought up by capillary action through the leaves. These exuded salt form visible salt crystals on the leaves in the relatively drier months. In Plate 4.4, photos of such salt crystals visible on the leaves of *Aegiceras* in the Henry's island are presented. The photos are taken in April, and because of the relative dryness of April, the salt crystals did not wash away. However,

Plate 4.4: Salt crystals on the leaves of *Aegiceras*.

such salt crystals were not observed in the Patibania island.

## 4.5 Areas of tidal inundation at different periods

Tidal inundation plays is a crucial factor in shaping the topographic features, development of settings like saltpans, and the development of mangrove ecology. However, Sundarban region is under active formation. The interplay of sediment deposition and natural subduction results in changing elevation layout and resultant changes in tidal inundation in the broader region. However, within a year itself, there is some variation in the area inundated under tidal water in the different seasons.

The principal cause of this variation is the vast freshwater influx during the monsoon season. This enormous water inflow results in a local abundance of water levels in Sundarban region, as the normal land to sea motion of river water is unable to keep pace with the rate of inflow, which overabundance of water in the land. During the high tides, the already overflowing rivers and creeks are further burdened with the saline tidal water from the sea and also the excess freshwater load from the estuary. Due to this, tidal inundation during the monsoons is higher compared to pre-monsoon and post-monsoon.

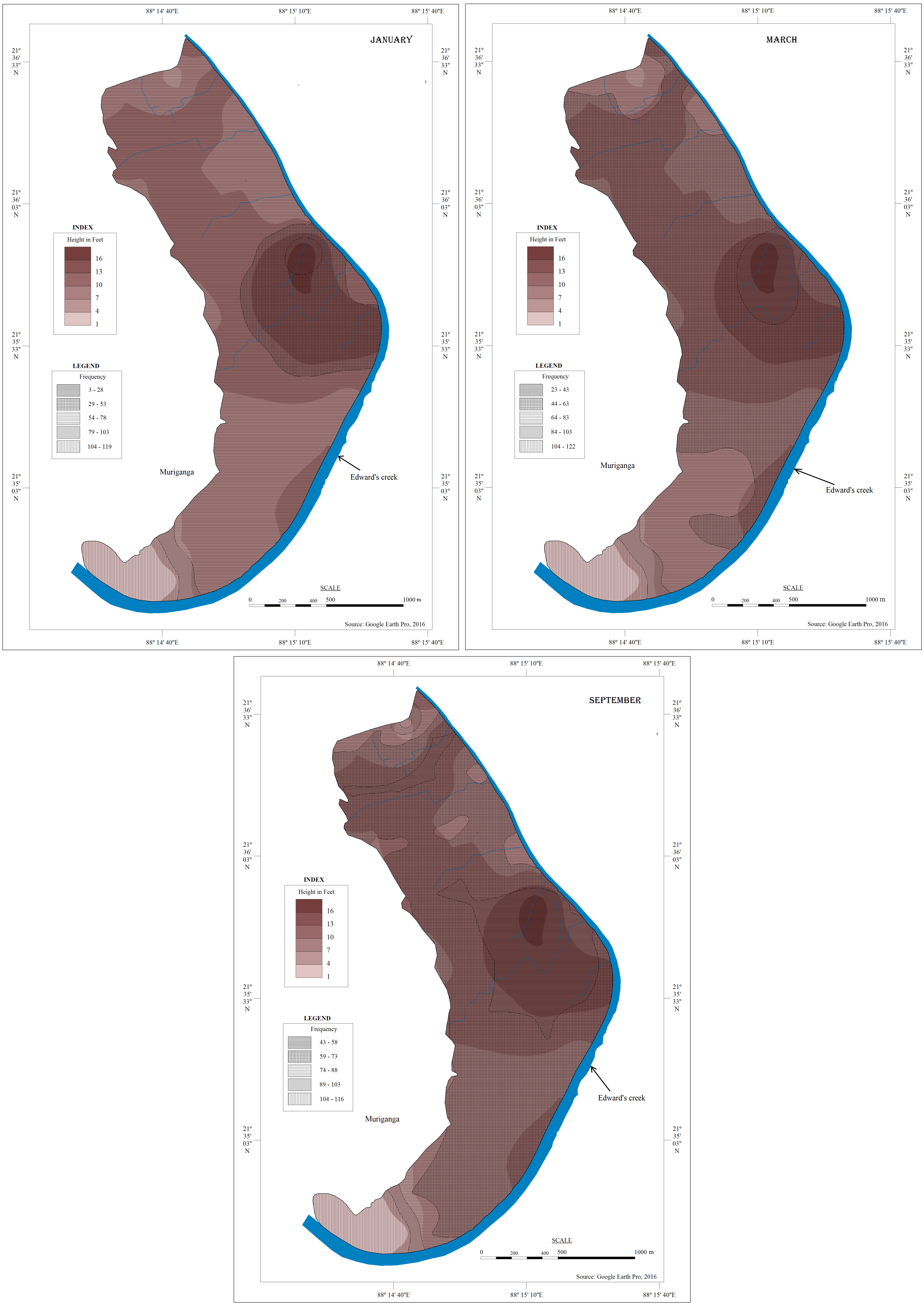


Figure 4.18: Tidal inundation frequency in the Patibania island.

