EFFECTS OF ECOLOGICAL FACTORS ON THE GROWTH OF *SONNERATIA APETALA* BUCH.-HAM. IN RANGABALI COASTAL ZONE OF BANGLADESH

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Dedicated
To
My Beloved Parents
and Supervisors

Table 3.3.5: Pollution level of some metals based on Enrichment factors (EF), Geo-accumulation index (I_{geo}) and potential contamination index (C_p) in two layers of three different chars of Rangabali coastal area

Chars	Years	Layers	EF values			I_{geo} values				C_p values			
			Mn	Zn	Pb	Mn	Fe	Zn	Pb	Mn	Fe	Zn	Pb
Motherbunia	2009	Upper	24.27	85.60	30.05	0	0	0	0	0.144	0.006	0.503	0.187
		Lower	23.78	51.51	109.65	0	0	0	0	0.189	0.008	0.405	0.962
	2010	Upper	51.37	84.90	69.08	0	0	0	0	0.310	0.006	0.510	0.338
		Lower	34.60	46.95	58.63	0	0	0	0	0.300	0.009	0.400	0.525
	2016	Upper	72.53	97.60	0.94	0	0	0	0	0.238	0.164	0.365	0.245
		Lower	67.44	88.69	1.55	0	0	0	0	0.229	0.127	0.383	0.215
	2017	Upper	172.23	238.85	251.67	0	0	0	0	0.489	0.004	0.667	0.640
		Lower	34.92	51.37	21.97	0	0	0	0	0.304	0.009	0.458	0.210
Taposhi	2009	Upper	2.48	5.16	8.92	0	0	0	0	0.197	0.080	0.413	0.687
		Lower	3.34	5.94	7.36	0	0	0	0	0.207	0.063	0.368	0.425
	2010	Upper	4.48	4.75	5.23	0	0	0	0	0.400	0.090	0.430	0.488
		Lower	4.53	5.43	BDL	0	0	0	0	0.300	0.067	0.360	BDL
	2016	Upper	51.31	66.96	0.77	0	0	0	0	0.215	0.064	0.347	0.225
		Lower	590.92	22.32	1.71	0	0	0	0	0.224	0.080	0.276	0.200
	2017	Upper	7.66	6.33	8.28	0	0	0	0	0.565	0.318	0.539	1.170
		Lower	11.14	10.61	7.92	0	0	0	0	0.452	0.249	0.428	0.550
Kashem	2009	Upper	31.66	40.86	64.41	0	0	0	0	0.229	0.007	0.292	0.450
		Lower	32.33	40.61	24.91	0	0	0	0	0.210	0.007	0.261	0.137
	2010	Upper	43.86	46.30	40.76	0	0	0	0	0.310	0.006	0.330	0.225
		Lower	39.15	44.03	33.01	0	0	0	0	0.250	0.007	0.280	0.190
	2016	Upper	10.69	12.76	0.41	0	0	0	0	0.241	0.062	0.337	0.110
		Lower	27.75	23.92	14.67	0	0	0	0	0.219	0.061	0.289	0.265
	2017	Upper	126.37	182.69	43.82	0	0	0	0	0.186	0.004	0.319	0.438
		Lower	998.31	1658.49	BDL	0	0	0	0	0.180	0.007	0.295	BDL

Table 3.3.6: Degree of metal pollution based on Enrichment factors (EF), Geo-accumulation index (Igeo) and potential contamination index (Cp) of some metals

Variables	Chars	Years	Mn	Fe	Zn	Pb	Cp index	According to
EF value	Motherbunia	2009	24.03	-	68.550	68.550	-	EF < 1 indicates no enrichment; 1 < EF < 3 is minor enrichment; 3 < EF < 5 is moderate enrichment; 5 < EF < 10 is moderately severe enrichment; 10 < EF <25 is severe enrichment; 25 < EF< 50 is very severe enrichment; and EF > 50 is extremely severe enrichment (Taylor 1964)
		2010	42.983	-	65.925	63.857	-	
		2016	69.99	-	93.140	0.856	-	
		2017	103.57	-	145.110	136.820	-	
	Taposhi	2009	2.91	-	5.550	5.550	-	
		2010	4.503	-	5.089	2.613	-	
		2016	321.12	-	44.640	0.982	-	
		2017	9.40	-	8.470	8.100	-	
	Kashem	2009	31.99	-	40.740	40.7400	-	
		2010	41.504	-	45.165	36.886	-	
		2016	19.22	-	18.340	8.192	-	
		2017	562.34	-	920.59	21.91	-	
C_p value	Motherbunia	2009	0.166	0.007	0.454	0.575	1.202	C_p< 1 indicates low contamination; 1<C_p<3 is moderate contamination; and C_p> 3 indicates severe or very severe contamination. (Davaulter and Rognerud 2001)
		2010	0.305	0.007	0.458	0.431	1.201	
		2016	0.234	0.146	0.374	0.235	0.989	
		2017	0.396	0.010	0.560	0.425	1.391	
	Taposhi	2009	0.202	0.071	0.391	0.556	1.220	
		2010	0.352	0.079	0.393	0.244	1.068	
		2016	0.219	0.072	0.312	0.163	0.766	
		2017	0.508	0.280	0.480	0.860	2.128	
	Kashem	2009	0.219	0.007	0.276	0.336	0.838	
		2010	0.280	0.007	0.307	0.206	0.800	
		2016	0.230	0.061	0.313	0.233	0.837	
		2017	0.183	0.010	0.310	0.055	0.558	

I_{geo} values for these metals during the studied years revealed that the soils of the three chars were uncontaminated (Abrahim and Parker 2008)

Table 3.3.7: Potential ecological risk factors and ecological risk indices in two layers of three different chars of Rangabali coastal area

Chars	Years	Layers	Ecological risk factors			Ecological risk index	Threshold values Ecological risk factors (E^i_r) (Singh *et al*. 2010, Chowdhury and Maiti 2016)	Threshold values Ecological risk index (ERI) Singh *et al*. 2010, Chowdhury and Maiti 2016)
			Mn	Zn	Pb			
Motherbunia	2009	Upper	0.144	0.503	0.938	1.585	E^i_r <40 = low ecological risk, 40< E^i_r <\80 = moderate potential ecological risk, 80< E^i_r <160 = considerable potential ecological risk, 160< E^i_r <320 = high potential ecological risk, E^i_r <320 = very high ecological risk	150 < ERI = low ecological risk, 150 < ERI < 300 = moderate ecological risk, 300 < ERI < 600 = considerable ecological risk, ERI < 600 = very high ecological risk
		Lower	0.189	0.405	4.813	5.407		
	2010	Upper	0.309	0.513	0.338	1.160		
		Lower	0.300	0.403	0.525	1.228		
	2016	Upper	0.238	0.365	1.225	1.828		
		Lower	0.229	0.383	1.075	1.687		
	2017	Upper	0.489	0.667	3.200	4.356		
		Lower	0.304	0.458	1.050	1.812		
Taposhi	2009	Upper	0.197	0.413	3.438	4.048		
		Lower	0.207	0.368	2.125	2.700		
	2010	Upper	0.402	0.429	0.488	1.319		
		Lower	0.301	0.358	BDL	0.659		
	2016	Upper	0.215	0.347	1.125	1.687		
		Lower	0.224	0.276	1.000	1.500		
	2017	Upper	0.565	0.539	5.850	6.954		
		Lower	0.452	0.428	2.750	3.630		
Kashem	2009	Upper	0.229	0.292	2.250	2.771		
		Lower	0.210	0.261	0.688	1.159		
	2010	Upper	0.306	0.329	0.225	0.860		
		Lower	0.254	0.284	0.190	0.728		
	2016	Upper	0.241	0.337	0.550	1.128		
		Lower	0.219	0.289	1.325	1.833		
	2017	Upper	0.186	0.319	0.438	0.943		
		Lower	0.180	0.295	BDL	0.475		

Table 3.4.5: Comparison of concentrations of different elements (%) and some heavy metals (µg/g) in different mangrove species. Standard deviation is shown in parenthesis. ND = Not detected, PRC = Peoples' Republic of China

Mangroves	Species	N	P	Zn	Mn	Source
Rangabali, Patuakhali 2009	*Sonneratia apetala*	1.108 (0.653)	0.102 (0.016)	38.92 13.44	2638 448	Present study
Rangabali, Patuakhali 2010	*Sonneratia apetala*	1.032 (0.077)	0.106 (0.019)	84.98 31.00	477.6 290.0	Present study
Rangabali, Patuakhali 2016	*Sonneratia apetala*	1.658 (0.422)	0.111 (0.011)	25.67 5.76	238.2 40.0	Present study
Rangabali, Patuakhali 2017	*Sonneratia apetala*	1.791 (0.540)	0.108 (0.025)	35.17 6.63	337.5 118.7	Present study
Hatia,Noakhali, Bangladesh.	*Sonneratia apetala*	0.987 (0.02)	0.812 (0.21)	101.86 (5.75)	337 (64)	Das 2012
Hatia,Noakhali, Bangladesh.	*Porteresia coarctata*	1.20 (0.03)	0.756 (0.215)	44.07 (2.21)	343.7 (26.6)	Das 2012
Hatia,Noakhali, Bangladesh.	*Derris trifoliata*	1.095 (0.017)	3.45 (0.343)	103.86 (2.21)	756.85 (26.6)	Das 2012
Futian, PRC	*Aegiceras corniculata* *Kandelia candel*	1.31 (0.01) 1.39 (0.01)	0.14 (0.04) 0.13 (0.01)	85.2 (28.6) 69.7 (25.2)	166 (89) 1048 (269)	Tam *et al.* (1995)
Queenlands, Australia	*Aegiceras corniculata*	0.85 (0.06)	0.10 (0.01)	15.5 (3.0)	158 (67)	Spain and holt (1980)
Fujian, PRC	*Aegiceras corniculata* *Kandelia candel*	1.22 (0.01) 1.88 (0.20)	0.12 (0.00) 0.87 (ND)	ND ND	ND ND	Lin and Lin (1985)
Tanshui, Taiwan	*Kandelia candel*	1.90	0.15	ND	ND	Chen (1982)

Abstract

A segment of the coastal zone of Bangladesh at Rangabali Upazilla, Patuakhali district was investigated to determine the growth of *Sonneratia apetala* Buch.-Ham. in relation to ecological factors to know whether the areas is under ecological risk or not. Vegetation cover, landscape dynamics and estuarine water quality were also studied. The dynamics of the landscape of the study areas and vegetation cover were estimated using satellite images (from 1989 to 2017). Water samples were collected from three locations during several sampling occasions and four replicates of water samples were collected from each location. For plant and soil samples collection, three chars were selected namely Char Motherbunia, Char Taposhi and Char Kashem on the basis of three different hydrological regimes. Plant height and diameter at breast height (dbh) were measured during sampling occasions. Biochemical and anatomical adaptation of *S. apetala* were also studied.

Although all the three chars showed a decreasing tendency in land area from 1989 to 1991, there were different patterns in the three chars. The area of Char Motherbunia gradually increased from 3006.8 ha (1991) to 8305.8 ha in 2017. As a consequence the mangrove covers also increased. Char Taposhi showed a fluctuating tendency. The mangrove vegetation covers also changed in a fluctuating manner. The land area of the Char Kashem showed a gradual decrease due to severe erosion of the char. As a result the vegetation cover also decreased except in 2010.

The water of the estuary was slightly alkaline with a decreasing tendency in pH. Slight acidifications of the studied estuarine waters observed in all the three locations till 2016 might be attributed to the rise in atmospheric CO_2 content due to climate changes. Salinity showed temporal and spatial variations among the locations. The salinity of Location 1 was nil since May 2005 whereas Location 2 showed temporal variation and was nil in May 2017. Temporal variations were also observed in Location 3 where lowest value 0.62‰ was also observed in May 2017. Two replicates of this location also showed no salinity. Fresh water supply from upstream reduced the intrusion of the sea water on the study area. Dissolved oxygen (DO) also showed similar patterns of temporal and spatial variations where DO values (>5.0 mg/l) were above pollution level. The Pb, Mn and Fe contents of the study estuarine water were below detection level indicating that the areas are still free from these heavy metals pollution.

Soils of three chars were found less heterogeneous especially during each sampling occasions with few exceptions such as iron (Fe) showed high variability during all sampling occasions. The Na and K contents of soil also showed very high variability during 2016. The overall values of pH during study times ranged from 6.0 to 7.9 indicating that soils of all three chars were slightly acidic to slightly alkaline. Salinity showed overall variation of 0.65 (in 2016) to 15.42 ‰ (in 2010). Both layers of soils of Char Motherbunia showed low salt content indicating that the soils of this char were non-saline which might be attributed to flashing of the char with freshwater of the nearby river. There were gradual decreases in soil salinity of three chars till 2016 when all three chars were in non-saline condition but in 2017 Char Taposhi and

Char Kashem showed saline condition. Organic matter (OM) content varied between 0.335 and 1.187% where both the minimum and maximum values were found during 2016. A gradual decrease in OM content in the upper layer soil was found in Char Kashem. Sudden rise in OM content in the soils of other two chars during 2016 were noticed. In the soils of the three chars, Pb was found in some soil samples. In Char Motherbunia the values ranged from 15 – 31 µg/g in 2009 and 11 to 24 µg/g in 2010. Lead was absent in Char Kashem during 2017 except in one sample. Enrichment factor for Mn was very high during 2017 in upper layers of Char Motherbunia (172.2) and Char Kashem (126.4), and in lower layer of Char Kashem (998.3); for Pb the value in Char Motherbunia was 251.7, for Zn the values were also very high in upper layers of Char Motherbunia (238.8) and Char Kashem (182.7), and in lower layer of Char Kashem (1658.5) indicating extremely severe enrichment of Zn. Potential contamination index (Cp) of the studied metals namely Mn, Fe, Pb and Zn indicated that the metals are in low contamination level. The geo-accumulation index (I_{geo}) indicated uncontaminated state of all the three chars. The study also revealed that the three chars are at low ecological risk in terms of potential ecological risk factors and hence ecological risk index.

The foliar mineral nutrient of *S. apetala* were also more or less similar and showed lesser variation in the sampling occasions in the three chars. Mean nitrogen content (%) of the leaves increased gradually since 2009 to 2017 whereas P content (%) showed fluctuation. It seems that the study area showed a change from N limited to P limited status over a period of 8 years time.

The average height of plants growing in Char Taposhi in 2003 (5 years old saplings) was 2.2 ± 0.23 m and the diameter in breast height (dbh) was 3.18 ± 0.71 cm. These parameters were increased to 16.27 ± 0.77 m and 33.29 ± 6.14 cm respectively in 2017. The relative growth rate (RGR) in terms of height in 2008, 2010 and 2017 were 0.24 ± 0.02, 0.23 ± 0.04 and 0.07 ± 0.01 respectively in comparisons to previous sampling year. The plant showed some adaptation in terms of anatomical and biochemical properties. The amount of crude protein content gradually increased in the leaves of *S. apetala* in Char Motherbunia and Char Taposhi. Highest values were found in Char Motherbunia indicated that stress condition due to flooding caused higher crude protein content. *S. apetala* was found to produce proline in the leaves to withstand salinity stresses. Proline content of the leaves of *S. apetala* was highest in the plants growing in Char Kashem where salinity was also the highest. Higher accumulations of Mn during 2009 and 2017 and of Fe during 2010 were recorded which is clear reflections of the bioavailability of these metals are.

The present study revealed that sea water intrusion due to sea level changes is not noticed in this coastal area of Bangladesh. The chars are still at low ecological risk. These chars should be protected as these will also act as barriers to safeguard from the sea water intrusion and provide the habitats for different mangrove species. The data provided here will be helpful for the management of the coastal areas and fisheries sectors also as these areas are considered as breeding ground of Hilsa fish.

1. Introduction

The coast has been defined as the space where terrestrial environments influence marine environment and vice versa (Carter 1991). There has had an uneasy but long relationship between the coasts and man. Human being has concentrated throughout its history towards the lowland river valleys and coastal plains (Wolanski *et al*. 2006), which are currently at about 60% of the world's population (Lindeboom 2002). The role of coast as food and security provider towards human being has been shifted to industrial and commercial development to leisure and conservation in the recent past. The coast provides rich ecological conditions (Van der Zwiep 1991). In these highly complex areas different attractive and culturally important landscapes are situated. Due to valuable ecosystem functions and services (Costanza *et al.* 1997) as well as high biological productivity (Blaber *et al.* 2000), the coastal zones of the world are under pressure from human activities. For example, large scale fisheries activities have extensively reduced biomass, altered diversity, degraded habitats which resulted in changed trophic- and community structure (Blaber *et al.* 2000; Pauly *et al.* 2002). In addition, coastal environments have been disturbed by the oil and gas exploration (Holdway 2002), bioaccumulation of contaminants (Matthiessen and Law 2002), large-scale development of shrimp cultivation (Fichet *et al.* 1998), deoxygenation, nutrient enrichment and toxic algal blooms (Carpenter *et al.* 1998) is attributed to the other industrial processes.

Now a day to harness offshore renewable energy focus has been given to coastal waters. This tendency is making the situation more complicated because each single developments near-shore waters have ecological footprints which is extended in and around several square kilometers (Gill 2005). Although loss and disturbance of local habitats and food supplies, nutrient status and cycling changes, sedimentary supply reduction, changes in the sea level inundation and vulnerability to natural disturbances (McLusky *et al.* 1992; Rogers and McCarty 2000; Schekkerman *et al.* 1994) have been resulted due to different near-shore activities and terrestrial land uses (Mason 2002; Matthiessen and Law 2002), the impact is still commonly ignored. Rather in estuaries and wetlands further development programs are being implemented. Such programs typically result in degradation of estuaries that have either been canalized and dyked for flood protection (Wolanski *et al.* 2006), or have been filled up for residential areas. Worldwide in many coastal regions, wide range of problems has been linked as a common thread (Hauxwell and Valiela 2004; Cloern 2001; Meeuwing 1999). That is resulted due to the cultural (anthropogenic) eutrophication (Hauxwell and Valiela 2004). The biodiversity and productivity of the estuaries are affected by eutrophication. As a result, the service provided by the coastal ecosystem to humans and the overall health of the estuaries are affected (Erzini 2005; Nixon 2003).

Coastal managers currently face issues that raise conflicts between developers, ecologists, and other interest groups. Basic and sound scientific knowledge is needed to tackle these conflicts. It is generally difficult to understand the processes and products of interaction in coastal environment and for solving problems adopting a holistic system approach is often considered as advantageous (Carter 1991). It is important to view the coastal zone, i.e. the whole river catchments as a single ecological unit - from the headwaters to the estuary and coastal waters (Wolanski *et al.* 2004).

1.1 Planted forests at a critical point

Trees have been planted by people for thousands of years for food or other non-wood forest products, shelter, ornamental, ceremonial or religious purposes. It is assumed that the olive tree (*Olea europaea*) was probably the first woody species selected and planted, around 4000 BC, which has been found to be cultivated since the Minoan era (3000 BC) in Greece (Evans 2009a). Tree planting was also practiced in ancient times in Asia. Fruit trees and pines have been cultivated for ornamental, religious and ceremonial purposes by the Chinese which may be dated back as long as 2000 BC.