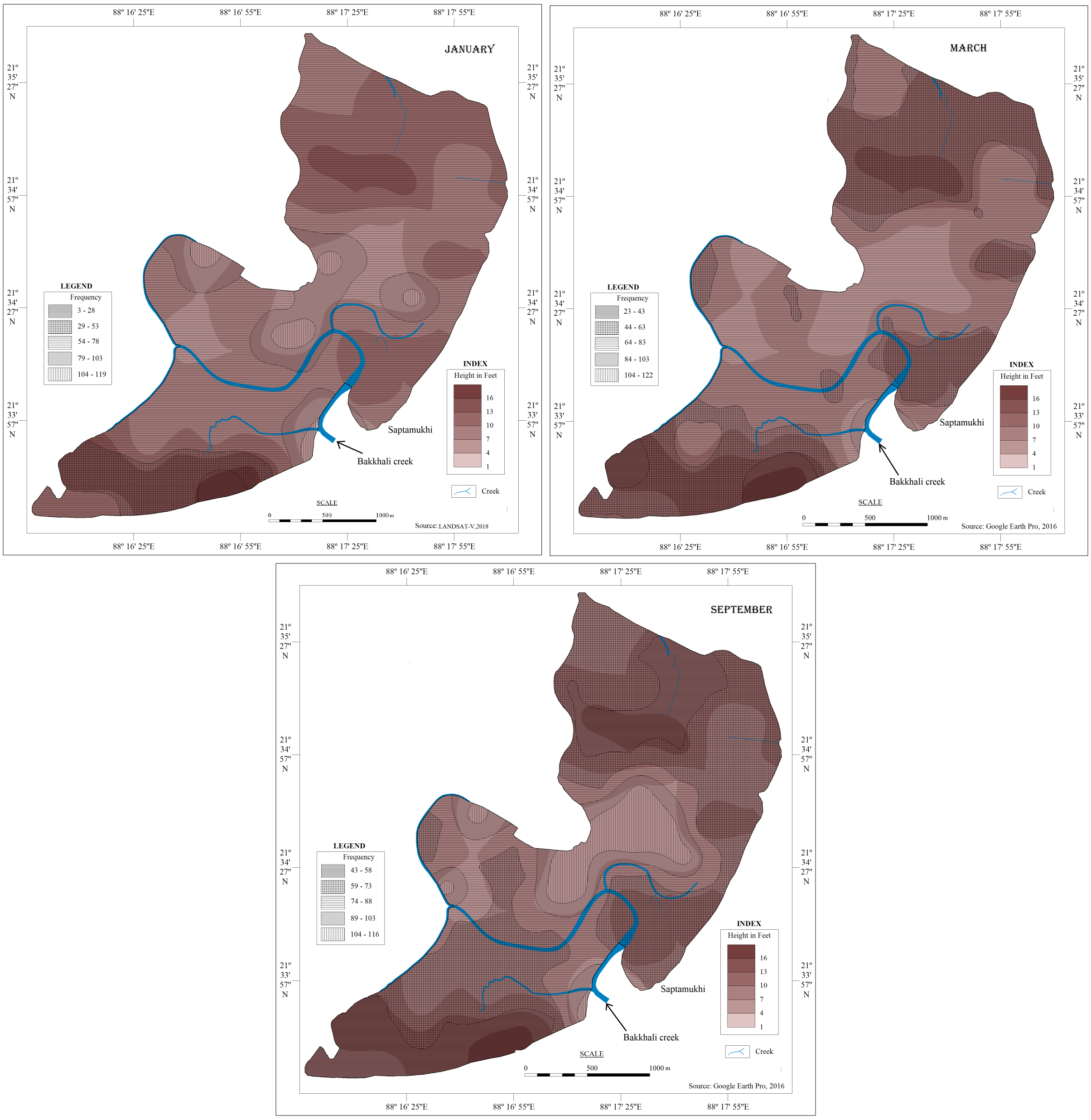


Figure 4.19: Tidal inundation frequency in the Henry's island.