From time to time agenda has been clearly set for the future when an occasion or set of circumstance arise. The ascendancy of planted forest helped to reach such a critical point over natural forests that have been supplying several environmental services, many commodities for industrial and social benefits and some wildlife benefits. Planted forests are often considered no less than the forester equivalent of a farm crop, that which can deliver some benefits by the proper and sound management (FAO 2009).

In recent times the area and impacts of planted forests have rapidly expanded. It was estimated that in 2005, only 2% of global land area constituted the planted forests (7% of forest area) which was equivalent to 271 million hectares. Some non-wood forests products, social, religious, cultural and environmental services are also provided now by the planted forests along with wood, fiber and fuel (Evans 2009) and will increase in the future. What the actual areas of the planted forests suggest, the role played by them are far in excess.

1.2 Mangrove plantation in coastal zones of Bangladesh

The coastal zone of Bangladesh is the lowest-lying part of the Himalayan river-basin ecosystem which started to form about 6000 years ago (Islam 2001). Biogeographically it is the part of the Bay of Bengal large Marine Ecosystem (Nishat *et al.* 2002) with an internal estuary water area of 7325 sq. nautical miles (ca 25,000 sq. km), up to 10 fathom of baseline depth, an economic zone of 41040 sq. nautical miles (ca 140,000 sq. km). The total marine water of 48,365 sq. nautical miles (ca 165,000 sq. km) is almost the same in size of Bangladesh (BFRSS 1986; Islam 2007). Vast network of rivers and channels crisscross the coast and occupy the 60% of the total coastal areas. The coast houses an abundant biodiversity (Iftekhar 2006) and higher productivity due to continuous flush of silts rich in nutrients and supply of organic litter falls of mangroves (Islam 2007). Water flows through these courses is about 200,000 m^3/s (Islam 2004). A key physiographic feature of the floodplains is newly accreted mud flats which turns into interconnected floodplain (>50% of the area) during rainy season (Nishat *et al.* 2002).

In this complex coastal ecosystem of Bangladesh where conjunction of three different conditions, such as water (fresh and saline), land and air take places, the largest mangrove plantations of the world, covering about 800 km^2, are situated and are mainly concentrated to the south-central districts of the country with primary goal to create permanent green belt to reduce the disastrous effects caused by cyclone and storm surges (Blasco *et al.* 2001). Mangrove plantations were, however, a rather new concept in the then forestry practices.

The vast shoreline Bangladehs was almost without tree cover except for small natural mangroves, until the regular mangrove afforestation program began in 1966. Though there was doubt about the success of the program in the minds of many people, the mangrove plantation program in the newly accreted chars has now proved its worth and is at present underway in Bangladesh (Siddiqi 2001). With time this planted areas have been naturalized with the advent of some other mangrove species such as, *Avicennia officinalis, Acanthus illicifolius, Excoecaria agallocha, Nipa fruticans, Tamarix dioica* etc. Forest department has released different wildlife e.g. spotted dears, monkeys, snakes etc. making these chars new ecosystems.

1.3 Mangrove ecosystem

The mangroves grow most extensively in the coastal zones of Asia, Africa and South America. Sundarbans estuarine system is the single largest continuous block of tidal halophytic wetland forest in the world and wild Royal Bengal Tigers live in these mangrove swamp forests on the earth (Manna *et al*. 2010). The term “mangrove” refers to an assemblage of tropical trees and shrubs that grows in the intertidal zone. To describe the diverse group of plants of wet and saline habitat a non-taxonomic term Mangrove is used. To describe an individual species the term Mangrove are typically used. Duke (1992) defined mangroves as a range of functional forms including palms, shrubs, trees, or a ground fern usually exceeding 0.5 m in height and generally grows above mean sea level in the intertidal zones of marine’s coastal environments, or estuarine margins. Different terms e.g. mangrove community, mangrove ecosystem, mangrove forest, mangrove swamp, and mangle have been used alternately to describe various mangrove community species. Differences in morphology, physiology, and reproductive biology are revealed by closer inspection of these species although at first glance plants of these habitats may appear very similar. Tomlinson (1986) included approximately 16 families and 40 to 50 species as mangroves. Mangroves are mainly comprised of two groups: (1) true mangroves and (2) mangrove associates. True mangroves are usually defined as trees, shrubs and palms that grow exclusively in the tidal and inter-tidal zones of the tropical and sub-tropical regions e.g. *Avicennia* sp. and *Sonneratia* sp. (Tomlinson 1986). Tomlinson (1986) mentioned that to designate a species “true or strict mangrove” the required criteria are as:

1. Complete fidelity to the mangrove environment.
2. Plays a major role in the structure of the community and has the ability to form pure stands.
3. Morphological specialization for adaptation to the habitat e.g. pneumatophores and salt exclusion.
4. Physiological specialization for adaptation to their habitat.
5. Taxonomic isolation from terrestrial relatives.

Different non-woody species such as ferns e.g. *Acrosticum* and a wide range of herbaceous, sub-woody terrestrial plants, e.g. *Acanthus* are found to grow in mangroves as associates (Tomlinson 1986).

1.4 Ecological significance of mangroves

Natural and planted mangrove forests are providing important ecosystem goods and services to the environment and densely populated coastal population that includes shoreline stabilization, storm protection, water quality maintenance, micro-climate stabilization, groundwater recharge and discharge, flood and flow control, sediment and nutrient retention, habitat protection and biodiversity, biomass, productivity and resilience, recreation, tourism and culture, hunting and fishing, forestry products, and water transport (Blasco and Aizpuru 2002; Dahdouh-Guebas *et al*. 2005; Duke *et al.* 2007). Asian mangroves are considered as the most carbon-rich forests in the tropics by some recent works (Donato *et al*. 2012). The carbon content is estimated to be 1.023 Mg carbon per hectare in the mangrove forests of Asia and the Pacific, of which more than 50% is stored in organic-rich soils (Donato *et al.* 2012). In South Asia, mangrove forests are being degraded or lost both by natural (such as erosion in the coastal areas, disturbances caused by tropical cyclones and tsunamis) and anthropogenic factors (e.g. over-harvesting, change in land use pattern, pollution, decline in fresh water availability, flooding, and reduction of silt deposition) in spite of importance socio-economic and ecological values (Giri *et al.* 2007).

Today mangrove forests are regarded by most ecologists as highly productive, ecologically important systems although early workers regarded them as low productive with unimportant, transitional communities. The following major roles have been recognized of mangrove swamps:

1. Coastlines stabilization and soil formation.
2. Upland runoff is filtered in the Mangroves.
3. Many marine organisms, invertebrates and wildlife serve as are inhabited in the mangrove systems.
4. Productivity in offshore waters is enriched by the large amounts of detritus produced in the Mangroves.

In addition to these attributes, mangrove forests possess ecologically important roles, which are important to human beings specifically:

1. Coastal communities are protected from storms such as hurricanes by the mangrove forests. The huge number of life loss in Bangladesh (300,000 to 500,000 lives) during the 1970 typhoon is considered partly due to the fact that the conversion of the mangrove swamps to rice paddies that were protecting those coastal regions which are highly populated.

2. Many marine organisms take the refuges in the mangrove forests that have commercial or sport value serve and thus mangroves act as nurseries of those organisms. A decline in fisheries has occurred where widespread destruction of mangrove took place.

3. In mangrove forests, many threatened or endangered species have been found to reside.

4. As aesthetics and tourism places, mangrove forests are also important. For different recreational pursuits and other activities such as bird watching, boating, sports fishing, people from the different places visit these areas.

1.5 The estuary and the water quality

The drainage basin and the sea are linked at the coast and changes in the river catchments as a result of human activities and global changes are filtered and recorded in the estuary (Chen *et al.* 2007). Frequently used definition of estuaries is given by Pritchard (1952, 1967) which stated "An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which the sea water is measurably diluted with fresh water derived from land drainage". Although the estuaries in the coastal systems have been studied most, a variety of complex physiochemical processes (Nichols and Biggs 1985) resulted in the poor understanding (Corbett *et al.* 2007). Various factors, e.g. population growth (Peierls *et al.* 1991; Nixon 1995), agriculture (Howarth *et al.* 1996; Jordan *et al.* 1997), land use changes (Hopkinson Jr. and Vallino 1995) in the watershed caused an increase of nutrient input in all over the world's estuaries (Caffrey *et al.* 2007). Hypoxia and anoxia conditions are common phenomenon in the estuaries and coastal systems of different parts of the world due to eutrophication and huge algal growth which is the result of increased inputs of nutrients (Rabalais and Turner 2001; Smith *et al*. 1992). In the tropical and sub-tropical estuarine systems, mangroves are the dominant intertidal vegetation (Chapman 1976; Duke 1992) that supports essential ecological functions (Shervette *et al*. 2007).

The total area of the Ganges-Brahmaputra-Meghna drainage basin is about 1.5 million km^2 of which approximately 8% is in Bangladesh and majority part is in India (about 61%). The soils of the Bangladesh coastal belt were formed mostly on recent (Quaternary) sediment deposition from a number of rivers flow the areas (Siddiqi 2001). The sediments discharged are the main caused in the building process of the largest delta of the world. Beside the accretion of land, erosion is also a common feature in coast of Bangladesh. Therefore the net gain in the process of accretion between 1972 and 1991 was estimated to the addition of 268 km^2 i.e. 13 km^2 per year (BUET/BIDS 1993). A study of the Meghna estuary during the period of 200 years (1776-1996) indicates a loss of 1969 km^2 and gain of 3881 km^2 land due to erosion and accretion i.e. net gain of land was 1912 km^2 or about 10 km^2 per year (Anonymous 1997).

1.6 Remote sensing as tool for change detection

Different interesting characteristics are observed in the coastal area of Bangladesh that include (i) a vast network of rivers, (ii) huge amount of sediments are carried to this areas through the enormous discharge of river waters, (iii) a large number of sandbars are formed in the channels and rivers, (iv) northward converging Bay of Bengal, (v) the central part is specially very shallow along with all over the coast, and (vi) in the western region, a submarine canyon called Swatch of No Ground. These make the coastal areas dynamic and undergo frequent changes for long time. Global warming and thus the rise in sea-level (SLR) are thought to have long term consequences in the different parts of the coastal ecosystems e.g. wetlands and coral reefs which are again aggravated with the anthropogenic activities (Klemas 2011). It is estimated that over the past century, the sea level has increased over the world at an approximate average of about 3 mm that resulted in the glaciers melting and expanded ocean water during the hot periods. It has also been predicted that the sea level rise (SLR) may accelerate in future and SLR rate may be up to 0.59 m by 2100 (IPCC 2007). To map a variety of ecosystem patterns and processes correlated with vegetation type remote sensing are used (Gould 2000).

By observing the condition of an object or phenomenon, the differences occurred in different times can be identified which is known as change detection. In this process, multitemporal data sets and quantification of temporal effects are involved. Change detection is one of the major applications of the data set that are obtained by the remotely–sensed data collected from the satellites orbiting the earth as repetitive coverage of the area are available at short intervals along with the quality consistent images (Anderson 1977; Ingram *et al.* 1981; Nelson 1983; Singh 1984). This change detection process is very useful in a diverse field such as analysis of change in land use, deforestation assessment, phonological changes in vegetation, monitoring of shifting cultivation and pasture production variation in different seasons and many other changes in the environment. Identifying change by handling the data manually using sequential images is tedious job (Adeniyi 1980). As the most satellite data are digital in nature, it is easily amendable by computer aided analysis. A change detector is definitely needed to correlate automatically and compare different imagery sets of different times of an area that will subsequently be displayed to the interpreter the changes took place along the gradients of the locations (Shephard 1964).

1.7 Spatio-temporal variation of the mangrove soil

Sediment of mangrove ecosystems act as the sink of heavy metals and several researchers have worked on the effect of anthropogenic pollutants on the mangrove sediments and halophytes (Lacerda *et al*. 1992; Tam and Wong 2000; Defew *et al.* 2005; Natesan *et al*. 2014; Chowdhury and Maiti 2016; Ataullah *et* *al*. 2018). The fragile mangrove ecosystem are easily deleteriously affected by the heavy metals as these metals entered into the food chain and getting biomagnified in the process (Defew *et al*. 2005). The asphyxiated mangrove sediment having unique physical and chemical properties along with high level of organic matter content helped in this high accumulation of metals (Harbison 1986; Silva *et al*. 1990; Tam and Wong 2000; Defew *et al*. 2005).

The seasonal and spatial dynamics of trace elements in water and sediment from Pearl River Estuary, South China have been studied by using principal component analysis (PCA) and hierarchical cluster analysis (HCA) (Zhang *et al*. 2013). Ogwueleka (2014) used HCA and PCA to identify pollution sources at Kaduna River in Niger State, Nigeria. Hejabi *et al*. (2011) studied the metal pollution status in water and sediments in the Kabini River, Karnataka, India. Kumar *et al*. (2015) have used PCA to identify two factors, in the surface sediments of Gulf of Kachchh mangrove ecosystem. Factor analysis namely PCA is a powerful and popular technique used to reduce dimensionality of the data set with a large number of interrelated variables (Chowdhury and Maiti 2016). This reduction is possible by transforming the data into new variables called Principle Components (PCs) by orthogonal rotation to get a meaningful group (Chowdhury and Maiti 2016).

To evaluate the level of pollution of the water bodies, the sediments and soils, different indices of pollution like Contamination Factors (Cf), Geoaccumulation

Index (I*geo*) along with multivariate statistics are widely used (Chowdhury and Maiti 2016; Ataullah *et al*. 2018). They have assessed the status of metal pollution in the Indian and Bangladesh Sundarbans using these Ecological risk index, Geoaccumulation index, Enrichment factor and Contamination factor. I_{geo} index compares the concentration of a particular pollutant with the background concentration. An *et al*. (2009) used I*geo* index to evaluate heavy metals and polychlorinated biphenyls pollution level in the sediment of Yangtze River estuary (China).

To evaluate the metal pollutions in the basin of Karwar, in the south west coast of India, Manjunatha *et al*. (2001), used I_{geo} values. In the natural ecosystems, Ecological Risk Index (ERI) has been extensively used method to determine levels of heavy metals pollution and to estimate their impact. To enumerate the heavy metals' impact on the different sensitive or fragile ecosystems this method has been practiced by several researchers. El-Said and Youssef (2013) have assessed the ecotoxicological impact of heavy metals in the mangrove sediment of the red sea, Egypt.

Considerable load of different metals in the ambient environment is one of the major environmental issues of the coastal zones of Bangladesh. Depending on the hydrological parameters like pH, salinity etc. the heavy metals in the estuarine system bioaccumulate within the organisms. From the contaminated soil, metals can be accumulated by different mangrove species in different extents.

Bioaccumulation factor (BAF) is used to estimate the ability of a plant to accumulate metals from any soils where BAF is the ratio of a given pollutant between the accumulated concentration in any vegetative parts of a plant species to that present in ambient media (Authman and Abbas 2007).

1.8 Foliar nutrient dynamics of *Sonneratia apetala*

With some studies on the species composition, community structure and zonation mangrove ecosystems are considered as poorly studied among the different ecosystems of the sub-tropical regions (Tam *et al.* 1995). Some studies focuses on identification, biological diversity, function, conservation and highly different object of concerns and scales were observed, from DNA to the biosphere level (Ahmed *et al*. 2017; Meffe and Carrol 1997). But the mineral nutrition status is until now poorly understood of mangrove tree species. Levels of plant mineral concentrations have important roles on herbivores and thus on trophic interactions and ecosystem functioning (Smith and Smith 2001). The mineral nutrient status is directly controlled by the growth and productivity of the plant where different factors of the environment along with the genetically fixed nutrient uptake potential and nutrient availability of soil controlled the status (Van den Driessche 1974). Other studies suggested that for the assessment of forest trees nutrient status, foliar analysis was better than those of the branch wood and stem analysis because in these cases high variability are observed (Drechsel and Zech 1991; Mengel and Kirby 2001). Data obtained on accumulation of nutrients in leaves of different plant species from various areas are more useful for the comparison of nutrient status of different species from different areas (Vitousek and Sanford 1986).

Nutrient deficiency have resulted in the limitation of early growth of different plant species growing in the mangrove forest that underscores the necessary of mineral nutrients study (Nussbaum *et al.* 1995) of mangrove species such as *S. apetala*. In the coastal afforestation program in newly accreted chars (sand bars) along the coast of Bangladesh *Sonneratia apetala* Buch.-Ham (Sonneratiaceae) is the most successful plant and is also a common tree plant in the Sundarban Mangrove Forests (SMF).

1.9 Growth of *Sonneratia apetala*

Plants growth and productivity directly linked with its mineral nutrient status. Different factors of the environment, soil nutrient availability and genetically fixed nutrient uptake potential controlled the nutrient status (Van den Driessche 1974). A fundamental and universal process of life on the earth is growth. In plant science and other branches such as production biology that may include agriculture, fishery and forestry among the many more, plant growth analysis and modeling are of particular concern (Pommerening and Muszta 2015). In comparative studies of plant growth performance, the relative growth concept of plant using analysis and modeling relative plant growth to size are considered as powerful tool and have long been used in plant science (Evans 1972). In the early stage of the 20th century the concept was first developed and is considered as the British school of thought for plant growth analysis specially at the Sheffield

University (Hunt 1982). Gillner *et al*. (2013) has suggested that plant mortality is closely related to this concept that indicated that for a long period of time low relative growth rates may be considered as a good indicator of imminent death. Gayon (2000) stated that for quantifying and modeling allometric relationships in plant relative growth analysis, relative growth rate is a pre-requisites. Pommerening and Muszta (2015) have observed that as in practice it is not possible to measure instantaneous growth rate, it is rather suitable to study the differences between interested growth characteristics at discrete points in time such as t1, t2,…, tn that may be taken as scheduled survey years.

1.10 Adaptation of *Sonneratia apetala*

A critical and detail evaluation is needed to understand the mechanism of adaption found in the salt tolerant plants specially for the plants of riverine shore with intertidal environment which are regarded as more complex ecosystem. Although salinity may significantly regulate the distribution of mangroves, the scientists are in different opinion to consider mangrove as facultative or obligate halophytes (Nascar and Palit 2015). Salt water is the physiological requirement for the survival of the mangroves with the variation in the tide in estuarine system (Chatterjee *et al*. 2013) may immensely be responsible for enriching the knowledge of salt adaptation mechanisms and mangrove species distribution (Lewis 2005). Longer duration tidal inundation is frequent at low elevation (Pennings *et al*. 2005) whereas tidal inundations are less frequent in the higher elevation zone. This often leads to soil drying between tidal cycles and a consequent increase in soil salinity. Such salinity gradients have been shown to influence species distribution and also the morphology of the plants (Maricle *et al.* 2009). Highly saline tolerant non mangrove grasses e.g. *Spartina* sp. (Lewis 2005), *Myriostachya* sp. (Rasid and Ahmed 2011) and *Porteresia* sp. (Naskar 2014) have great role as nursery for the establishment of different seedlings of mangrove species, like *Sonneratia* and *Avicennia* spp. (Nascar and Palit 2015).