Freshwater inflow gradually declines after the monsoon rains recede, and in the early post-monsoon season, tidal inundation is lower than the monsoon inundation. However, with the onset of winter, freshwater inflow drops farther due to lack of rainfall, and tidal inundation also drops. Next, in the pre-monsoon season with the onset of summer, due to sporadic summer rains and the availability of snowmelt water from the Himalayas in the rivers, freshwater level marginally increases. Hence in the summer, tidal inundation is higher than in the winter months. So, the seasonal variation in tidal inundation is due to the imbalance of the seasonal freshwater availability, and particularly the overabundance of freshwater from the monsoonal rains.

In Figure 4.19, the maps of tidal frequency in different regions of the Henry's island are presented in the months of January, March and September. Among the three months, September is a monsoon month, while January is a post-monsoon winter month and March is a pre-monsoon month. It can be seen in Figure 4.19 that the extent of tidal inundation in the month of September is the higher than those in the months of January and March, while the tidal inundation in the month of March is higher than the month of January.

The maps of tidal inundation frequencies in the Patibania island is presented in Figure 4.18 for the months of January, March and September. The same observations from the case of the Henry's island, that the extent of tidal inundation is higher in the month of September than March and January and that tidal inundation is higher in the month of March compared to January, are repeated in the Patibania island.

Tidal inundation is intricately related to the elevation of the region. Areas with higher elevations naturally undergoes lestidal inundation compared to the areas with lower elevation. In the tidal inundation frequencies maps in Figure 4.19 and Figure 4.18, this fact is also reflected.

## 4.6 Impact of overwash process on the mangroves

Coastal areas often contain sand dunes or other deposits which form a barrier behind the beach. Normal waves cannot crest and overflow these higher topographic forms. However, during storm surges, the resulting higher wave run-up can reach the top of the sand dunes and overflow behind them. When such an event occurs, the high wave energy associated washes off the sand and soil layers from the top of the sand or other coastal barriers. This washed off debris are deposited in the lower area behind the sand dunes. The process of waves cresting the sand dunes and washing off its top surface is called overwash. The resulting deposits in the area behind the dunes are called as overwash deposits (also called washover deposits) (Donnelly et al., 2006).

Overwash can significantly erode sand dunes and change the beach geomorphology. As the sand dunes erode, their elevation decrease, which in turn increases the likelihood of further overwash (Figlus et al., 2011). Overwash deposits can be of two types based on the wave run-up that created it. It the height of the wave is lower than the maximum elevation of the sand dunes, then the waves cannot inundate the dunes completely, and the overwash is transported inland through relatively narrow channels, where the waves lose their kinetic energy and the washed off debris are deposited. The results of this type of overwash deposition are fan-shaped deposits, which are called as overwash fans. However, if the wave run-up is high enough to overflow the entire sand dune system, the overwash forms a curtain of deposits, which is called as overwash terrace (Williams, 2016).

Overwash deposits are visible in many places in the south-western Sundarban (Paul, 2002). Repeated overwash process may flatten a sand dune system by decreasing its elevation. The overwash deposits are generally sorted horizontally and vertically, reflecting the reducing wave energy as the wave moved further inland (Paul, 2002). Overwash deposit buries the vegetation present in the areas behind the sand dunes in a thick layer of sand and other deposits. This significantly alters the extant ecology by destroying much of the plant life. However, it is also observed by Walters and Kirwan (2016) that a small amount of overwash deposit may increase herbaceous mangrove growth in salt marshes.

In Plate 4.5, satellite images of the Henry's island are presented which depict the overwash deposits in the island on the years of 2010 and 2020. It can be seen that the overwash deposits have formed an overwash terrace in the south-eastern coast of the island.

Overwash deposits can erode or accrete based on erosion and further storm surges. In **??**, the distributions of the overwash deposits along the coasts of the study area containing the Henry's island and the Patibania island are depicted for the years 2005, 2010 and 2015. It can be seen that the Patibania island had negligible overwash deposits in 2005 and 2010. However, in 2015, it had noticeable overwash deposits along the coast. The overwash deposits in the Henry's island are spread over its coast. However, in 2015, the overwash deposits along the north-eastern coast of the Henry's island had eroded.

In Plate 4.6, some photos of overwash deposits and the mangroves therein are presented. It can be seen that the bigger mangrove trees protrude out of the thick layer of whitish sand of the overwash deposits. Most of the herbaceous mangroves are buried under the sand, and much of them will die off from it.

Overwash destroys much of the existing mangrove habitat consisting of the smaller herbaceous plants. However, it also transports nutrients inland to the salt marsh areas. Overwash deposits occurring over saltpans decrease the salinity of the top soil. These changes are favorable to new proliferation of mangroves to areas which may have been harsh for mangrove growth before.

The predicted sea level rise would increase the occurrence of overwash. Overwash also forces a landward migration of mangroves. The pioneer species establish themselves on top of


Plate 4.5: Satellite images of overwash deposits in the Henry's island in 2010 (top image) and 2020 (bottom image).