Few studies have focused on the linkage between anatomy and micromorphology of various parts of mangrove plants such as leaves stems and roots of the plants that have adapted to higher salinity and light intensity environments (Gielwanowska *et al*. 2005). The mangroves with uniform leaf shape and texture resulted in the dull, uninspiring and unchanging aspect that are exhibited by the mangal along with the evergreen habit (Tomlinson 1986). Although there are some resemblances, leaf morphology and anatomy showed clear systematic difference especially in case of epidermal organization (Ellis 1986). Maricle *et al*. (2009) observed in mangroves environmental tolerance extended to a large degree of variability suggested the study of adaptation of closely related species is an ideal system. For the tolerance of salinity the presence of large vacuolar space is one of the mechanisms for storage of salts (Munns and Tester 2008). Leaf anatomical and stomatal features are influenced by the salinity induced stresses to a greater degree rather than phylogenetic relationships (Baumel *et al*. 2002). That resulted in the development of salt secreting glands that helps in reducing internal salt concentration. Relatively smaller leaves with lesser stomata in an unit area, higher degree of succulence along with the thick leaf cuticle helps in conserving water that resulted in sustained plant growth in salty habitats (Dickison 2000). Fewer developments of bundle sheath fibers along with absences of the extensions of bundle sheath are responsible for the firm but pliable texture of mangrove leaves (Tomlinson 1986). Enlarged terminal tracheids found in all common mangrove genera are the characteristic features except some species of *Bruguiera* (Zimmermann 1983).

In aquatic ecosystems, the plant growth and productivity is limited by several environmental factors, among them salinity is one of the major factors. Seasonal variation is found in salinity in the coastal water bodies and the factors influencing the changes in salinity include water levels, precipitation, evaporation (Schallenberg *et al*. 2003), hydrological alterations (Howard and Mendelssohn, 1999) and anthropogenic activities (Roache *et al.* 2006). Different morphological, physiological and biochemical changes have been observed in plant bodies when they are exposed to salinity that might be due to excess of ions and deficit in water (Greenway and Munns 1980; Maskri *et al*. 2010). Plant productivity (Doganlar *et al*. 2010; Hasegawa *et al*. 2000), and other changes such as nutrient imbalances (Ashraf 2009), accumulation of different osmoprotective compounds, such as proline (Bohnert *et al*. 1995) took place due to high salinity concentration in plant cells.

Increased temperature in the future due to the global climate change has intensified soil salinity that indicated that it is very urgent to identify plants that could tolerate salinity (Nascar and Palit 2015). Plants have to develop sophisticated mechanisms that help to survive in undesirable environment as they can’t move. Several compatible solutes namely polyols, betaine, trehalsose, ectoine, proline etc. have been found to accumulate in plants under salt stress conditions (Hasegawa 2000). Proline is one of the most common osmolyte for osmoprotection and research has been done extensively researched on these (Huang *et al.* 2013).

Although information on the physical-chemical properties of coastal water, soil quality of mangrove wetlands, nutrient dynamics of mangrove species, growth and adaptation of these species have been studied throughout the world in scattered way, there is no comprehensive survey to determine organic productivity and the oceanographic features of the Bay of Bengal and its estuary especially at Rangabali coastal area of Patuakhali district of Bangladesh. Consequently, a lack of basic information is found, although some fragmentary data is available due to some studies of the shelf area and deeper part of the bay focusing on the primary productivity that owe to the Indian Ocean Expedition (Islam 2007; Krey 1976; Wyritki 1971) that started in the 1880s. Some reports are available also on the physical and chemical properties of the soils collected from various offshore islands and from the mainland (Hasan 1987; Chaudhuri and Chaudhuri 1994; Karim 1994; Khan *et al.* 1998). The management and utilization of the coastal resources of Bangladesh is limited although it has been exploited since long without understanding the basic functional ecological systems that is a prerequisite for the sustainable resource management (Islam 2007). The protection and maintenance of estuaries and their habitat is paramount in of all good ecological and environmental status. The protection and maintenance requires in depth knowledge of ecosystem functioning (Ducrotoy and Elliott 2006). Although monitoring and descriptive studies of communities and ecological relationships are regarded as basic science, such descriptions are fundamental in order to quantify ecosystem degradation as a result of human activities (Olenin and Ducrotoy 2006).

Therefore, the present study focused to fill the gaps of knowledge in relation to:

1. Dynamics of vegetation cover and landscape of the coastal area at Rangabali, Patuakhali through satellite images and GIS, spatio-temporal dynamics of the water quality of the River Buragauranga estuary.
2. Spatio-temporal dynamics of physical and chemical properties of soils of different islands (chars) as affected by different tidal regimes.
3. The pollution status of the chars using geoaccumulation index (I*geo*), contamination factor (Cp) and enrichment factor (EF), ecological risk factors (ERF) and index (ERI).

4. Spatio-temporal dynamics of foliar nutrients and metals of a mangrove species namely *Sonneratia apetala* Buch. Ham. growing in these chars and bioaccumulation of different metals in this species.
5. Growth analysis of *S. apetala* and their adaptation to different conditions.

2. Materials and Methods

As the coastal zones are regarded as zone of mixing and triple conjunction of air, water and soil takes place there, a holistic approach was made to study the ecology of the coastal zone of Bangladesh at Rangabali Upazilla of Patuakhali District. For this reason, water, soil samples along with the available satellite images were collected in different years to detect the spatio-temporal variations of the area and growth parameters of *Sonneratia apetala* Buch.-Ham were studied.

2.1. Geomorphology of the coastal region of Bangladesh

Bangladesh, situated in the north eastern part of the South Asia**,** is surrounded by India in west, north and east and it has a small border with Myanmar on the south-east corner. The Bay of Bengal is situated at the south of the country. The Himalaya is situated at the north of the country. The two contrasting settings result in dramatic weather conditions characterized by the floods, droughts, monsoons, cyclones, and storm surges. Bangladesh is very flat with low topography deltaic plain formed by the three mighty rivers – the Ganges, the Brahmaputra and the Meghna (GBM) that together form one of the largest river systems in the world. Huge amount of water and sediments are carried by these rivers to the Bay of Bengal**,** where the conditions of the Bay leads in the dynamic actions that resulted coastal erosion, land accretions and other activities (Ali 1999).

The coastline of the country is about 710 km long (latitude 21^{o}-23^{o} N and longitude 89^{o}-93^{o} E) (Siddiqi 2001) with several ecosystems of conservation values such as estuaries, coral islands, beaches, islands and mangroves that supports habitat for numerous plant as well as fish and wildlife. The area are extended along the Bay of Bengal from the mouth of the river Raimangal in the west to the mouth of the river Teknaf (Siddiqi 2001) which include the greater districts of Chittagong, Noakhali, Barishal and Patuakhali and estuaries and islands (sand bars or chars) near the mainland. These coastal areas could be divided into 3 distinct regions: the western, central and eastern coastal zones (Ali 1999) (Fig. 2.1). The western part is characterized by numerous criss-crossed channels and creeks, low and flat topography and comprised mainly of semi-active delta. This zone is also known as Ganges tidal plain where Sundarban mangrove forests (SMF) is situated. A submarine canyon called “Swatch of No Ground” is present at 25 km south of the western coastline. The enormous discharged by the three mighty GBM rivers featured the central zone that resulted in continuous accretion and erosion making the central zone most active of the 3 zones (Ali 1999). Tropical cyclones and storm surges lashes this area and the area is very vulnerable to such calamities. The eastern coastal zone is featured by the presence of sea beach, coral islands, hilly cover and is the most stable coastal zone (Ali 1999).

2.2. Climate

Tropical maritime climate prevails in the coastal zones of Bangladesh (Hossain 2001). The mean temperature in the coastal areas varies between 19°C in winter and 29°C in summer. The amount of rainfall varies from about 3,000 mm in the west, down to 2,300 mm in the centre and as high as 4,000 mm in the east. Heavy rainfall occurs in the months of July to September during the monsoon when precipitation amount to about 80% of the total annual rainfall (Siddiqi 2001). Mean monthly average temperature of this district ranged from 17.1 ºC (January) to 30.0 ºC (May) (Source: Meteorology Department). Total monthly rainfall varied from 0 mm to 1084 mm where minimum total rainfall are recorded in different months between December to March and maximum total rainfall are recorded in June. Average monthly humidity values ranged between 71% and 92%. The

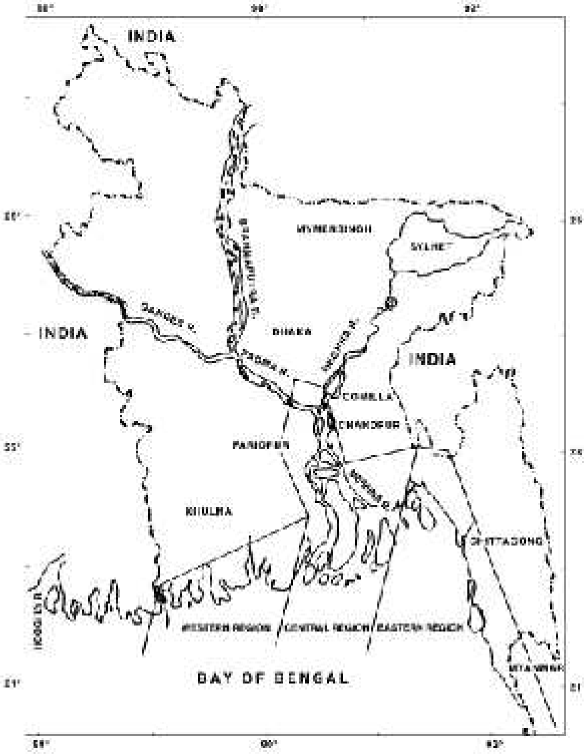


Fig. 1. Map of Bangladesh showing coastal area and the major river system

(Source: Ali 1999)

minimum value is usually recorded during the month of February, and maximum values are found in June and August. Data were collected from the Climate division, Bangladesh Meteorological Department, Government of the Peoples Republic of Bangladesh.

2.3. Sample Collection

A segment of the coast was studied at the Rangabali Upazilla (sub-district) of Patuakhali District (21°53'10"-22°0'0" N and 90°27'0"-90°30'30" E) to get a view of the ecological conditions of the estuary and coastal zone of Bangladesh.

Available thematic mapper (TM) (from 1989 to 2010) and enhanced thematic mapper (ETM) (2017) satellite images for the Rangabali coastal zone at Patuakhali district, collected from the Bangladesh Space Research and Remote Sensing Organization (SPARRSO) and glovis.usgs.gov, have been used to show the dynamics of the river bed and vegetation cover of the study area. Methodologies used for processing images are depicted in flow chart (Fig. 2.2).

In the landscape of Bangladesh, rivers are prominent and important feature and in their courses they are known by different names. The Ganges-Brahmaputra-Meghna (GBM) rivers in its course are also known in different names. Near the coastal zone, one of the branches is known as river Buragauranga in Rangabali Upazilla, Patuakhali district. Water samples (500 ml) were collected from the river Buragauranga from 3 locations at a stretch of about 8 km (Fig. 2.3). Water samples were collected in 4 replicates from each location. Samples were collected

45 to 60 cm depth from the surface with the help of water sampler and brought to the surface with minimum disturbances (Ashfaque 2004; Lakshminarayana 1965).

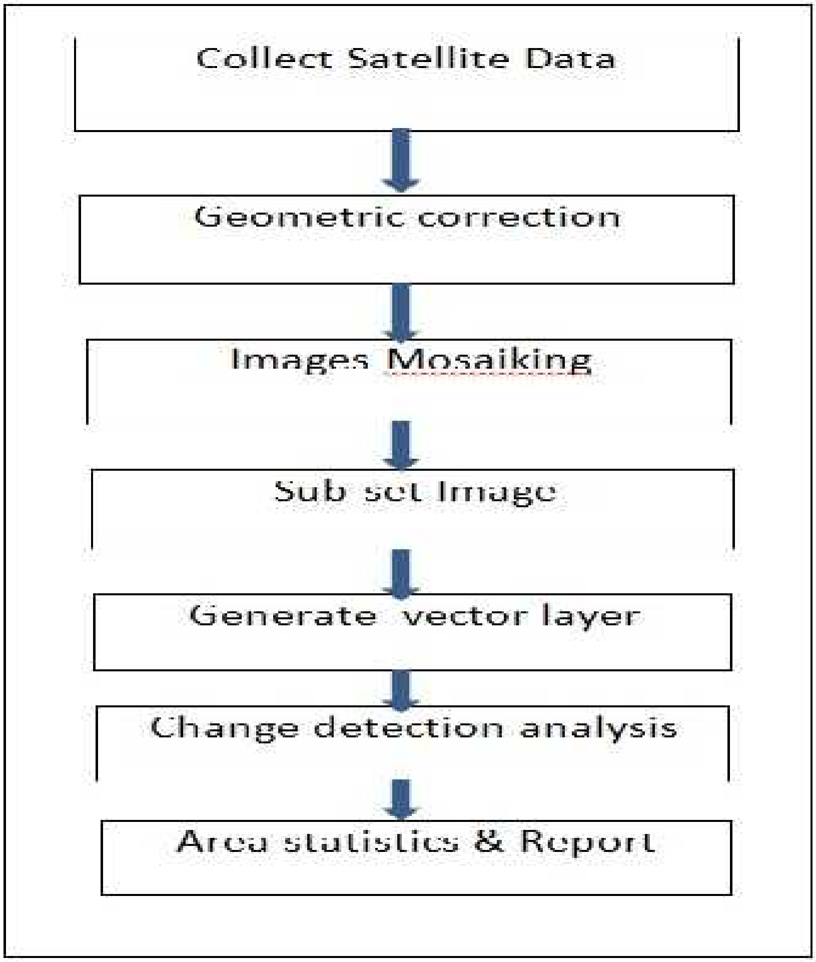


Fig. 2.2. Flow chart of methodology used for processing images

For water samples collection three locations were selected namely Location 1: across the Buragaurana River near Char Motherbunia; Location 2: east of Char Taposhi and Location 3: between the Char Taposhi and Char Kashem. Water samples were collected eight times during 16 December 2003 (high tide, HT), 10

February 2005 (HT), 22 May 2005 (low tides, LT and HT), 21 February 2008 (LT), 22 May 2009 (LT and HT), 27 December 2010 (HT), 23 December 2016 (LT) and 4 May 2017 (HT). Four replicates of water samples were collected from each location from a depth of about 60 cm.

2.4 Analytical methods

2.4.1 Water samples

The following variables of water were studied with standard methods:

2.4.1.1. Water temperature

Water temperature was recorded 10 cm below the surface with a centigrade thermometer during the time of collection.

2.4.1.2. Air temperature

Air temperature was recorded at breast height with a centigrade thermometer during field visits.

2.4.1.3. Humidity

Humidity was recorded with the help of hygrometer.

2.4.1.4. Water pH

The pH (HANNA pH meter, pHeP), conductivity (Aqua Lytic CD 22), salinity (Hand Refractometer, S/Mill, Salinity 0-100‰) dissolved oxygen (DO) (titration method till 2009 and with EcoSense DO 2000A meter afterward), and free CO_2 (Titration method APHA 1975) of the water samples were measured immediately after collection.

2.4.1.5. Different variables of water

The BOD_5, temporary, permanent and total hardness (EDTA) and filtrable, non-filtrable, and total residues were determined according to standard methods (APHA 1975).

2.4.1.6. Metals present in water

Sodium and K contents were determined by flame photometer and Ca, Mg, Mn, Fe, Zn and Pb by atomic absorption spectrophotometer from 2010 to 2017.

2.4.2 Soil samples

Soil samples were collected from a segment of the coastal zone of Bangladesh at the Rangabali Upazilla of Patuakhali district. Soil samples were collected on 22 May 2009, 27 December 2010, 23 December 2016 and 4 May 2017 from three different islands (chars) with different hydrological regime. Three chars namely Char Motherbunia (latitude 21º56'48" - 21º58'24"N and longitude 90º28'48" - 90º29'E), Char Taposi (latitude 21º52' - 21º54'18" N and longitude 90º29' - 90º30'48"E) and Char Kashem (latitude 21º52' - 21º54'18"N and longitude 90º25' - 90º27'48"E), were selected from the central coastal zone of Bangladesh (Fig. 2.1). Soil samples were collected from five points from each char. The distance between two sampling points was about 200 m.

2.4.2.1 Soil pH

Soil pH was determined by using 10 g fresh soil to 25 ml distilled water with a ratio of 1 : 2.5 with the help of a pH meter (Hanna pHeP).

2.4.2.2 Soil conductivity

Twenty gram fresh soil was leached with 100 ml deionized distilled water maintaining 1 : 5 ratios and the conductivity of the leachate was measured by electrical conductivity meter (Aqualitic 22). The values were multiplied by 5.

2.4.2.3 Water soluble sodium and potassium

Leachate prepared for conductivity measurement was used to determine water soluble Na and K by flame photometer (Jenkin, UK).

2.4.2.4 Total and available nitrogen

Total and available N of the soil was determined by the modified Kjeldahl method as described by Jackson (1973).

2.4.2.5 Organic carbon and matter

Organic C (%) was determined wet oxidation method (Walkley and Black 1934). Organic matter content was calculated from the organic carbon value by multiplying with a factor 1.724.

2.4.2.6 Total phosphorus and metals

One gram air dried soil sample was digested with nitric acid-perchloric acid mixture (2:1) (Piper 1950). Total Phosphorus content of the digest was determined by vanadomolybdophosphoric yellow colour method in nitric acid system as described by Jackson (1973). Total calcium, Mg, Mn, Fe, Zn and Pb as ions were determined by atomic absorption spectrophotometer.

2.4.2.7 Enrichment factor

According to Aprile and Bouvy (2008) the enrichment factor (EF) for metal concentration was calculated as:

$$EF = \frac{X/Fe\ (\text{sediment})}{X/Fe\ (\text{Earth's crust})}$$

where, X is the metal studied and X/Fe is the ratio of the concentration of element X to iron.

Iron was chosen as the element of normalization also because of natural sources (98%) vastly dominates its input (Kamau 2002). For background concentration of metals, the average shale values for different metals were used for Pb = 20 mg/kg, Mn = 850 mg/kg, Fe = 50,000 mg/kg and Zn = 95 mg/kg (Turekian and Wedepohl 1961).

2.4.2.8 Geoaccumulation index

According to Abrahim and Parker (2008) the geoaccumulation index (I_{geo}) for metal concentration was calculated as:

$$I_{geo} = \log \frac{\text{Sediment}}{1.5\ \text{reference sample}}$$

The factor 1.5 was introduced to minimize the effect of possible variations in the background values which might be attributed to lithologic variations in the sediments (Alhaidarey *et al. 2010).* For background concentration of metals, the average shale values for different metals were used for Pb = 20 mg/kg, Mn = 850 mg/kg, Fe = 50,000 mg/kg and Zn = 95 mg/kg (Turekian and Wedepohl 1961).

2.4.2.9 Contamination factor

An estimate of the amount of metallic elements detectable from sediment analysis was obtained by using the potential contamination factor (Cp) demonstrated by Davaulter and Rognerud (2001). The potential contamination factor could be calculated by the following method (Aprile and Bouvy 2008):

$$Cp = (\text{Metal})\ \text{max}/(\text{Metal})\ \text{Ba}$$

where (Metal) max is the maximum concentration of a metal in sediment, and (Metal) Ba is the average value of the same metal in a background level.

For background concentration of metals, the average shale values for different metals are used for Pb = 20 mg/kg, Mn = 850 mg/kg, Fe = 50,000 mg/kg and Zn = 95 mg/kg (Turekian and Wedepohl 1961).

2.4.2.10 Ecological risk factor and index

Hakanson (1980) proposed a method to assess the potential ecological risk for areas under special interest. According to this method, the potential ecological risk factor (E^i_r) of a single element can be assessed with a formula incorporating the toxic response of each metal as:

$$\text{Ecological risk factor } (E^i_r) = Ti \times Cp$$

where, Cp = contamination factor,

Ti = toxic response factor of i-th element which is as follows; Pb = 5, Zn = 1, and Mn = 1 (Hakanson 1980).

Ecological risk index (ERI) is the summation of the ecological risk factors

2.4.2.11 Determination of relative growth rate and anatomical and physiological features

According to Blackman (1919), Whitehead and Myerscough (1962) and Hunt (1982, 1990) periodic relative increment or mean relative growth rate, pk, over a time period Δt is the difference of the logarithms of y_k and y_{k-1} divided by Δt, (Causton 1977).

$$pk = \frac{\log y_k - \log y_{k-1}}{t_k - t_{k-1}}$$

$$= \frac{\log y_k - \log y_{k-1}}{\Delta t}$$

$$= \frac{\log (y_k / y_{k-1})}{\Delta t}$$

2.4.3 Foliar nutrient analysis

Different mangrove species were planted in the coastal areas where *Sonneratia apetala* proved to be the most successful which alone constitutes about 94.5% of the total existing mangrove plantations (Siddiqi 2001). The leaves of *S. apetala* were collected from the above mentioned chars along the lines from where soil samples were collected. Plantation program started in the Char Motherbunia in 1983, whereas the plantation started in Char Kashem and in Char Taposhi in 1985 and 1988 respectively. Leaves were dried at 70º C in the heating cabinets immediately after arriving to the laboratory. The dried samples were finely ground (particles size less than 1mm) and stored at room temperature until analyses (Ogner *et al*. 2000).

2.4.4 Methods of extraction and determination of proline

According to the method describe by Bates *et al.* (1973), proline content in the leaves of *S. apetala* was estimated

2.4.4.1 Extraction of proline

One gram fresh leaf tissues of *S. apetala* were taken in clean mortar and were homogenized in 10 ml of 3% (w/v) aqueous sulphosalicylic acid using a clean glass mortar and pestle. The homogenate was transferred to centrifuge tubes and centrifuged for 15 minutes at 9500 rpm, and the supernatant was collected and estimation of proline was done using acid ninhydrin.

2.4.4.2 Preparation of acid ninhydrin

By dissolving 1.25 g of Ninhydrin in a mixture of 30 ml of glacial acetic acid and 20 ml of 6 M orthophosphoricacid, acid Ninhydrin was prepared.

2.4.4.3 Preparation of standard proline solution

A stock of 100 mM proline was used to dispense proline content in range of 0-20 µM proline.

2.4.4.4 Determination of proline

From the supernatant 2 ml was taken in test tubes and equal volumes of glacial acetic acid and acid ninhydrin were added to it. The tubes were then heated in a bath of boiling water for an hour and then the reaction was terminated by placing the tubes in an ice bath. For colour development 4 ml of toluene was added to the reaction mixture and stirred well for 20-30 seconds. Then the toluene layer was separated carefully and brought to room temperature. The colour intensity of the solution was measured at a wave length of 520 nm. L-Proline was used as the standard.

Proline µg FW tissue = c . f s . c × 0.115× v . o f e. / F of t

2.4.5 Method to analyze anatomical adaptation of *S. apetala*

To study internal structures of leaves of *S. apetala*, transverse section of the leave samples form three different chars were done. Fresh leaf materials were collected for the study of the anatomical adaptation and internal structures of the plant. Free hand sectioning of leaf was done with the help of a razor blade. The sections were then dipped and stained with safranin and mounted in 20% glycerin. Transverse sections were studied at different magnification under a compound light microscope (Carl Zeiss Lab A1 microscope) fitted with digital camera (AxiocamERc 5s). Photomicrographs were taken from various regions of the sections using different magnifications through Axio Vision Release 4.8.2 software.

2. 5 Statistical analysis

Different variables of water, soil and plant samples were each subjected to analysis of variation (ANOVA). Island and location were used as factors. To compare soil samples among the islands and locations and for the three locations of the river Buragauranga, ANOVA was performed using general linear model procedures in SAS 9.1 program. Interactions between islands and locations were also tested for soil samples and between locations and samples for water samples. Differences in concentrations of some of the elements of plant samples were tested with one-way ANOVA using islands as factor by Minitab 14 software. The Tukey multiple comparison test was used to test for pair wise differences between islands at a significant level of 0.05 using Minitab 14 software.

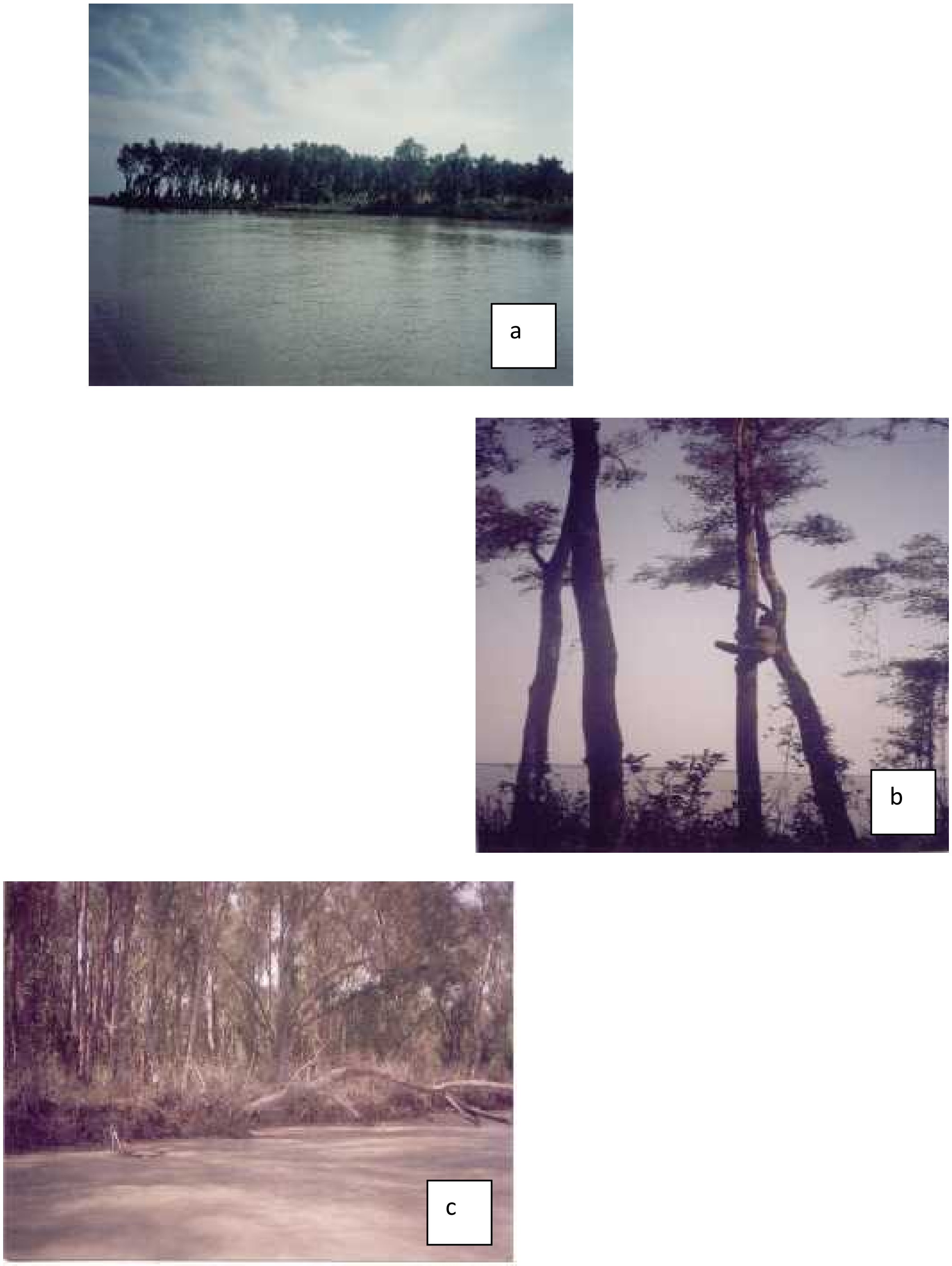


Fig 2.4. Photos showing the different studied islands. (a) Char Taposhi with the *Sonneratia apetala* plantation, (b) leaves samples collection from the plant in Char Kashem and (c) erosion destructing lands as well as plants in Char Taposhi.

3.1 Dynamics of the study area

Coastal regions are very important, as they are the most intensely used areas settled by humans. The regions have been under intensive pressure throughout history and the situation is likely to continue in the future. Beside this, in the coastal area erosion and accretion are common phenomena since it is dynamic in nature. The present studied area situated in Rangabali upozila is also very dynamic as the large volumes of sediments are deposited here by three great river systems Ganges-Brahmaputra-Meghna (GBM) (Fig. 3.1.a – 3.1.g). Erosion and accretion rates are very high along the coast of Rangabali. Although all the three studied chars showed a decreasing tendency in land area from 1989 to 1991, there were fluctuations in land area changes afterward and different patterns were found in the three chars. The area of Char Motherbunia was gradually increasing from 3006.8 ha in 1991 to 8305.8 ha in 2017 (Fig. 3.1.h – 3.1.i, Table 3a and 3b). The mangrove forest covers also increased (there were no cover in 1991) to 5505.1 ha in 2017. Char Taposhi showed a fluctuating tendency i.e. area increased to 8614.9 ha in 1997 but decreased in 2001 and again the area increased in 2006 (6904.9 ha). After that, there was gradual decrease in area of the char (5923.9 ha). The mangrove vegetation covers also changed in a fluctuating manner. The land area of the Char Kashem showed a gradual decrease due to severe erosion. As a consequence the vegetation cover also decreased except in 2010 when there was slight increase. Ali *et al*. (2013) has studied the erosion-accretion pattern in Manpura Island, Bhola district, in coastal areas of Bangladesh over a 37 years period from 1973-2010 where they observed that the island is under the threat of erosion and the total area gradually decreased from 148 km^2 to 114 km^2 and the area of mangrove forests have also decreased to 6 km^2. Ahmed *et al*. (2011) reported the changes of mangrove vegetation, river and canals and land area of Sundarban Mangrove Forests (SMF) of Bangladesh for a period of 21 years which showed an increasing land mass of two Ranges for 1989 to 2000 which subsequently decreased in the next decade (2000 to 2010). Giri *et al.* (2007) reported an increase in the net forest area by 1.4% from the 1970s to 1990s and a decrease by 2.5% from 1990 to 2000 of the total SMF of both Bangladesh and India. Ahmed *et al*. (2018) in an another study of forest cover and land area changes of overall Bangladesh Sundarbans through satellite images and GIS techniques revealed that the forest and water area of SMF decreased gradually till 2015 in comparison to 1972. The bare land of Sundarbans showed a significantly increasing trend till 2015 since 1972. It is also clear from these studies that the coastal zone of Bangladesh especially the central and western parts are experiencing different fate. In some place land accretion exceeded the land erosion resulting in an increase of total land surface and in some areas; reverse situation was found that revealed a decrease in land surface and subsequently mangrove vegetation cover.

Table 3a. Dynamics of the landscape and vegetation cover (1989 to 2001)

Name of islands / chars	Years							
	1989		1991		1997		2001	
	Land area (ha)	Mangrove (ha)	Land area (ha)	Mangrove (ha)	Land area (ha)	Mangrove (ha)	Land area (ha)	Mangrove (ha)
Motherbunia	3178.1	NO	3006.8	NO	6266.8	2810.1	6887.9	3390.0
Char Taposi	5975.4	1524.6	2954.0	2142.6	8614.9	4800.2	6242.8	5040.5
Char Kashem	9624.8	6199.9	8117.8	5738.1	7935.5	5319.2	7536.0	5121.7

Table 3b. Dynamics of the landscape and vegetation cover (2006 to 2017)

Name of islands/ chars	2006		2010		2017	
	Land area (ha)	Mangrove (ha)	Land area (ha)	Mangrove (ha)	Land area (ha)	Mangrove (ha)
Motherbunia	7529.2	4592.8	7714.3	4946.4	8305.8	5505.1
Char Taposi	5495.4	4826.8	5361.2	4956..7	5494.7	4964.5
Char Kashem	6904.9	4782.7	6629.7	4830.1	5923.9	4459.5

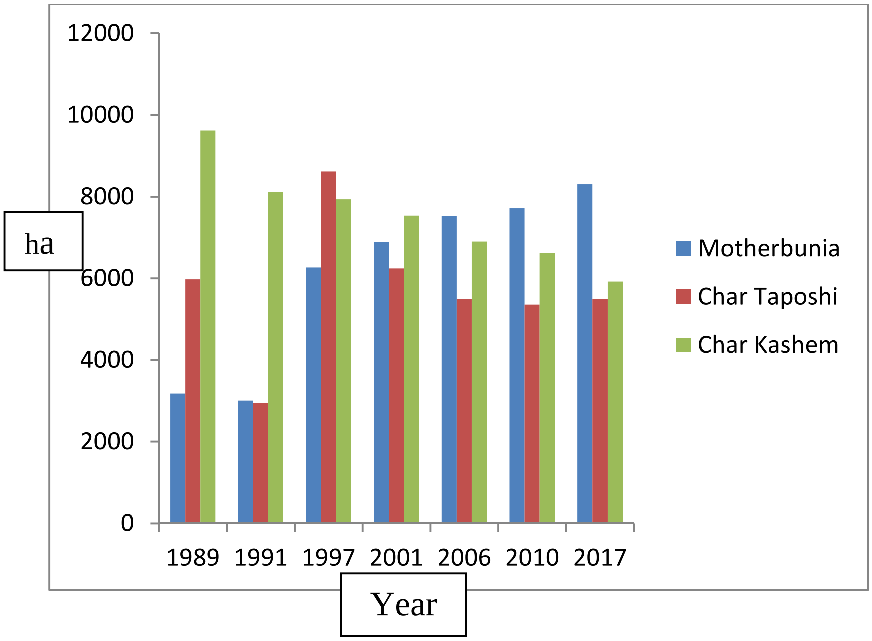


Fig 3.1.h. Changes of the land area (ha) of the studied areas

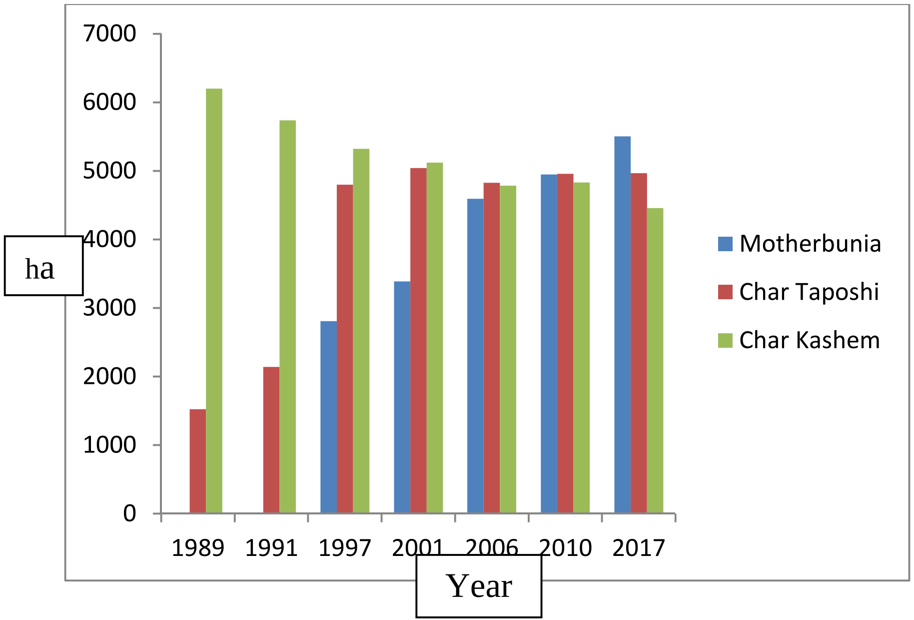


Fig 3.1.i. Changes of the vegetation cover (ha) of the studied areas

3.2 Spatio-temporal variation of water of Buragauranga river estuary

Water conditions can be monitored in many ways (EPA 2002). For water qualities monitoring generally focuses are given on the physical and chemical parameters and a few key biological parameters. There is no consensus on the class or complex set of variables that are responsible for characteristics of water quality in the estuary (Fatema *et al*. 2015). Different physical and chemical variables of water such as dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, suspended solids, pH, conductivity, salinity, temperature, nitrogen in the form of ammonia, turbidity, dissolved solids, total solids, nitrates, chloride, and phosphates are considered to represent water quality status by some authors (Iscen *et al*. 2008; Mustapha and Abdu 2012). Combining some of these physical and chemical parameters with the chlorophyll pigment contents, measurements have used to examine water quality status by others (Meera and Nandan 2010).

Two different water bodies are found to meet and mix in an estuary which is regarded as a partially enclosed body. Fresh water coming from rivers or streams mixes in an estuary with salt water coming from the ocean. Because of the dynamic mixing of these two contrasting fresh and salt water in the estuary estuarine water quality fluctuates naturally (NOAA 2016). Physical and chemical properties of water of the Buragauranga estuary, air temperature and relative humidity in the present study have also showed spatio-temporal variation. But no specific pattern of variation was observed. Air temperature of the study area varied from 26° C to 37° C during the study period. Relative humidity varied from 63 to 85. Water temperature varied from 22.5°C to 30.9 °C. Akter (2016) found that the temperature of water samples of different rivers flowing within Bangladesh Sundarbans varied from 27.6 to 30.8 °C in April 2015 and these were 28.8 to 31.0 °C in March 2016. Rahman *et al.* (2013) recorded water temperature between 19.9 °C and 31.0 °C in their study on Sundarban mangrove forests. Water temperature varied from 29.5 to 29.7 °C at surface of the Morbok estuary, Malaysia (Fatema *et al*. 2015) and they found that as the estuary was shallow in nature, water temperature is controlled by atmospheric temperature. Temperature has been considered as the most important factor to maintain the growth, reproduction, survival, and distribution of organisms in the physical environment (Langford 1990). Temperature also controls behavioral characteristics of organisms, solubility of gases and salts in water (Vincy *et al*. 2012).