Plate 4.6: Overwash deposits at the beach ridge of the Patibania island (top left), at the Bakkhali sea beach (top right and bottom left), at the Kiran beach of the Henry's island.

the overwash deposits, which have buried the more established mangrove plants.

## 4.7 Bioturbation in the coastal sediments

Bioturbation is the alteration of soil and sediment layers by the activities of the local fauna and flora. Animals burrow in the soil, some species ingest the sediment to consume the micronutrients and microorganisms present within, or also ingest soil along with their preys. The expelled waste by the animals after the digestion process has significantly different composition than the sediment ingested. Other biological wastes from the dwelling animals also significantly alter the composition and characteristics of the soil and the sediment. The tree roots propagate through the soil, providing a degree of protection from erosion to loose soil. The network of roots of dead plants, when exposed, may provide dwelling places for small animals, which may then work towards further bioturbation.

In the coastal and estuarine areas, the loose soil and sediment layers are particularly amenable to bioturbation due to their unconsolidated nature. It is easier for burrowing animals to tunnel through, the short distance to the sea are favorable to the semiaquatic and saltwater animals. Further, the special root adaptations of the halophytic vegetation growing here also significantly rework the sediment layers. The dense network of aerial roots serve as sediment trappers and also as dwelling places for small animals. The algal patches growing under the influence of wave and tidal action work to consolidate the sediment surface.

Bioturbation alters the sediment and terrain structure built by physiographic processes, while enhancing the nutrient contents and conditions for further growth of flora and fauna. The biological wastes and carcasses of the dwelling animals and plants enhance the organic matter present in the soil.

To gauge the effect of bioturbation, observations were made and sediment samples were collected from the tidal flats of Bakkhali beach next to the Henry's island and inland of the Henry's island in a saltpan area. In the Bakkhali beach, some of the notable organisms in the fauna involving in bioturbation include snails, clams, crabs, polychaetes or worm tubes, etc. In

Plate 4.7: Some creatures involving in bioturbation in the Bakkhali beach: red crab (top left), ghost crab (top right), broad conical gastropod (bottom left) and conical gastropod (bottom right).

Plate 4.7, some of the organisms involving in bioturbation in the Bakkhali beach are presented.

Some outcomes of bioturbation in the Bakkhali beach are presented in Plate 4.8 and Plate 4.9. The molted crab shells visible in the figure add nutrients to the soil. The tracks, trails, footprints,


Plate 4.8: Some outcomes of bioturbation in the Bakkhali beach: crab shells (top left), tracks and trails (top right), algal grazing (bottom left), algal grazing on mud ripples (bottom right). The lengths of the wooden scale and the pen are 30 cm and 15 cm, respectively

burrowing activities as well as the algal grazing alter the surface sediment layers and the wave-created topographic features. The gastropods also alter the sediment layers, and the shells of dead gastropods increase the nutrient level in the soil.

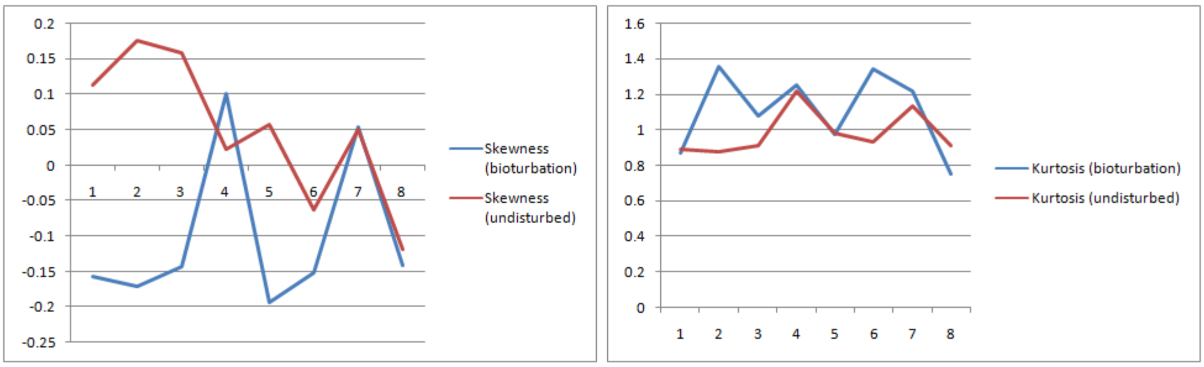


Figure 4.20: Skewness and kurtosis of the grain size of sediment samples from eight sites with bioturbation and eight undisturbed sites.