3.2.1 Water pH

For the survival of most aquatic plants and animals the pH of water is critical. The changes in pH of water bodies were monitored frequently by researchers to improve our understanding of the water’s health (EPA 2006). Since pH is responsible for other chemical reactions such as solubility and metal toxicity, the pH of a water body is very important for the determination of water quality (Fakayode 2005). In the present study the water of Buragauranga river was neutral to alkaline in nature (Table 3.2.1a, Fig. 3.2.1). The observed lowest value was 7.08 and it was found during December 2003 (high tide) and the highest value of 8.80 was found during May 2017 (high tide). Carbonate and bicarbonate dissolved in the water are responsible for the slightly alkaline pH which is due to the natural buffering of these compounds (EPA 2006). Very little fluctuation was observed during each sampling occasion and the maximum coefficient of variation was observed to 3.91. Thasneem *et al.* (2018) also reported more or less uniform pH values in the Cochin estuary, India in their study. The sampling occasion and location wise pH values are shown in Fig. 3.2.1a, 3.2.1b and Table 3.2.1a, where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value during December 2003 (high tide) was 7.08, maximum value was 7.85 and the coefficient of variation was 2.79. The mean value was 7.62 ± 0.23. The minimum value during February 2005 (high tide) was 7.70, maximum value was 8.13 and the coefficient of variation was 2.03. The mean value was 7.95 ± 0.16. The minimum value during May 2005 (high tide) was 7.6, maximum value was 8.20 and the coefficient of variation was 2.06. The mean value was 7.83 ± 0.16. During these three sampling occasions at high tide condition, significant differences were observed among the three locations where location 2 and 3 (downstream) showed comparatively higher values than location 1 (upstream) (Fig. 3.2.1a). The minimum value during May 2005 (low tide) was

7.20; maximum value was 7.60 and the coefficient of variation was 1.84. The mean value was 7.45 ± 0.14. The minimum value during February 2008 (low tide) was 7.30, maximum Table 3.2.1a. Descriptive statistics of different variables of water of three different locations of Buraguaranga river Estuary, Rangabali, Patuakhali value was 7.60 and the coefficient of variation was 1.19. The mean

Table 3.2.1. Descriptive statistics of different variables of three different locations of Buragauranga river estuary, Rangabali, Patuakhali (HT stands for high tide, LT stands for low tide)

Variables of water						
a. pH						
Sampling time	Mean	StDev	CoefVar	Minimum	Median	Maximum
2003 Dec HT	7.62	0.23	2.79	7.08	7.69	7.85
2005 Feb HT	7.95	0.16	2.03	7.70	8.00	8.13
2005 May HT	7.83	0.16	2.06	7.60	7.80	8.20
2005 May LT	7.45	0.14	1.84	7.20	7.50	7.60
2008 Feb LT	7.44	0.09	1.19	7.30	7.41	7.60
2009May HT	7.37	0.22	2.97	7.10	7.35	7.70
2009May LT	7.42	0.19	2.56	7.10	7.45	7.70
2010Dec HT	7.43	0.17	2.32	7.10	7.45	7.70
2016 Dec LT	7.39	0.16	2.12	7.10	7.40	7.70
2017May HT	8.05	0.32	3.91	7.70	7.90	8.80
b. Conductivity mS/cm						
2003 Dec HT	2.87	1.84	64.17	0.59	2.94	5.09
2005 Feb HT	9.81	4.15	42.32	4.30	11.00	14.47
2005 May HT	12.12	6.24	51.50	1.62	15.35	17.70
2005 May LT	8.90	5.43	61.02	1.39	11.91	14.66
2008 Feb LT	7.41	4.14	55.92	1.68	10.08	10.55
2009May HT	4.58	2.72	59.40	0.90	5.74	7.54
2009May LT	4.76	2.49	52.42	1.47	5.28	7.91
2010Dec HT	3.19	2.29	71.65	0.55	2.98	6.45
2016 Dec LT	3.26	2.22	68.26	0.86	2.94	7.00
2017May HT	1.26	1.63	128.74	0.18	0.32	5.03
c. Salinity ‰						
2003 Dec HT	4.25	3.27	76.98	0.50	4.00	9.00
2005 Feb HT	7.08	2.06	29.16	4.00	7.50	10.00
2005 May HT	5.00	3.74	74.83	0.00	7.00	8.0

2005 May LT	3.08	2.50	81.18	0.00	4.00	7.00
2008 Feb LT	3.75	2.96	78.88	0.00	4.50	7.00
2009May HT	2.92	2.27	77.99	0.00	4.00	6.00
2009May LT	2.33	2.46	105.51	0.00	1.50	6.00
2010Dec HT	2.85	2.31	81.14	0.00	3.10	5.50
2016 Dec LT	2.04	2.00	98.21	0.00	1.75	5.50
2017May HT	0.21	0.49	239.09	0.00	0.00	1.50

value was 7.44 ± 0.09. Maximum and minimum values during May 2009 (high tide) were 7.10 and 7.70 respectively while co-efficient of variation was 2.97. The mean value was 7.37 ± 0.22. The minimum value during May 2009 (low tide) was 7.10, maximum value was 7.7 and the coefficient of variation was 2.56. The mean value was 7.42 ± 0.19. During these three sampling occasions at low tide condition, no significant differences were observed among the locations. ANOVA analysis showed that comparatively lower (at 0.05% level) pH values were observed during low tide condition (Fig. 3.2.1a). The minimum value during December 2010 (high tide) was 7.10, maximum value was 7.70 and the coefficient of variation was 2.32. The mean value was 7.43 ± 0.17. The minimum value during December 2016 (low tide) was 7.10, maximum value was 7.70 and the coefficient of variation was 2.12. The mean value was 7.39 ± 0.16. The pH values were higher in high tide condition in all sampling occasion. The minimum value during May 2017 (high tide) was 7.70, maximum value was 8.80 and the coefficient of variation was 3.91. The mean value was 8.05 ± 0.32.

Slight acidifications of the studied estuarine waters observed in all the three locations till 2016 which might be attributed to the rise in atmospheric CO_2 content due to climate changes. Islam (2011) found slightly alkaline (7.4 to 7.8) pH of the water in the Meghna estuary near Char Tamaruddin, Hatia, Noakhali. Akter (2016) reported that the pH of the different rivers of SMF of Bangladesh ranged from 6.6 – 7.8 in April 2015 and 6.3-7.5 in March 2016 in different

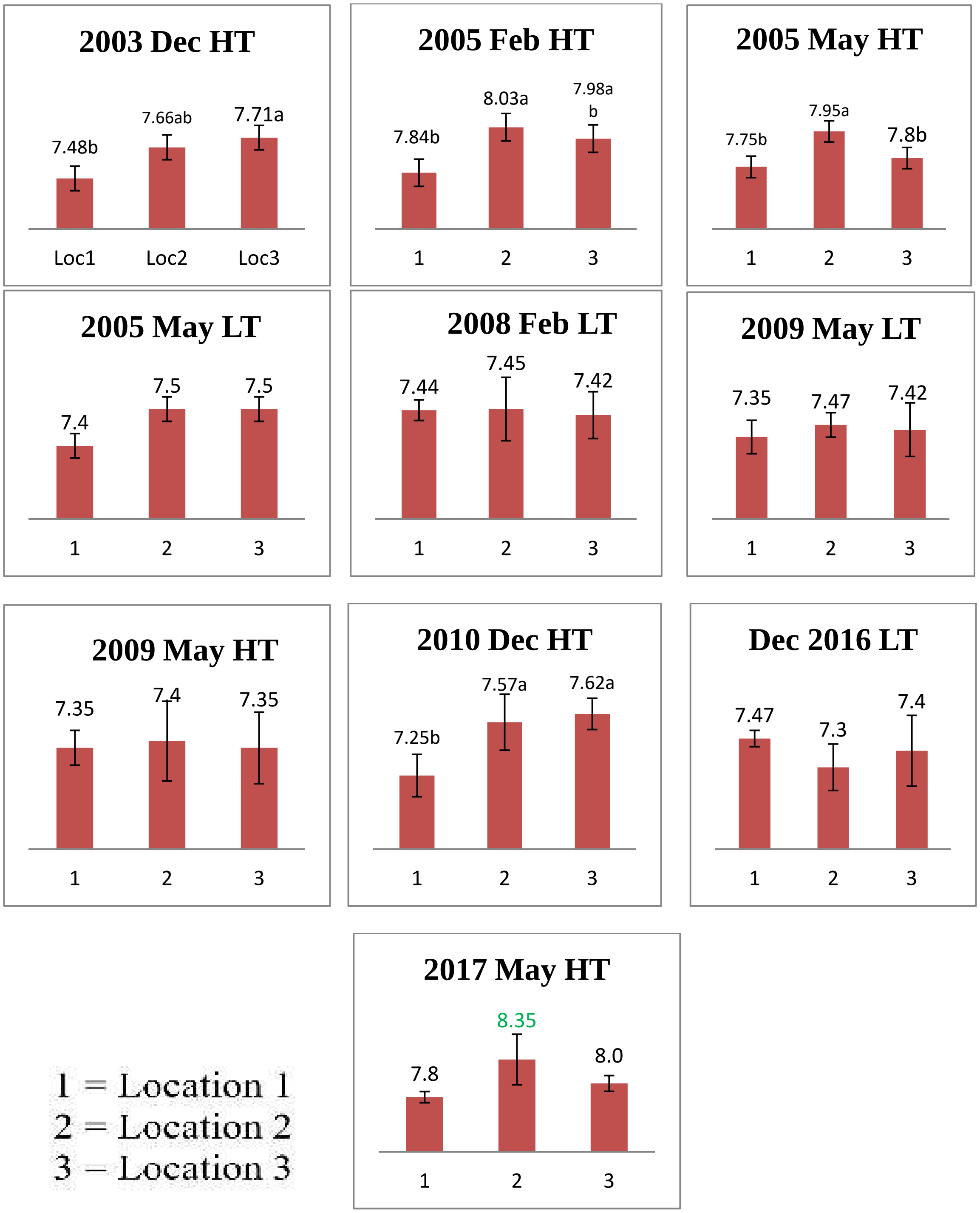


Fig. 3.2.1a: Spatio-temporal dynamics of the water pH of the three locations of Buragauranga river estuary during high tide (HT), and low tide (LT). Same letter over the top of bars or bars without any letter indicated that these locations do not vary significantly; different letters indicated that they vary significantly at 95% level.

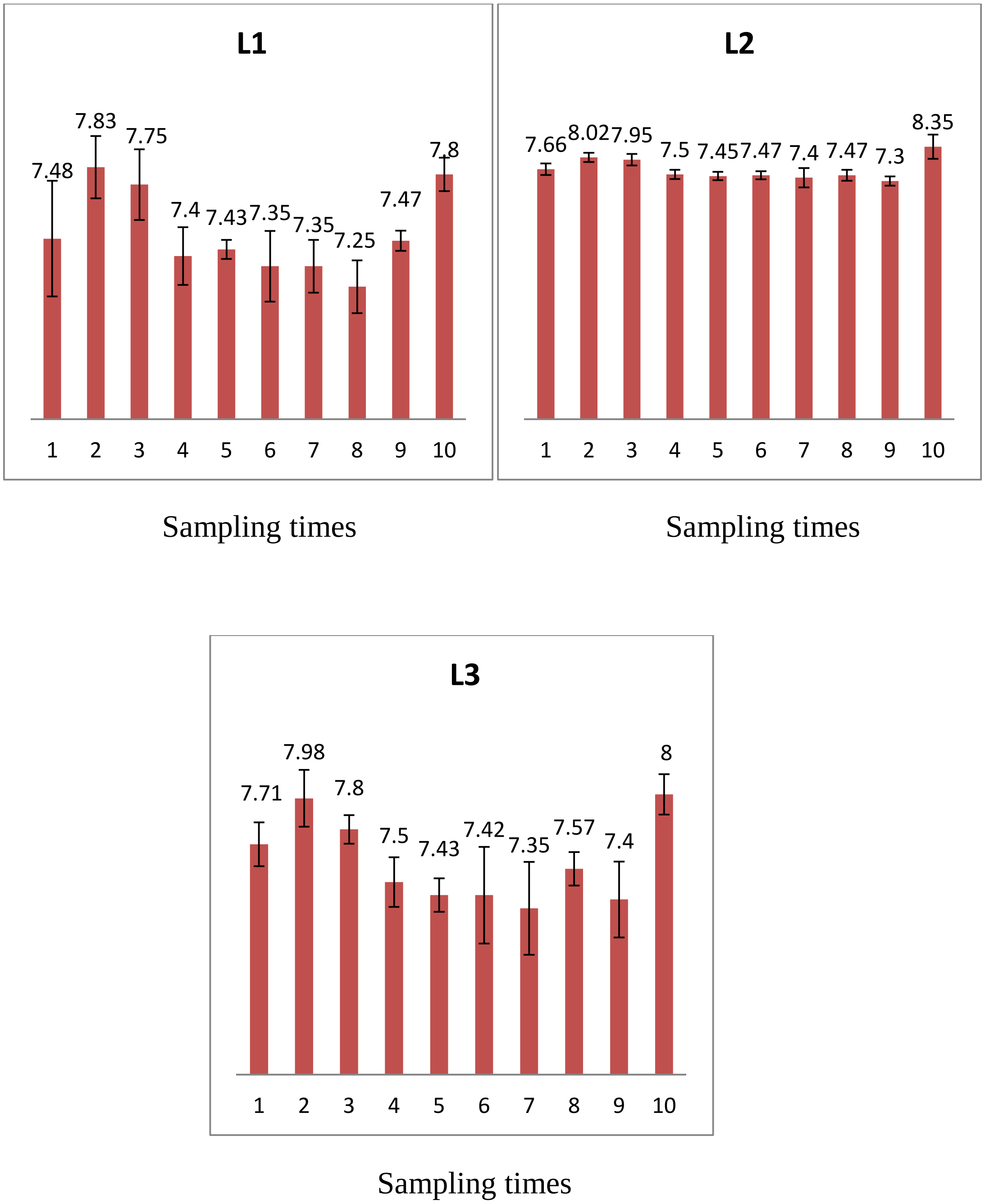


Fig. 3.2.1b: Location wise temporal variations of pH of Buragauranga river estuary
(L1 = Location 1, L2 = Location 2, L3= Location 3)

Sampling times:

1 = 16 December 2003 (high tide, HT), 2 = 10 February 2005 (HT), 3 and 4 = 22 May 2005 (low tides, HT and LT), 5 = 21 February 2008 (LT), 6 and 7 = 22 May

2009 (LT and HT), 8 = 27 December 2010 (HT), 9 = 23 December 2016 (LT) and 10 = 4 May 2017 (HT) tidal conditions. She also found slight acidification of river waters since 2010 (Aziz *et al*. 2012). It might also be due to the increase in CO_2 content in air due to global climate change. The pH of a water bodies changes daily, seasonal, and annual basis due to primary production (plant growth). The pH increases during photosynthesis during daylight hours, because carbon dioxide is removed from the water whereas an decrease in pH is observed during respiration at night that might be attributed to the fact that organisms release carbon dioxide that resulted in a decrease in pH when respiration is dominant. Similarly, pH is higher during the winter season when grazing by zooplankton is low compared to productivity.

In the coastal marine ecosystems a decrease in the pH occurs due to estuarine acidification. Decrease in the pH has become a common phenomenon due to the fact that carbon dioxide (CO_2) is observed from the atmosphere resulting ocean acidification (Caldeira and Wickett 2003). Decline in the pH of surface water of the ocean may be attributed to the increase in carbon dioxide as the 30-40% CO_2 emitted to the atmosphere are absorbed by the ocean (James *et al.* 2005). Almost similar pH (6.8 - 7.9) was found from the water Padma at Mawaghat, Munshiganj (Ashfaque 2004) and from the Manipur river system (Singh *et al.* 2010). Higher pH values were found than the present study in the Hoogly river (8.3 - 8.4) (Roy 1955), in the Padma near north western region of the Bangladesh (8.1) (Talukdar *et al*. 1994). The pH of the surface water of Merbok estuary, Malaysia was in the range of 6.90–7.34 (Fatema 2015). Shuhaimi-Othman *et al*. (2007) observed that pH varied from 5.72 to 7.38. The standard of pH ranged from 6.50 - 8.50 (WHO

1995). Some studies on Indian estuaries reported higher pH toward the downstream (Upadhyay 1988, Murugan and Ayyakkannu 1991). Water of the present studied estuary could be regarded as slightly alkaline and unpolluted (Fakayode 2005).

3.2.2 Conductivity

To measure total dissolved ions and total solids rapidly the measurement of conductivity of the medium is a good method. Higher is the value of total solids, greater is the amount of ions in water (Bhatt *et al.* 1999). The minimum value during the study period of the Buragauranga estuary was recorded during May 2017 (high tide) and maximum values were found during May 2005 (high tide) and values were found to be 0.18 and 17.7 mS/cm, respectively. The sampling occasion and location wise conductivity values are shown in Fig. 3.2.2a, 3.2.2b and Table 3.2.b where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value of conductivity during December 2003 (high tide) was 0.59 mS/cm, maximum value was 5.09 mS/cm and the coefficient of variation was 64.17. The mean value was 2.87 ± 1.84 mS/cm. Highest value was found at location 2 whereas lowest value was found at location 1 which showed the influence of fresh water on the value of conductivity. Location 1 was more away from the sea than those of location 2 and 3. The minimum value during February 2005 (high tide) was 4.30 mS/cm, maximum value was 14.47 mS/cm and the coefficient of variation was 42.32.