In the low to middle parts of the intertidal zone, a high density of crab holes were observed

Plate 4.9: Some outcomes of bioturbation in the Bakkhali beach: tracks of organisms (top left), footprints of creatures (top right), gastropods buried in the mud (bottom left) and a red crab burrowing (bottom right). The lengths of the wooden scale and the pen are 30 cm and 15 cm, respectively

with relatively bigger diameters. However, the crab holes became narrower and more scattered towards the upper intertidal zone. This may be due to the increasing distance from the sea and also that the soil consolidation increases as one moves away from the water level, which makes the act of burrowing more laborious. In the lower levels of the tidal flats, clams and snails were also observed. The crabs dwelling in the upper part were somewhat larger in size compared to those burrowing in the lower part.

In the saltpan area, crabs or burrows were not observed. However, snails were found in this habitat. In Plate 4.10, some photos of molluscs in thr saltpan area are presented.

To investigate the effect of bioturbation on the sediment, samples were collected from eight sites with bioturbation and eight undisturbed sites. The grain sizes of the samples were analyzed. In Figure 4.20, the skewness and the kurtosis of the grain sizes for each of the sediment samples are presented. It can be observed that the grain size distribution from sites with bioturbation are more often negatively skewed, which signifies the presence significant portion of coarser

Plate 4.10: Creatures involving in bioturbation in a saltpan in the Henry's island: clam shells on the cracked soil of a saltpan (left), molluscs in a *Salicornia* bush (middle) and snails next to an *Avicennia* plant (right). The length of the pen is 15 cm.

grains. This happens because the creatures involved in bioturbation mixes the fine sediment layer with small grain size with the coarser subsurface layers. The kurtosis of the grain size distribution from the sites with bioturbation is almost always higher than the undisturbed sites. This indicates that the samples from the sites with bioturbation contains a more diverse mixture of grain sizes. The grain size of the samples from the undisturbed sites are more uniform in nature. From these observations, it is clearly reflected that the bioturbation activity results in the mixing of different sediment layers containing fine as well as coarse grains.

## 4.8 Changes in the shoreface environment

In the dynamic geomorphology of the south-western Sundarban region, the shoreface is being shaped actively by waves and tidal processes, vegetation propagation and animal and human actions. The south-western Sundarban region witnesses the activities of the open estuarine system of the Hooghly river, including its freshwater discharge and sediment deposition. Being situated on the coast, the region also witnesses the continuous wave and tidal activities, the resulting erosion and deposition. The interplay of these two major systems of activities play the principal role in shaping and forming the shoreface of the region along the sea.

The shoreface consists of the region from the low water level of the sea through the breaker zone, where the waves break, to the relatively flat inner shelf. The shoreface in the south-western Sundarban region contains a diverse group of physiographic settings because of the interplay of the estuarine and marine processes. The primary physiographic settings of this zone contains the tidal mudflats, sand flats and the bases of the sand dunes that form the back barrier ridges along the beach. Behind the shoreface region, salt marshes and mangrove swamps are observed.

Plate 4.11: Top left: bioturbation on the swash and backwash marks in the intertidal zone in the Bakkhali coast; top right: *Salicornia* and *Suaeda* bushes on the upper tidal mudflat beside the Kalisthan creek in Bakkhali; bottom left: Exposed mudbanks in the Henry's island; bottom right: Exposed roots of coastal plants in the Patibania island due to erosion.

Based on the distance from the low water level, the shoreface can be divided in several regions, among which there are the lower shoreface and the upper shoreface. The lower shoreface consists of the region from the low water level to the average water level. This region lies subaqueous most of the time. Due to the relatively higher water level and wave energy, the average grain size of the deposition here is comparatively larger. The vegetation growing here are littoral in nature. Next, the upper shoreface consists of the region from the average water level to the breaker region. The wave energy decreases here progressively, and as wave energy decreases, the average grain size of the sediments also decreases. However, the seasonal fluctuation of freshwater influx, tides and storm surges cause a local overabundance of water and a resultant temporary increase in the local sea level. So, portions of the upper shoreface may become part of the lower shoreface, and farther upshore areas become part of the upper shoreface. These temporary changes cause significant changes in the shoreface environment.