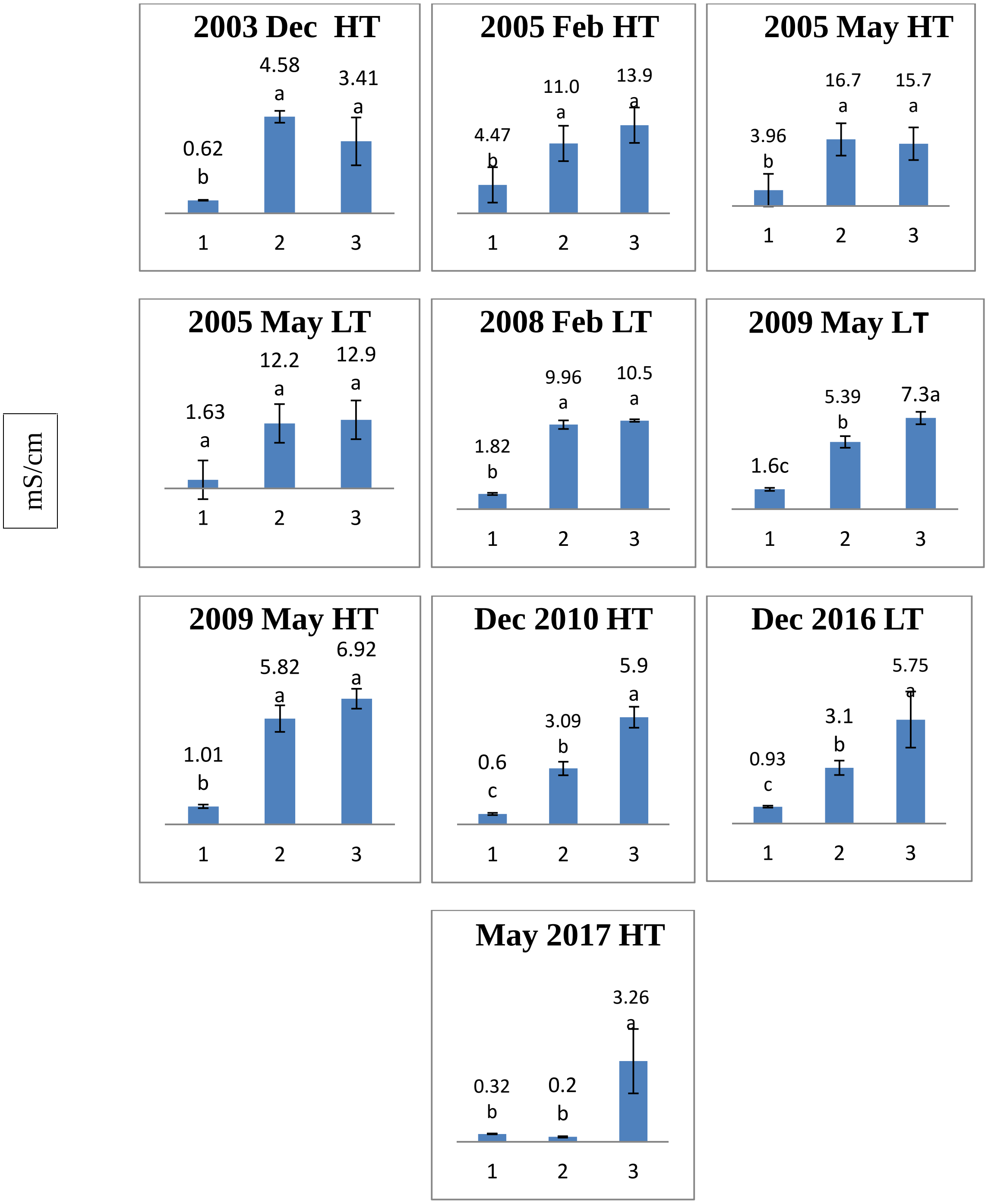


Fig. 3.2.2a: Spatio-temporal dynamics of the water conductivity (mS/cm) of the three locations of Buragauranga river estuary (1, 2 and 3; and LT and HT have been explained in Fig. 3.2.1a)

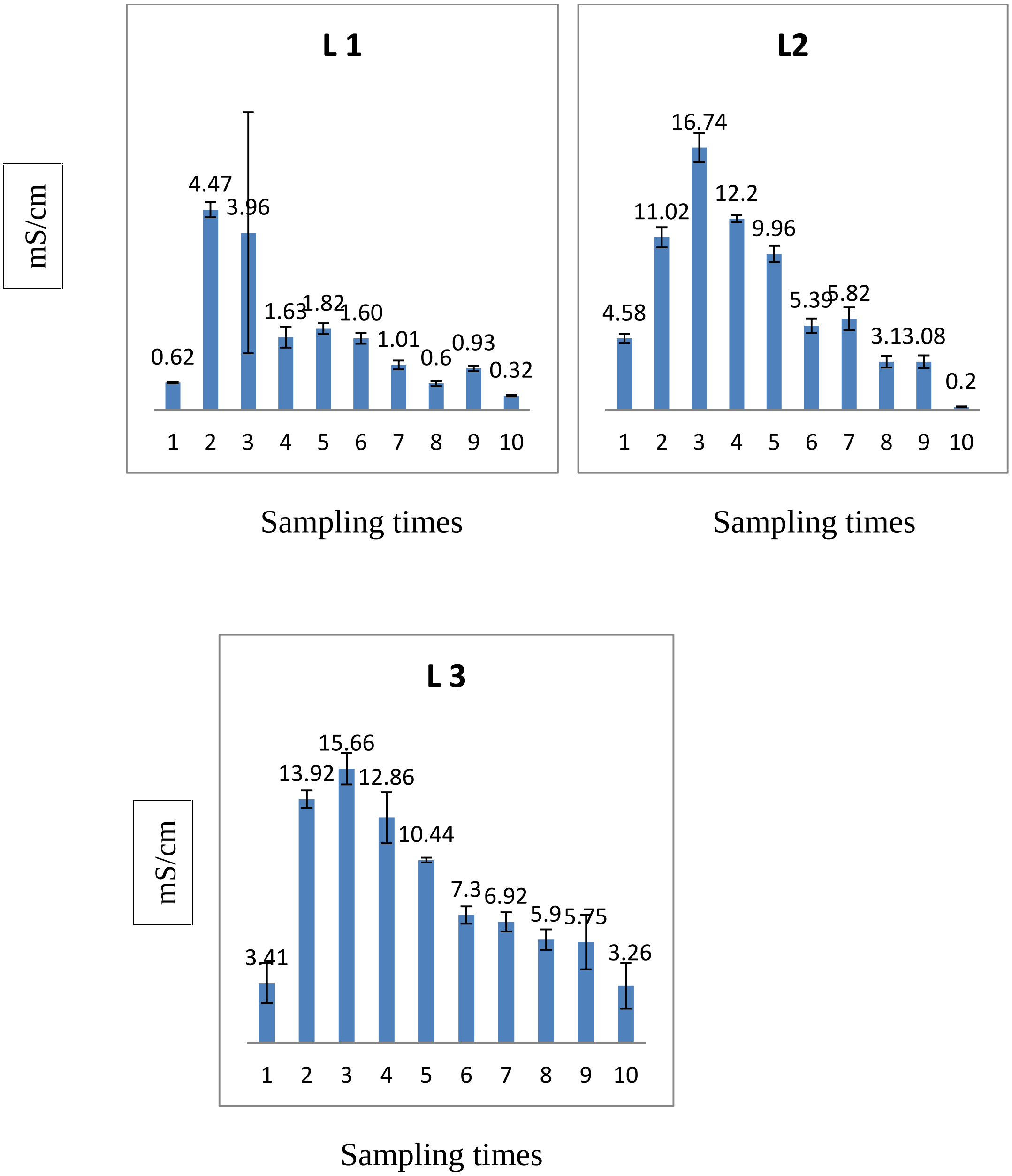


Fig. 3.2.2b: Location wise temporal variations of conductivity (mS/cm) of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

The mean value was 9.81 ± 4.15 mS/cm. The highest value was found in location 3 and the values decreased gradually at locations 2 and 1. The minimum value during May 2005 (high tide) was 1.62 mS/cm, maximum value was 17.70 mS/cm and the coefficient of variation was 51.50. The mean value was 12.12 ± 6.24 mS/cm. During this sampling occasion, the value of location 2 was comparatively higher than those of location 3 and 1. After this sampling occasion, highest values were found at location 3. The minimum value during May 2005 (low tide) was 1.39 mS/cm, maximum value was 14.66 mS/cm and the coefficient of variation was 61.02. The mean value was 8.90 ± 5.43 mS/cm. The minimum value during February 2008 (low tide) was 1.68 mS/cm, maximum value was 10.55 mS/cm and the coefficient of variation was 55.92. The mean value was 7.41 ± 4.14 mS/cm. The minimum value during May 2009 (high tide) was 0.90 mS/cm, maximum value was 7.54 mS/cm and the coefficient of variation was 59.40. The mean value was 4.58 ± 2.72 mS/cm. The minimum value during May 2009 (low tide) was 1.47 mS/cm, maximum value was 7.91 mS/cm and the coefficient of variation was 52.42. The mean value was 4.76 ± 2.49 mS/cm. The minimum value during December 2010 (high tide) was 0.55 mS/cm, maximum value was 6.45 mS/cm and the coefficient of variation was 71.65. The mean value was 3.19 ± 2.29 mS/cm. The minimum value during December 2016 (low tide) was 0.86 mS/cm, maximum value was 7.00 mS/cm and the coefficient of variation was 68.26. The mean value was 3.26 ± 2.22 mS/cm. Very low conductivity was found during May 2017 especially in location 1. This might be due to sudden flash flood at upstream of Meghna River in late March which resulted into fresher water supply in the downstream. It reduced the influences of sea water in the area. The minimum value during this time (high tide) was 0.18 mS/cm, maximum value was 5.03 mS/cm and the coefficient of variation was 128.74, that indicated that there were very high variations in conductivity. The mean value was 1.26 ± 1.63 mS/cm.

Akter (2016) found the conductivity of water samples at different rivers of SMF varied from 8.00 to 32.30 mS/cm in April 2015 and from 9.48 to 31.6 mS/cm in March 2016. Islam (2011) found the minimum conductivity value of 5.15 mS/cm and maximum conductivity was 9.95 mS/cm in the Meghna estuary. Aziz *et al.* (2012) found the minimum conductivity to be 14 mS/cm and maximum conductivity was 40.3 mS/cm where mean value was 26.664 ± 7.375 mS/cm in the different rivers of SMF. Ashfaque (2004) reported 106.0 - 2009.0 µS/cm conductivity in his study of river Padma. Patra and Azadi (1987) reported 94.18 µS/cm conductivity in the river Halda. Singh *et al.* (2010) reported 65 - 467 µS/cm in the river Manipur, India. Conductivity of the present study (0.180 - 17.70 mS/cm) was more than recommended value (750 µS/cm or 0.750 mS/cm) as given by WHO (1995) and hence water might not be safe to use for domestic and agricultural purposes in regards to conductivity.

3.2.3 Salinity

One of the major limiting factors in distribution of living organisms is salinity and flora and fauna living in the intertidal zone is most likely are influenced by the variation in salinity level due to dilution (Gibson 1982). Higher variations in salinity were observed in the study area during the studied period. The minimum value during the study period of the Buragauranga estuary was recorded during several occasions in both low and high tide conditions and maximum values were found during February 2005 (high tide) and values were 0.0 and 10.0 ‰ respectively. The sampling occasion wise and location wise salinity values are shown in Fig. 3.2.3a, 3.2.3b and Table 3.2.c where the mean, minimum and maximum values along with the coefficient of variation are also shown. The lowest values were observed at the location 1 (upstream) and values gradually increase towards downstream (location 2 and 3). The pattern was the same in all sampling occasions except February 2008 when sampling during low tide showed highest value at location 2. Significant differences (at 95% level) were observed among the locations especially between location 1 and 2, and between location 1 and 3. The minimum value of salinity during December 2003 (high tide) was 0.50 ‰, maximum value was 9.0 ‰ and the coefficient of variation was 76.98. The mean value was 4.250 ± 3.27 ‰. The minimum value was found in the upstream and maximum in the downstream towards the sea. The minimum value during February 2005 (high tide) was 4.0, maximum value was 10.0 ‰ and the

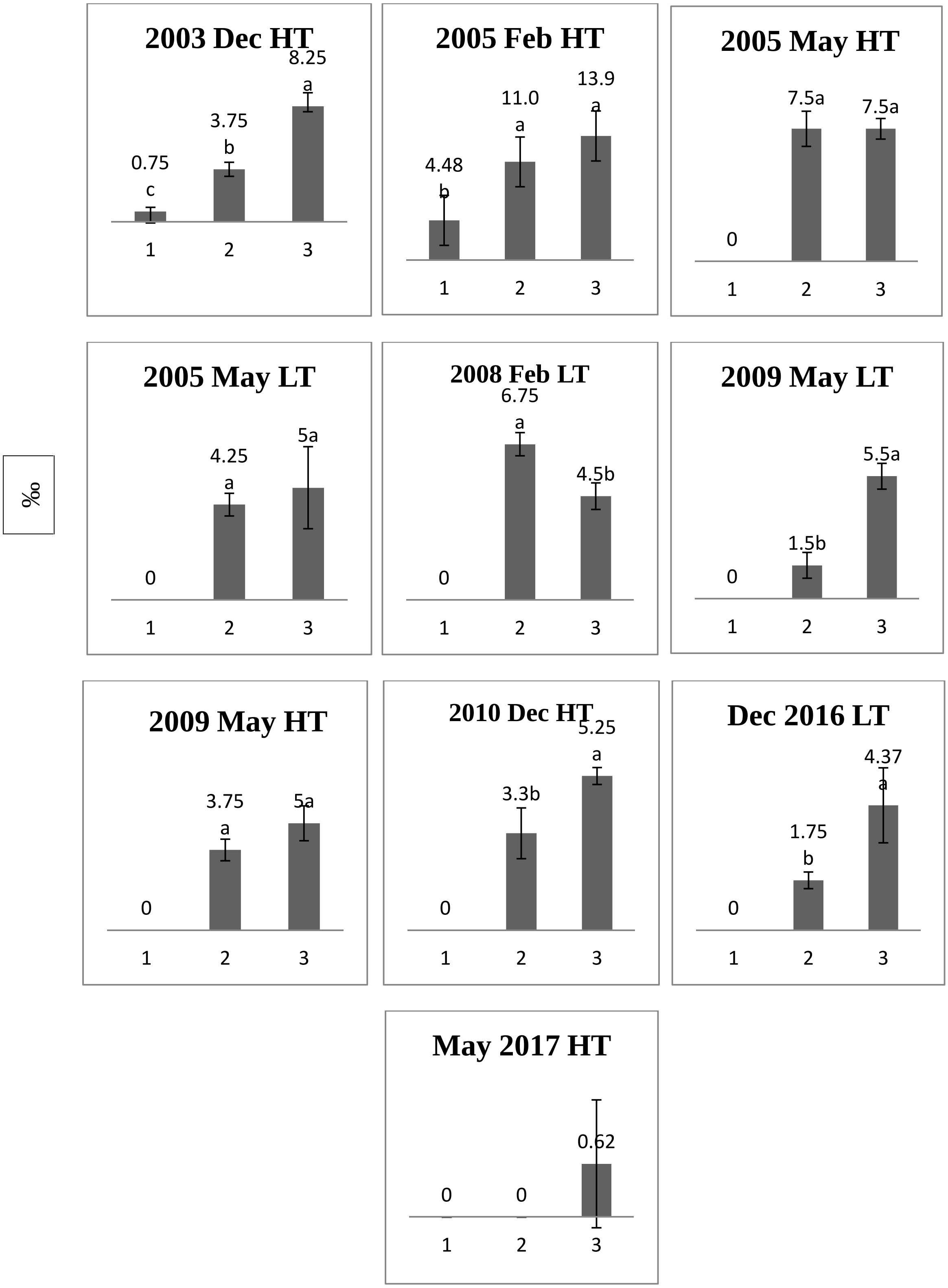


Fig. 3.2.3a: Spatio-temporal dynamics of the water salinity (‰) of three locations of Buragauranga river estuary (1, 2 and 3; and LT and HT have been explained in Fig. 3.2.1a)

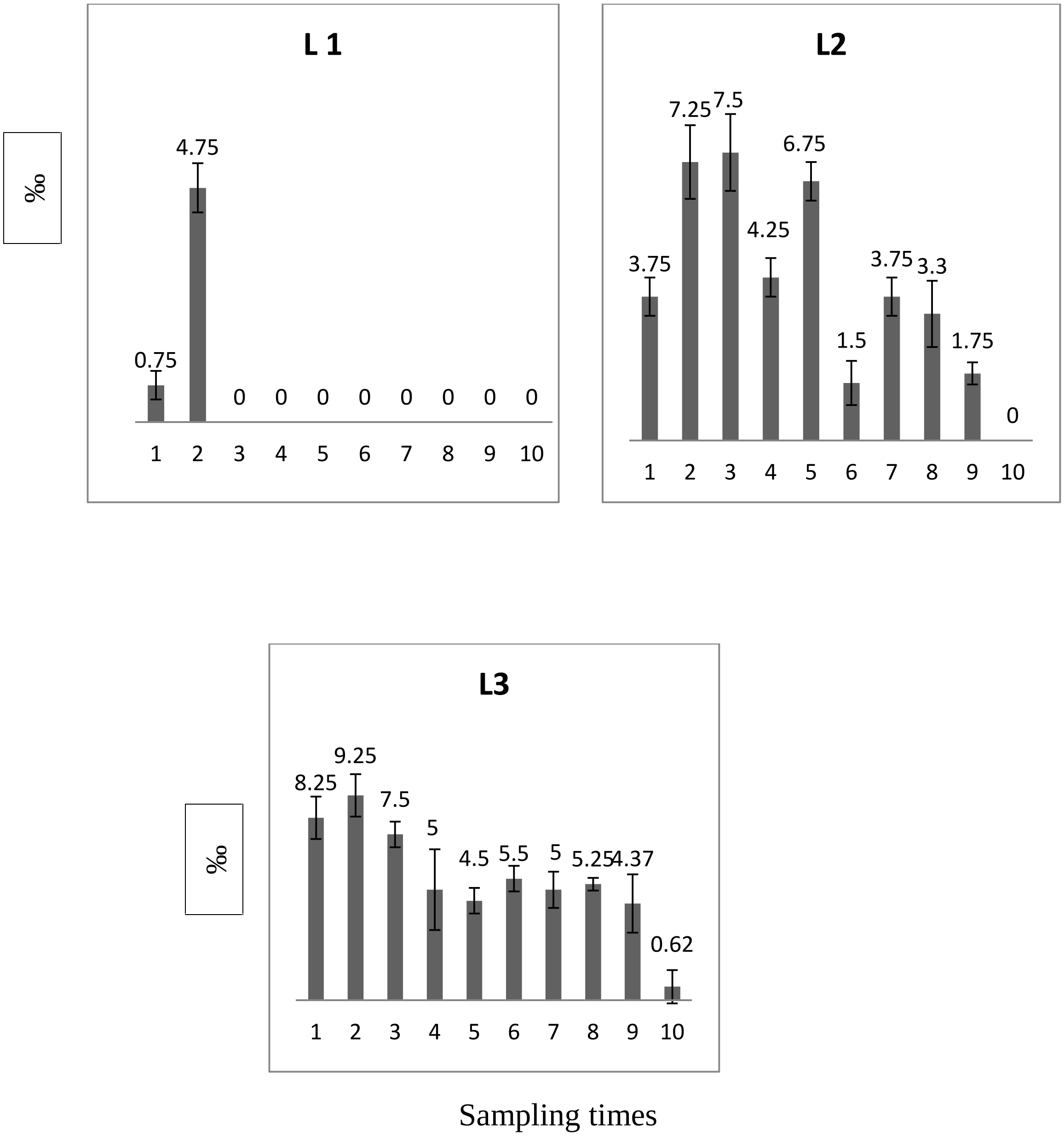


Fig. 3.2.3b: Location wise temporal variations of water salinity (‰) of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

coefficient of variation was 29.16 ‰. The mean value was 7.08 ± 2.06 ‰. From May 2005 (high tide) the value of salinity at the location 1 started to show to be nil (0.0 ‰) till 2017. The minimum value during this time was 0.0 ‰, maximum value was 8.00 ‰ and the coefficient of variation was 74.83. The mean value was 5.00 ± 3.74 ‰. The minimum value during May 2005 (low tide) was 0.00 ‰, maximum value was 7.00 ‰ and the coefficient of variation was 81.18. The mean value was 3.08 ± 2.50 ‰. It is interesting to note that the salinity of the water in this estuary started to show a decreasing tendency from this time and decreased drastically especially in 2017. The minimum value during February 2008 (low tide) was 0.0 ‰, maximum value was 7.00 ‰ and the coefficient of variation was 78.88. The mean value was 3.75 ± 2.96 ‰. The minimum value during May 2009 (high tide) was 0.00 ‰, maximum value was 6.00 ‰ and the coefficient of variation was 77.99. The mean value was 2.92 ± 2.27 ‰. The minimum value during May 2009 (low tide) was 0.00‰, maximum value was 6.00 ‰ and the coefficient of variation was 105.51. The mean value was 2.33 ± 2.46 ‰. The minimum value during December 2010 (high tide) was 0.0 ‰, maximum value was 5.50‰ and the coefficient of variation was 81.14. The mean value was 2.850 ± 2.31 ‰. The minimum value during December 2016 (low tide) was 0.00 ‰, maximum value was 5.50 ‰ and the coefficient of variation was 98.21. The mean value was 2.04 ± 2.00 ‰. The minimum value during May 2017 (high tide) was 0.00 ‰, maximum value was 1.50 ‰ and the coefficient of variation was 239.09. The mean value was 0.21 ± 0.49 ‰. During this period, location 2 also showed

0.00 ‰ salinity along with the location 1 although this location (location 2) is at the mouth of the estuary. It is clear from the present study that Location 1 was in fresh water (< 0.5 ‰) to oligohaline condition in nature (0.5 – 5. 0 ‰) whereas location 2 and 3 could be considered as mesohaline in nature (5 – 18,0 ‰). A typical characteristic of estuarine ecosystem is gradual increase in saline from head to mouth of estuary (Thasneem *et al*. 2018) was found in the present study. Thasneem *et al*. (2018) also reported similar condition in the Cochin estuary.