In certain parts of the shoreface of the two islands under study and also the bigger region of south-western Sundarban, tidal flats have formed spanning the lower and the upper shoreface. The role of the vast sediment load of the estuarine system is observable in the composition of the tidal flats, the chief constituents of which are clay and silt depositions. The topographic and ecological characteristics of the tidal flats also differ between lower, middle and upper portions of the tidal flats. In the lower parts, little vegetation is visible, and the soil is loose and saturated with water due to continuous tidal action. However, the loose soil makes this region suitable for abundant bioturbation (Paul, 2002), which plays a significant role in changing the shoreface. In the top left of Plate 4.11, a photo of bioturbation on the swash and backwash marks in the intertidal zone in the Bakkhali coast next to the Henry's island is presented. The crab holes formed from the bioturbation act as sediment traps aiding in the accumulation of sediment in that zone. In the middle through the upper parts, at first thin algal mats are visible, which help in consolidating the soil and thus preparing it for later mangrove succession (Paul, 2002). In the upper parts, pioneer mangrove species like *Salicornia* and *Suaeda* mangrove species are visible. In the top right of Plate 4.11, a photo of the upper tidal mudflat beside the Kalisthan creek in Bakkhali next to the Henry's island is presented. The *Salicornia* and *Suaeda* bushes propagating in this region is clearly visible. These species are highly salt tolerant and can withstand the tidal action in this region. In the network of their foliage and roots, seeds of bigger mangrove plants are captured, which find a favorable growing environment there due to the nutrient rich tidal flats. In tidal flats deposition of sediments occurs alongside erosion of soil layers. The exposure and subsequent erosion of subsurface soil layers may itself act as a source of further deposition. In the bottom left of Plate 4.11, the exposed mudbanks in the Henry's island are observable, which is an outcome of the erosion of the top surface. This clay and silt from this exposed mudbank is scattered and deposited nearby by the tidal waves acting upon it. Tidal action thus makes the tidal mudflat wider by this interplay of deposition and erosion. In parts of open coasts, sand flats are visible. The sand flats are primarily formed from marine processes as opposed to estuarine processes. Sand is deposited by longshore and cross-shore currents on the shore by wave action, and the sand is generated mostly from erosion elsewhere. Continued deposition makes the sand flat gradually wider over time, unless the deposition processes change direction, and an area for deposit accumulation becomes an area of erosion. In the photo presented in the bottom right of Plate 4.11, the impact of the erosion activity in the Patibania coast is reflected in the exposed roots of the plants. The eroded sediment layers have exposed the roots that were underground before.

In the top left photo in Plate 4.12, the outcome of coastal erosion in the Henry's island is conveyed through the series of plants with exposed roots. However, some erosion is the result storm activities, which increase wave energy and thus the ability of the waves to wash off sediments. Also, uprooting of trees during storms loosen the soil on which the tree was standing earlier, making it easier to wash away that soil.

Plate 4.12: Top left: exposed roots of coastal plants in the Henry's island due to erosion; top right: Overwash deposits in the shoreface of the Henry's island; bottom: a saltpan in the back-dune area in the Henry's island.

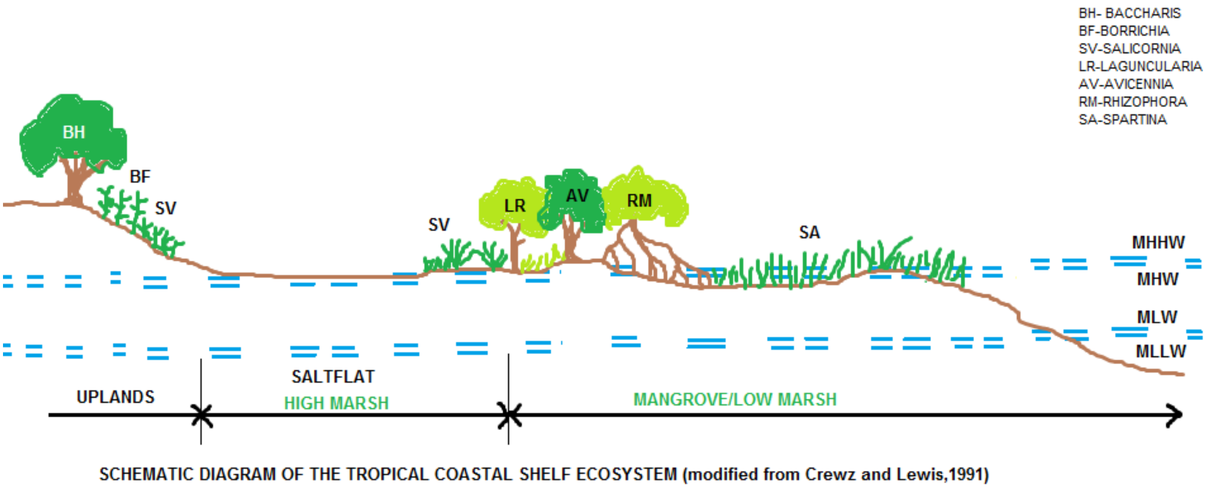


Figure 4.21: Schematic diagram of a tropical coastal shelf ecosystem (modified from Crewz and Lewis (1991)).

In Figure 4.21, the schematic cross section of a tropical coastal shelf ecosystem is presented.

Overwash depositions also significantly alter the shoreface by washing off the crests of the sand dunes and barrier ridges which form the boundary of the shoreface region, and them depositing the washed off debris inland. Flattening the sand dunes and ridges by repeated overwash effectively broaden the shoreface region. The overwash process also buries and destroys existing smaller plants at the boundary of the shoreface. In the top right of Plate 4.12, the impact of the overwash process in altering the shoreface of the Henry's island is reflected. The accretion of sediment as a result of overwash changes the shoreface, which can also be observed in this photo. As mangroves are good adapters to changing environmental conditions and rising sea level, a landward migration of mangroves is visible in this region. At the boundary of the shoreface and next to it, there are mangrove swamps and salt marshes. Mangrove swamps form where there is no shortage of water, while salt marshes form in the presence of water deficiency and resultant high salinity. Both mangrove swamps and salt marshes are dynamic with respect to geomorphology and ecology, and play their parts in the process of changing the shoreface environment. Mangrove swamps contain the bigger mangrove trees, while the salt marshes contain mostly herbaceous plants. In some parts behind the shoreface, where water availability is very low due to tidal drainage loss, saltpans form due to salinity buildup. In the bottom of Plate 4.12, the photo of a saltpan situated next to the shoreface in the back-dune area in the Henry's island is presented. Due to loss of tidal drainage, the water influx in this area is very low. Desiccation cracks form on the surface here due to the lack of water, which can be observed in the figure. The soil salinity and the pore water salinity both are very high here. The high salinity makes the growing mangroves dwarf, and mostly salt marsh vegetation thrive here. However, as the salinity is lower in the adjacent regions, bigger mangroves are visible in the boundary of the saltpan.

The enormous sediment load and the very low slope causes siltation on the channel beds of the creeks in the south-western Sundarban region, which decrease their carrying capacity. As a result, during high tides, the creek beds cannot contain the water inflow, and the tidal inundation of land gradually increases over time. This inundation also inundates parts of the beach, and hence serves a role in the change of shoreface. In addition, the reduced carrying capacity of the creeks aid in the inflow of tidal water inland, which helps in developing bigger mangrove trees there.

The changes in the shoreline, described in Chapter 3, has an obvious effect on the change of the shoreface. Similar natural processes alter the geomorphology of both the shoreface and the shoreline.

Human activity also has a significant influence in changing the shoreface of the region. In the Henry's island, artificial plantation is developed on the portions of the shore ridge having higher elevation. This plantation consisting of true mangrove woody trees has notably altered the boundary of the shoreface of the Henry's island.

## 4.9 Physiographic settings of mangroves and salt marshes

Salt marshes form at the upper part of the intertidal zone, where the water availability is relatively lower. Due to the lower wave energy in the upper regions of the intertidal zone, herbaceous halophytic plants can proliferate there. However, the environment may not be always suitable for the growth of larger mangrove trees.

The salt marsh region is rich in organic matter brought by tidal water. However, the frequent inundation and the saline condition prevalent there favor the growth of certain bacteria, which while decomposing the organic matter make the environment hypoxic in nature. The decomposition of the organic matter results in the formation of peat. Also, the hypoxic environment decreases the rate of decomposition, which maintains the high levels of organic matter in the salt marsh region.

The herbaceous plants and grasses growing in the salt marsh region form a dense web of roots. This web of roots, and the already prevalent low energy tidal environment increase the rate of deposition of sediments in the salt marsh region. The sediment deposition over time increases the elevation of the salt marsh region, and the soil is consolidated from the action of the plants and shrubs in the salt marsh. So, over time, the salt marsh region becomes suitable to support larger woody mangrove trees. The web of roots also trap the seeds and seedlings of mangroves, which may develop over time in large trees in a favorable environment.

Plate 4.13: Salt marsh on the eastern bank of the Edwards's creek (left), and dense mangrove forest in a mangrove swamp on the western bank of the Edward's creek (right).

Mangrove swamps containing large canopy-forming halophytic trees grow in a very similar environment with the salt marshes. The most significant difference in the environments of the salt marsh and the mangrove swamp is the level of tidal energy. The salt marsh environment has relatively higher tidal energy, which may sweep away the seedlings of the trees. In locations the tidal energy is lower, the seedlings may establish themselves in the soil to grow as large trees. This effect of the difference in the levels of tidal energy can be clearly seen in the two banks of the Edward's creek (Plate 4.13). In the western bank, which is the eastern boundary of the Patibania island, there is a bank margin ridge which slopes towards the Edward's creek with a relatively high angle. This sloping bank absorbs the tidal energy, but does not obstruct the supply of water. A dense mangrove forest with high species diversity has grown up along this bank. On the other hand, the eastern bank of the Edward's creek is almost totally flat with little to no surface feature obstructing the tidal waves. An expansive salt marsh with halophytic grasses has grown up in this region.

The salt marshes and the mangrove swamps are among the most productive parts of a mangrove ecology. The biological litter generated here serves as a plentiful source of organic matter. Both the regions undergo frequent, almost daily, tidal inundation. Small to mediumsized aquatic species visit these regions during high tides. The parts of these regions that remain underwater during low tide serves as breeding grounds and hatcheries of a variety of fishes. The dense web of roots provide a suitable habitat for smaller aquatic creatures. Thus, the salt marsh region supports a diverse and vibrant ecology.