The level of salinity indicated that the fresh water supply from upstream reduced the intrusion of the sea water in the study area i.e. till now the effect of sea level rise has not been felt. Usually the influx of saline water from the oceans and the low discharge of freshwater by rivers are responsible for the increase of salinity in the estuary. But a reverse situation is prevailing in the Buragauranga estuary of Bangladesh that resulted in very low, almost nil, salinity. Akter (2016) has found the salinity of water samples on different rivers of SMF to vary from 5.50 to 23.00 ‰ in April 2015 and from 5.00 to 24.00 ‰) in March 2016 i.e. meso- to polyhaline condition of the rivers. Aziz *et al.* (2012) found the minimum salinity 10.4 ‰ and maximum salinity was 26.2 ‰ in the different rivers of SMF. Rahman *et al*. (2013) recorded salinity 2 - 23 ‰ in different rivers of Bangladesh Sundarbans. Salinity of the water of Meghna river estuary ranged from 5.5 - 23 ‰ where the mean value was 15.02 ‰ which indicates the water body was in mesohaline condition (Islam 2011). Salinity ranged from 13.31 to 24.22 ‰ in the surface water of Morbok estuary, Malaysia (Fatema *et al*. 2015). The influx of fresh water as a result of land runoff during monsoon and/ or by tidal variations resulted in changes in general in habitats with saline condition such as estuaries and mangrove etc. The freshwater inflow from the land has been found to moderately reduce the salinity in the Godavari estuary (Saisastry and Chandramohan 1990) and in the Bay of Bengal (Mitra *et al*. 1990).

3.2.4 Dissolved Oxygen

For supporting aquatic life the amount of dissolved oxygen (DO) plays an important role and the values are changed with slight environmental changes (Ashfaque 2004). As a result of high community respiration, dissolved oxygen generally depleted. DO has been used as an important indicator of water quality and the freshness of a river can be evaluated by its amount in the media (Fakayode 2005). The quality of water along with the organic pollution of the water bodies are well indicated by this important parameter (Wetzel and Likens 2006). The sampling occasion and location wise pH values are shown in Fig. 3.2.4a, 3.2.4b and Table 3.2.2a where the mean, minimum and maximum values along with the coefficient of variation are also shown.

The minimum value of dissolved oxygen (DO) during December 2003 (high tide) was 9.00 mg/l, maximum value was 11.00 mg/l and the coefficient of variation was 5.73. The mean value was 10.14 ± 0.58 mg/l. This indicated that the value of DO showed good health condition of the estuary water. The minimum value during February 2005 (high tide) was 11.00 mg/l, maximum value was 12.70 mg/l and the coefficient of variation was 4.42. The mean value was 11.71 ± 0.52 mg/l. The values of DO showed a decreasing tendency in May 2005 and 2008 where the values were below the standard value of WHO (1995). The minimum value during May 2005 (high tide) was 3.20 mg/l, maximum value was 3.50 mg/l and the coefficient of variation was 3.27. The mean value was 3.35 ± 0.11 mg/l. The minimum value during May 2005 (low tide) was 3.40 mg/l, maximum value was 4.00 mg/l and the coefficient of variation was 5.43. The mean value was 3.68 ± 0.20 mg/l. The minimum value during February 2008 (low tide) was 4.00 mg/l, maximum value was 4.25 mg/l and the coefficient of variation was 1.80. The mean value was 4.17 ± 0.08 mg/l. Low DO values during this period of time indicated the biologically stress condition of the estuary (Thasneem *et al.* 2018). After 2008, the DO content of the water of the estuary started to increase and it was within the range of standard value of WHO (1995) except in 2016 at locations 2 and 3. The minimum value during May 2009 (high tide) was 7.20 mg/l, maximum value was 8.60 mg/l and the coefficient of variation was 6.44. The mean value was 7.99 ± 0.51 mg/l. The minimum value during May 2009 (low tide) was 6.70 mg/l, maximum value was 7.80 mg/l and the coefficient of variation was 3.77. The mean value was 7.07 ± 0.27 mg/l. The minimum value during December 2010 (high tide) was 4.03 mg/l, maximum value was 7.52 mg/l and the coefficient of variation was 18.74. The mean value was 5.54 ± 1.04 mg/l. The minimum value during December 2016 (low tide) was 2.90 mg/l, maximum value was 7.00 mg/l and the coefficient of variation was 24.72. The mean value was 4.85± 1.19 mg/l. It is clear

Table 3.2.2. Descriptive statistics of different variables of three different locations of Buragauranga river estuary, Rangabali, Patuakhali (HT stands for high tide, LT stands for low tide)

a. Dissolved oxygen (mg/l)						
Sampling time	Mean	StDev	CoefVar	Minimum	Median	Maximum
2003 Dec HT	10.14	0.58	5.73	9.00	10.00	11.00
2005 Feb HT	11.71	0.52	4.42	11.00	11.80	12.70
2005 May HT	3.35	0.11	3.27	3.20	3.35	3.50
2005 May LT	3.68	0.20	5.43	3.40	3.65	4.00
2008 Feb LT	4.17	0.08	1.80	4.00	4.20	4.25
2009May HT	7.99	0.51	6.44	7.20	8.10	8.60
2009May LT	7.07	0.27	3.77	6.70	7.02	7.80
2010Dec HT	5.54	1.04	18.74	4.03	5.45	7.52
2016 Dec LT	4.85	1.19	24.72	2.90	4.60	7.00
2017May HT	7.53	0.81	10.77	6.30	7.54	9.13
b. BOD mg/l						
2003 Dec HT	8.06	1.01	12.50	5.70	8.10	9.40
2005 Feb HT	4.53	0.46	10.10	3.70	4.50	5.50
2005 May HT	1.81	0.44	24.14	1.35	1.62	2.85
2005 May LT	1.55	0.29	18.78	1.10	1.60	2.10
2008 Feb LT	3.67	0.72	19.70	2.30	4.10	4.25
2009May HT	5.51	0.56	10.20	4.41	5.50	6.35
2009May LT	6.00	1.11	18.55	4.15	5.84	8.66
2010Dec HT	1.77	0.91	51.72	0.38	1.88	3.12
2016 Dec LT	2.33	0.49	21.03	1.50	2.28	3.20
2017May HT	4.49	0.49	11.05	3.67	4.62	5.17
c. Free CO_2 (mg/l)						
2003 Dec HT	0.90	0.12	13.40	0.70	0.90	1.10
2005 Feb HT	2.76	0.74	26.93	1.90	2.45	4.00
2005 May HT	16.74	0.95	5.70	14.50	16.85	18.25
2005 May LT	17.58	0.77	4.40	16.50	17.80	18.50
2008 Feb LT	10.19	2.83	27.82	6.58	9.47	14.15
2009May HT	8.25	0.58	7.03	7.16	8.27	8.90
2009May LT	9.24	0.42	4.50	8.67	9.13	9.95
2010Dec HT	14.98	4.06	27.11	10.50	13.93	22.08
2016 Dec LT	11.39	1.89	16.57	8.14	11.65	14.40
2017May HT	10.65	0.66	6.20	9.60	10.76	11.50
d. **Chloride (mg/l)**						
2003 Dec HT	1927	1712	88.82	330	1324	4998
2005 Feb HT	5505	3013	54.73	1416	6982	8253
2005 May HT	4662	2762	59.24	532	6066	7338
2005 May LT	3395	2168	63.86	425	4431	6026
2008 Feb LT	3185	1949	61.21	461	4077	5318
2009May HT	1359	1057	77.78	213	1099	2730
2009May LT	1020	621	60.91	389	884	2268
2010Dec HT	1298	715	55.13	578	994	2548
2016 Dec LT	977	574	58.80	427	697	1891
2017May HT	4923	74.6	15.14	358	501	591

from the Fig. 3.2.4a that during this sampling occasion, location 2 and 3 showed lower DO content than the standard value of WHO (1995). In 2017, the DO contents of all three locations were above the standard values of WHO (1995). The minimum value during May 2017 (high tide) was 6.30 mg/l, maximum value was 9.13 mg/l and the coefficient of variation was 10.77. The mean value was 7.53 ± 0.81 mg/l.

The concentrations of DO (mg/l) of water samples of different rivers of SMF were found to vary from 3.5 to 6.35 mg/l where the mean value was 4.76 mg/l in April 2015 (Akter 2016). The concentration of DO (% Sat.) was 46.60 to 82.00 % in April 2015. The values DO in rivers of SMF were only 0.11 to 5.33 mg/l and the value of % Sat. DO was 1.2 to 95.2 in March 2016 (Akter 2016). Fatema *et al.* (2015) found that the DO of surface water of Morbok estuary, Malaysia was 3.29 to 5.65 mg/l. The standard of DO content in the water bodies ranged from 5.0 - 7.0 mg/l (WHO 1995). These limits permit the water for drinking purposes. EPA (1971) has suggested that DO value less than 5.0 mg/l will be regarded as polluted water. The mean value and the values of the most locations of the rivers of the SMF during April 2015 and March 2016 were found to be lower than this standard value indicating the polluted nature. The air-sea interface and *in situ* photosynthetic production are considered as the major primary source of oxygen in the aquatic environment (Best *et al.* 2007). The complex interactions among various physical, chemical or biological processes contributed to the dynamic pattern in estuarine dissolved oxygen (Borsuk *et al*. 2001).

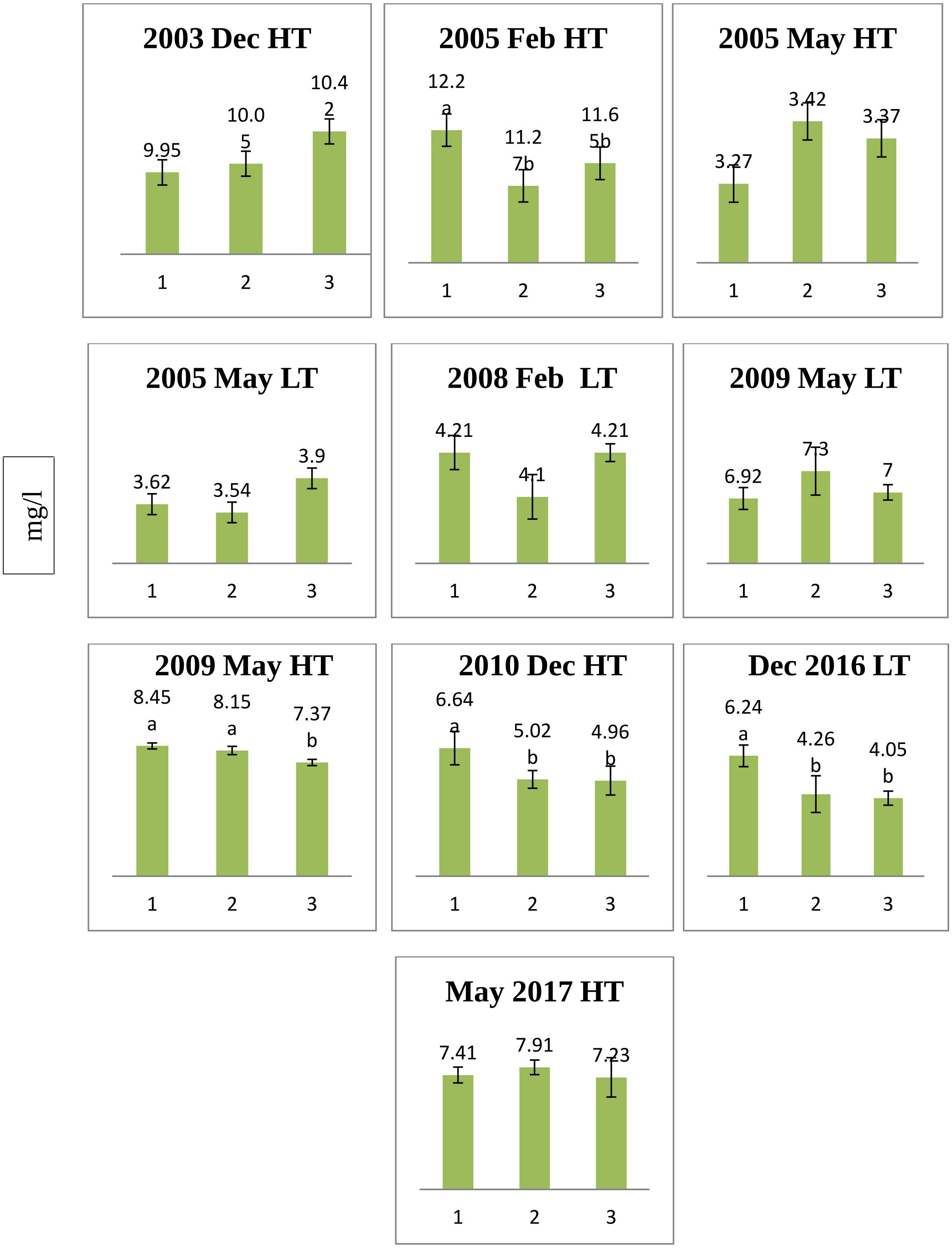


Fig. 3.2.4a: Spatio-temporal dynamics of the dissolved oxygen (DO mg/l) of water of the three locations of the Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

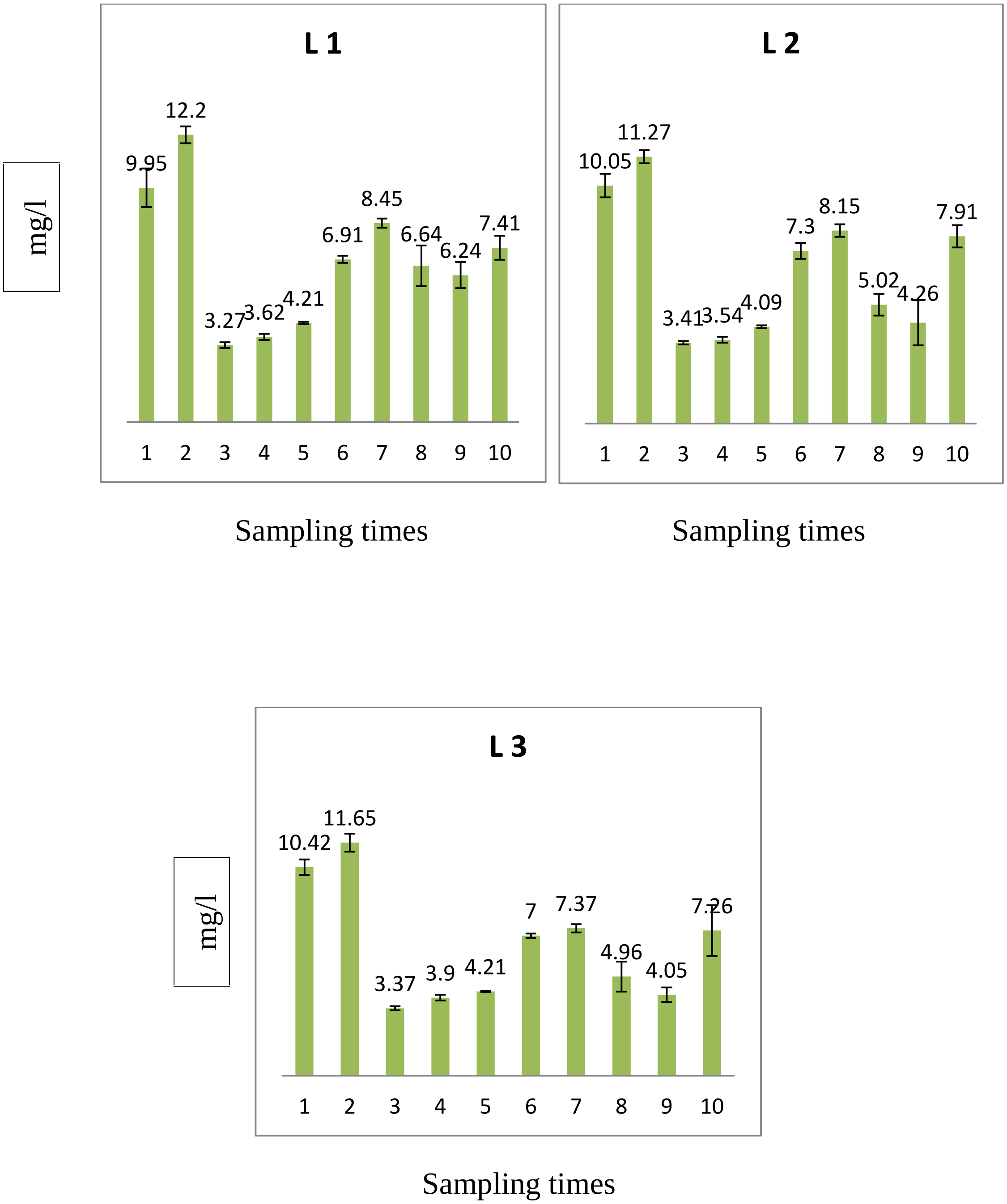


Fig. 3.2.4b: Location wise temporal variations of dissolved oxygen (mg/l) of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

A variety of environmental conditions such as temperature, freshwater discharge, salt water intrusion, circulation, biological productivity and respiration resulted in the formation of strong dissolved oxygen gradient (Stanley 1993). Periodic inundation and high protosynthetic activities limit the oxygen level of the estuary (Anilakumary *et al.* 2007). Local production, diffusion and advection, exchange of oxygen across the surface were observed by them and biochemical utilization control DO in many aquatic envrionment, and biochemical utilization are also controlling factors for DO in many aquatic environments.