A significant portion of the ecological services of a mangrove habitat are obtained from the mangrove swamp, as this zone is most suitable for supporting the larger mangrove trees. Timber from the large trees and honey gathered from the beehives established on the tree-branches are among the notable ecological products obtained from the mangrove swamps in Sundarban.

## 4.10 Restoring of mangroves by eco-engineering process

Mangroves are by nature able to adapt to changing conditions. However, the ongoing climate change and resultant sea level rise is expected to strongly affect the mangrove ecology by extensive inundation in Sundarban region (Hazra et al., 2002; Payo et al., 2016). Though the sea level rise is a long term threat to the survival of the mangrove ecology, anthropogenic activities is already a cause of extensive degradation of mangroves (Lewis III, 2005). So, human intervention by careful ecological engineering towards restoration of mangroves would have a beneficial effect on the ecosystem (Bosire et al., 2003). Restoration of mangroves also results in an increase in the biodiversity of the region (Bosire et al., 2008).

One principal cause of mangrove degradation is over-exploitation of the ecological services provided by them. The human settlements within Sundarban region are dependent on the mangroves for their livelihoods. However, the same dependence harms the mangrove ecology due to the high population level, and in turn will harm the human population in the middle to long term through the depletion of mangrove resources.

Due to the human involvement in the degradation of mangroves, it is important to be careful towards the human needs while designing any plan for ecological engineering for the restoration of mangroves. It was suggested by Hossain et al. (2017) that a core area may be designated for the restoration of the mangrove species nearing local extirpation, and the human entry may be prohibited there. Encircling this core area, another region may be designated with restricted human activities with an eye towards the safety of mangroves there.

In Gopal (2014), it is argued that mangroves are wetlands, and distinct characteristics different from forests. So, the conservation and restoration project of mangroves should be designed keeping that in mind. Lewis III (2005) pointed out that the principal factor determining the success of a mangrove restoration project is the local hydrology, which determines which types and species of mangroves would grow well in a particular region. Mangroves have evolved to grow in regions undergoing diurnal tidal inundation. The duration of inundation, th depth of the inundating tidal water as well as the frequency of tidal inundation – all of these are salient factors in the proliferation of a mangrove species in a region (Lewis III, 2005). Certain species may survive in the presence of less water and higher levels of salinity, as seen in earlier parts of the thesis. However, these are of the dwarfed variety. The bigger mangrove trees like *Heritiera fomes* requires lower levels of salinity to propagate (Pal et al., 2017), and keeping the salinity level low requires an adequate supply of water. In a region where the mangrove habitat has degraded, the more likely species to suffer are those which cannot tolerate higher salinity. Due to these reasons, the principal component of an eco-engineering plan to restore a degraded mangrove habitat is concerned with restoring the hydrology of the region, which can be achieved by by the removal of objects that have blocked the erstwhile streams carrying water to that habitat. After restoring water supply, care needs be taken to ensure that the hydrology is not further changed by the construction of dikes or other similar structures (Lewis III, 2005). However, over-flooding can also create stress for the mangroves species not accustomed to it (Lewis III, 2005), and care should be taken to maintain a balance.

Lewis III (2005) also observed that mangroves recover naturally over time, and if that has not happened, there should be underlying factors that prevented the regeneration of mangroves. In that case, identifying and removing those factors are necessary for a successful regeneration of the mangrove habitat. In addition, an eco-engineering project should not be rushed through, and before starting to implement it, observations should be made on the status of mangrove recovery. Also, it is essential to keep an eye towards the design and the practical implementation of the project to avoid cost overruns.

Based on the above discussion, it can be deduced that the restoration of mangroves is not too hard, if a small number of factors including the local hydrology is taken care of. In the Henry's island, much of the inland mangroves has been cleared off to make space for human activities. Need of mangrove restoration was felt after the devastation of Aila in 2009. Mangroves can act as shields to storm devastation (Sandilyan and Kathiresan, 2015; Mitra, 2020). The supercyclone Aila caused extensive damages to the community and facilities in the Henry's island, and to prevent similar damages in the future, plantations of salt tolerant mangroves were established

Plate 4.14: A new mangrove plantation on the tidal flat in the Henry's island.

along the sand dunes behind the sea beach. The plantation has flourished there, and these mangroves also serve a degree of protection from soil erosion in the sand dune region. Similar plantation projects has been also undertaken recently in other parts of the island. In Plate 4.14, a photo of such a plantation in a tidal flat in the Henry's island is presented. The Patibania island however is off limits to normal human activities, and natural mangroves flourish there.