3.2.5 Biological oxygen demand

The biological oxygen demand (BOD_5) is a measure of the amount of oxygen essential for the growth of aquatic organisms that will be consumed in five days. However, excessive concentrations of nutrients can stimulate decomposition of organic matter under aerobic conditions (Masters 2004). The sampling occasion and location wise BOD_5 values are shown in Fig. 3.2.5a, 3.2.5b and Table 3.2.2b where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value of BOD_5 during December 2003 (high tide) was 5.70 mg/l, maximum value was 9.40 mg/l and the coefficient of variation was 12.50. The mean value was 8.06 ± 1.01 mg/l. The minimum value during February 2005 (high tide) was 3.70 mg/l, maximum value was 5.50 mg/l and the coefficient of variation was 10.10. The mean value was 4.53 ± 0.46 mg/l.

The minimum value during May 2005 (high tide) was 1.35 mg/l, maximum value was 2.85 mg/l and the coefficient of variation was 24.14. The mean value was 1.81 ± 0.44 mg/l. The minimum value during May 2005 (low tide) was 1.10 mg/l, maximum value was 2.10 mg/l and the coefficient of variation was 18.78. The mean value was 1.55 ± 0.29 mg/l. The minimum value during February 2008 (low tide) was 2.30 mg/l, maximum value was 4.25 mg/l and the coefficient of variation was 19.70. The mean value was 3.67 ± 0.72 mg/l. The minimum value during May 2009 (High tide) was 4.41 mg/l, maximum value was 6.35 mg/l and the coefficient of variation was 10.20. The mean value was 5.51 ± 0.56 mg/l. The minimum value during May 2009 (low tide) was 4.15 mg/l, maximum value was 8.66 mg/l and the coefficient of variation was 18.55. The mean value was 6.00 ± 1.11 mg/l. The minimum value during December 2010 (high tide) was 0.38 mg/l, maximum value was 3.12 mg/l and the coefficient of variation was 51.72. The mean value was 1.77 ± 0.91 mg/l. The minimum value during December 2016 (low tide) was 1.50 mg/l, maximum value was 3.20 mg/l and the coefficient of variation was 21.03. The mean value was 2.33 ± 0.49 mg/l. The minimum value during May 2017 (high tide) was 3.67 mg/l, maximum value was 5.17 mg/l and the coefficient of variation was 11.05. The mean value was 4.49 ± 0.49 mg/l. In the Meghna estuary, the minimum BOD_5 was found to be 0.38 mg/l and maximum BOD_5 was 3.24 mg/l (Islam 2011). Fatema *et al.* (2015) have found that the biological oxygen demand varied from 1.25 to 4.48 mg/L for surface water of Morbok estuary. Average biological oxygen demand of the Cochin estuary was 2.42 ± 1.53 mg/l (Thasneem *et al*. 2018). Higher BOD in the estuary may be attributed to organic suspended materials from discharged wastewater from the surrounding areas. This condition

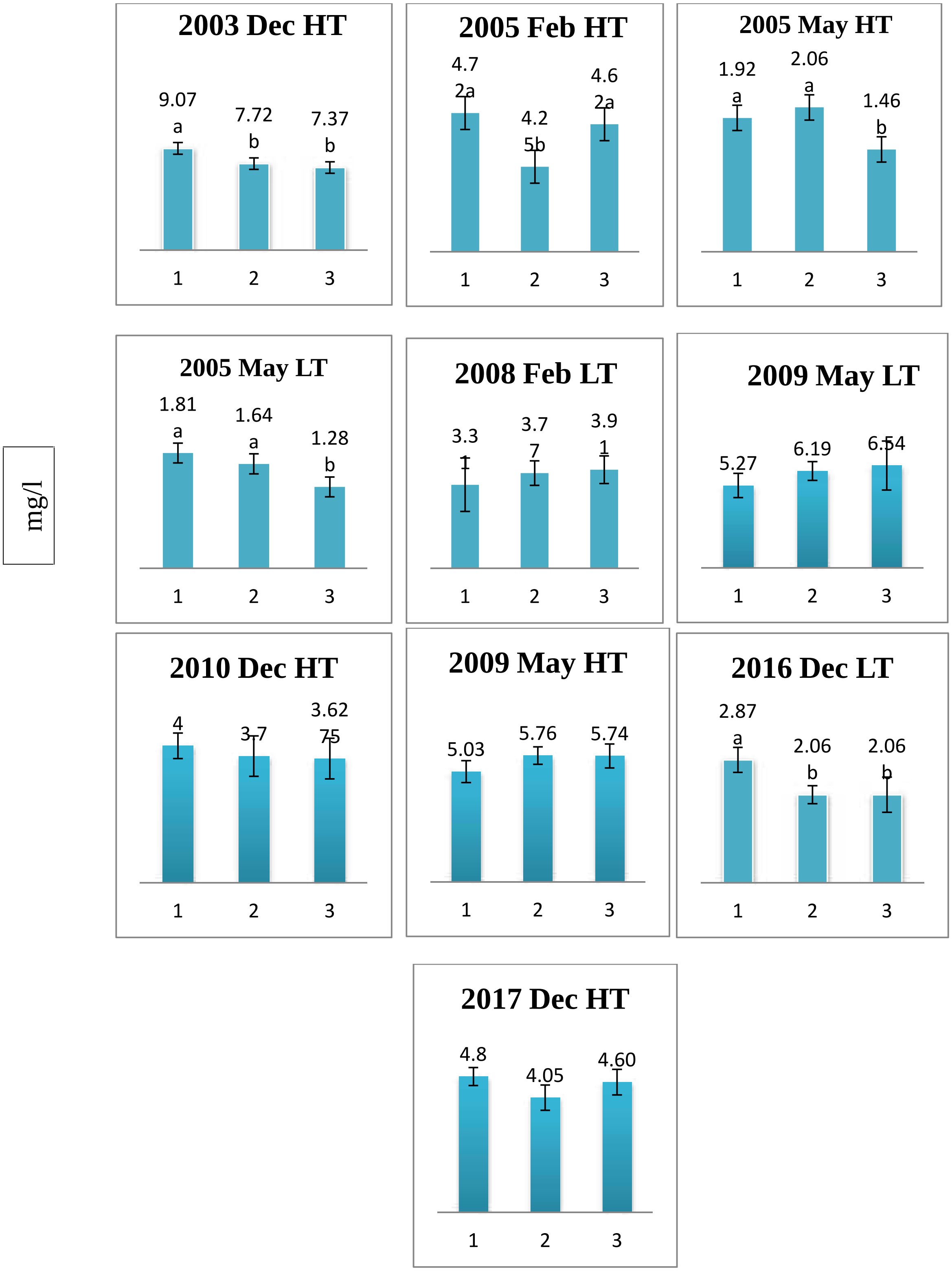


Fig. 3.2.5a: Spatio-temporal dynamics of BOD_5 (mg/l) of the water of the three locations of Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

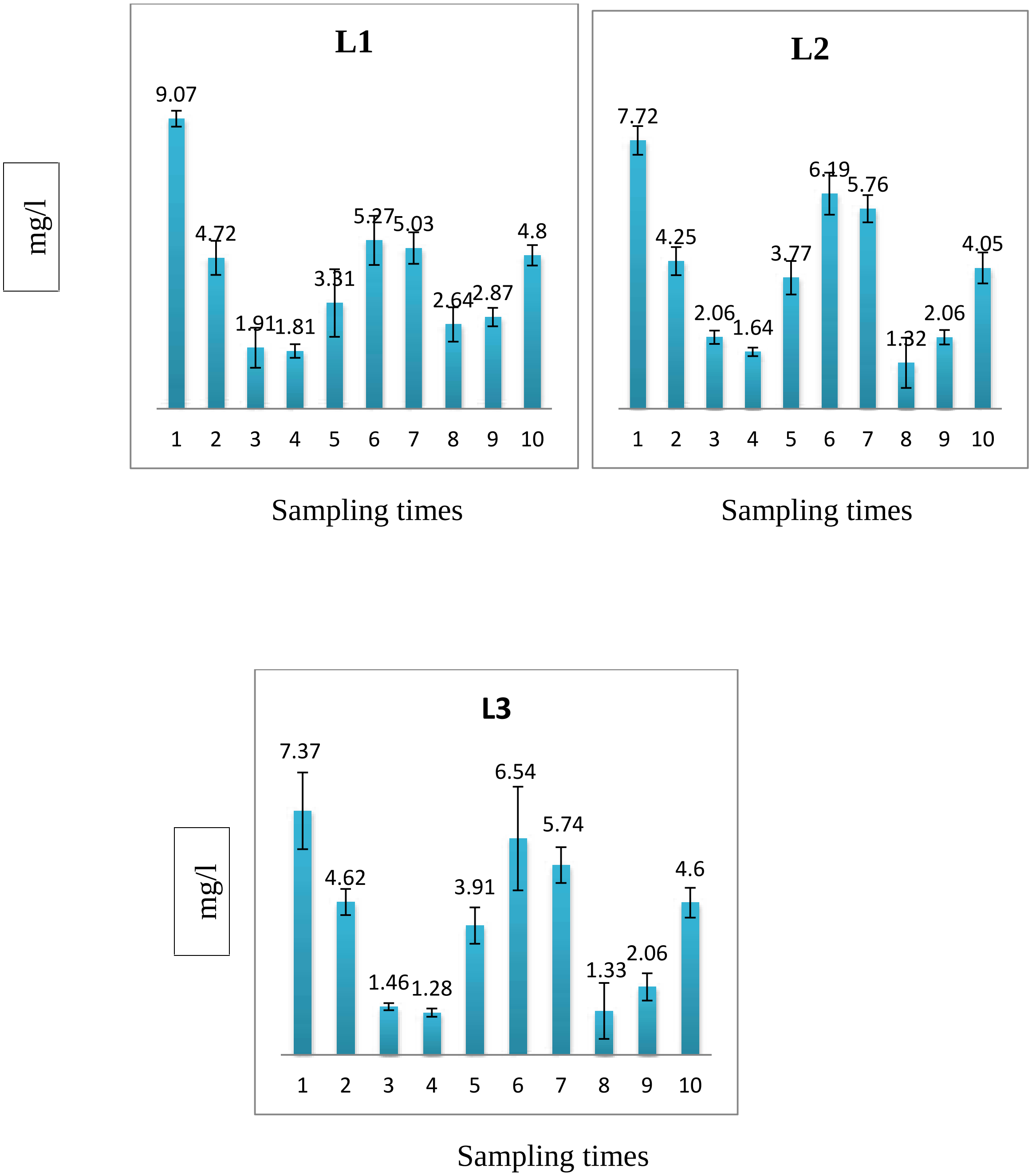


Fig. 3.2.5b: Location wise temporal variations of biological oxygen demand (mg/l) of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

may also be due to the effect of dead and decaying mangrove vegetation resulting in increased BOD (Fatema *et al.* 2015). Similar results were also observed by other studies (Grafny *et al*. 2000; Fianko *et al*. 2010). BOD_5 is also an indicator of organic pollution. Unpolluted natural waters have a BOD_5 of 5 mg/l or less (Schulze *et al*. 2001).

3.2.6 Free Carbon Dioxide (CO_2)

The values of free CO_2 in the three location of the water of Buragauranga estuary were comparatively lower during the first two visits in December 2003 and February 2005, but from May 2005 the values were very high even sometime exceeding the tolerance limit (10.00 mg/l) of fishes (Michael 1992). The sampling occasion wise and location wise free CO_2 values are shown in Fig. 3.2.6a, 3.2.6b and Table 3.2.2c where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value of free CO_2 during December 2003 (high tide) was 0.70 mg/l, maximum value was 1.10 mg/l and the coefficient of variation was 13.40. The mean value was 0.90 ± 0.12 mg/l. The mean values of free CO_2 among the locations did not show significant difference and the values were almost similar. The minimum value during February 2005 (high tide) was 1.90 mg/l, maximum value was 4.00 mg/l and the coefficient of variation was 26.93. The mean value was 2.76 ± 0.74 mg/l. Significantly higher value was observed in location 1 than those of locations 2 and 3. The minimum value during May 2005 (high tide) was 14.50 mg/l, maximum value was 18.25 mg/l and the coefficient of variation was 5.70. The mean value was 16.74 ± 0.95

mg/l. The minimum value during May 2005 (low tide) was 16.50 mg/l, maximum value was 18.50 mg/l and the coefficient of variation was 4.40. The mean value was 17.58 ± 0.77 mg/l. In both cases, location 3 had significantly higher values than those of location 1 and 2. During the high tide condition, location 1 and 2 had almost similar values whereas during low tide location 2 had almost similar values to location 3. The minimum value during February 2008 (low tide) was 6.58 mg/l, maximum value was 14.15 mg/l and the coefficient of variation was 27.82. The mean value was 10.19 ± 2.83 mg/l. The minimum value during May 2009 (high tide) was 7.16 mg/l, maximum value was 8.90 mg/l and the coefficient of variation was 7.03. The mean value was 8.25 ± 0.58 mg/l. The minimum value during May 2009 (low tide) was 8.67 mg/l, maximum value was 9.95 mg/l and the coefficient of variation was 4.50. The mean value was 9.24 ± 0.42 mg/l. The minimum value during December 2010 (high tide) was 10.50 mg/l, maximum value was 22.08 mg/l and the coefficient of variation was 27.11. The mean value was 14.98 ± 4.06 mg/l. The minimum value during December 2016 (low tide) was 8.14 mg/l, maximum value was 14.40 mg/l and the coefficient of variation was 16.57. The mean value was 11.39 ± 1.89 mg/l mg/l. The minimum value during May 2017 (high tide) was 9.60 mg/l, maximum value was 11.50 mg/l and the coefficient of variation was 6.20. The mean value was 10.65 ± 0.66 mg/l.

Surface water usually contain free CO_2 concentration less than 10.00 mg/l. Higher values found in this study might be due to high community respiration and consequences of global climate change that resulted in an increase of CO_2 level.

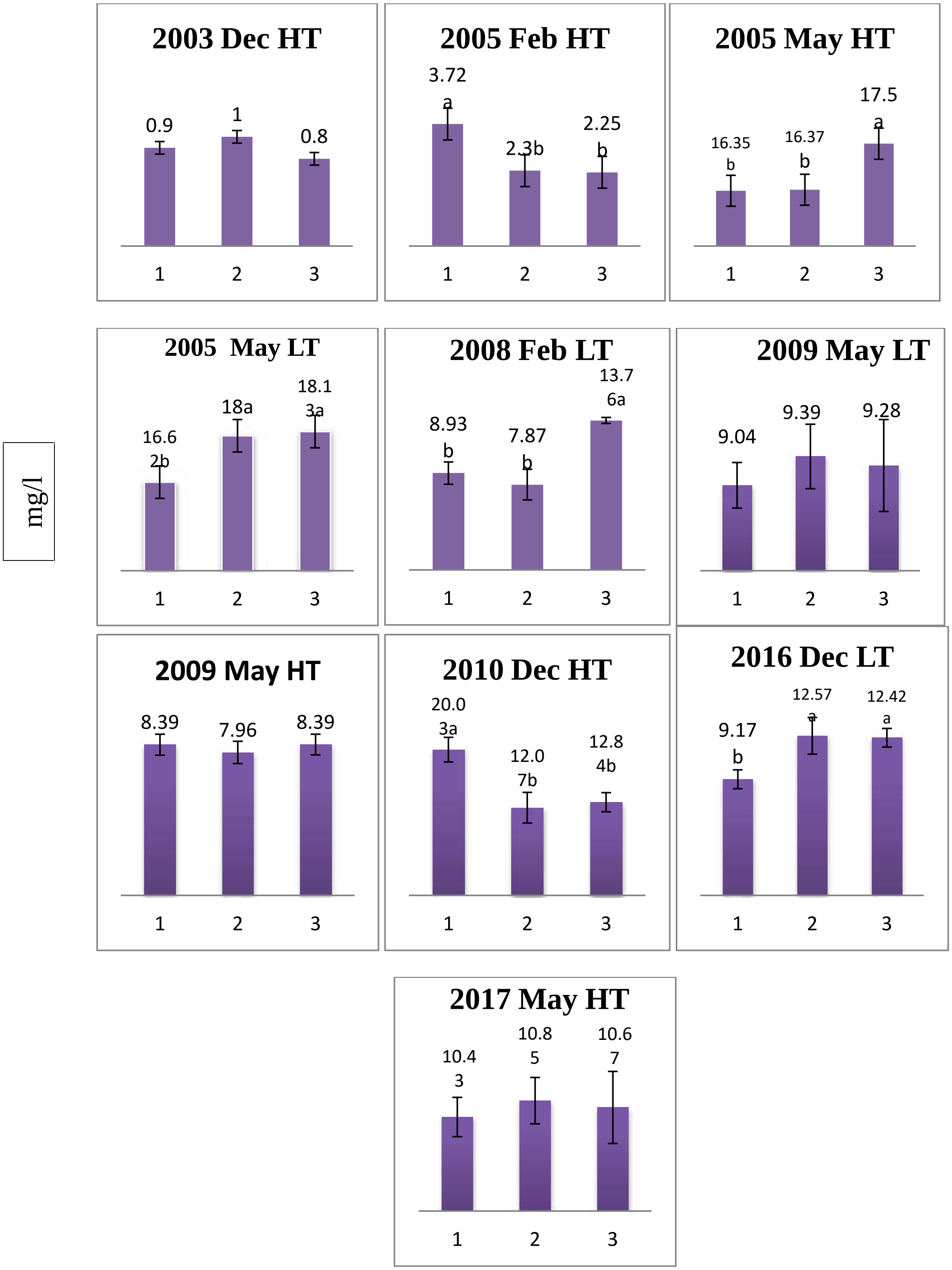


Fig. 3.2.6a: Spatio-temporal dynamics of Free CO_2 (mg/l) of the water of the three locations of Buragauranga river estuary (1, 2 and 3; and LT and HT have been explained in Fig. 3.2.1a)

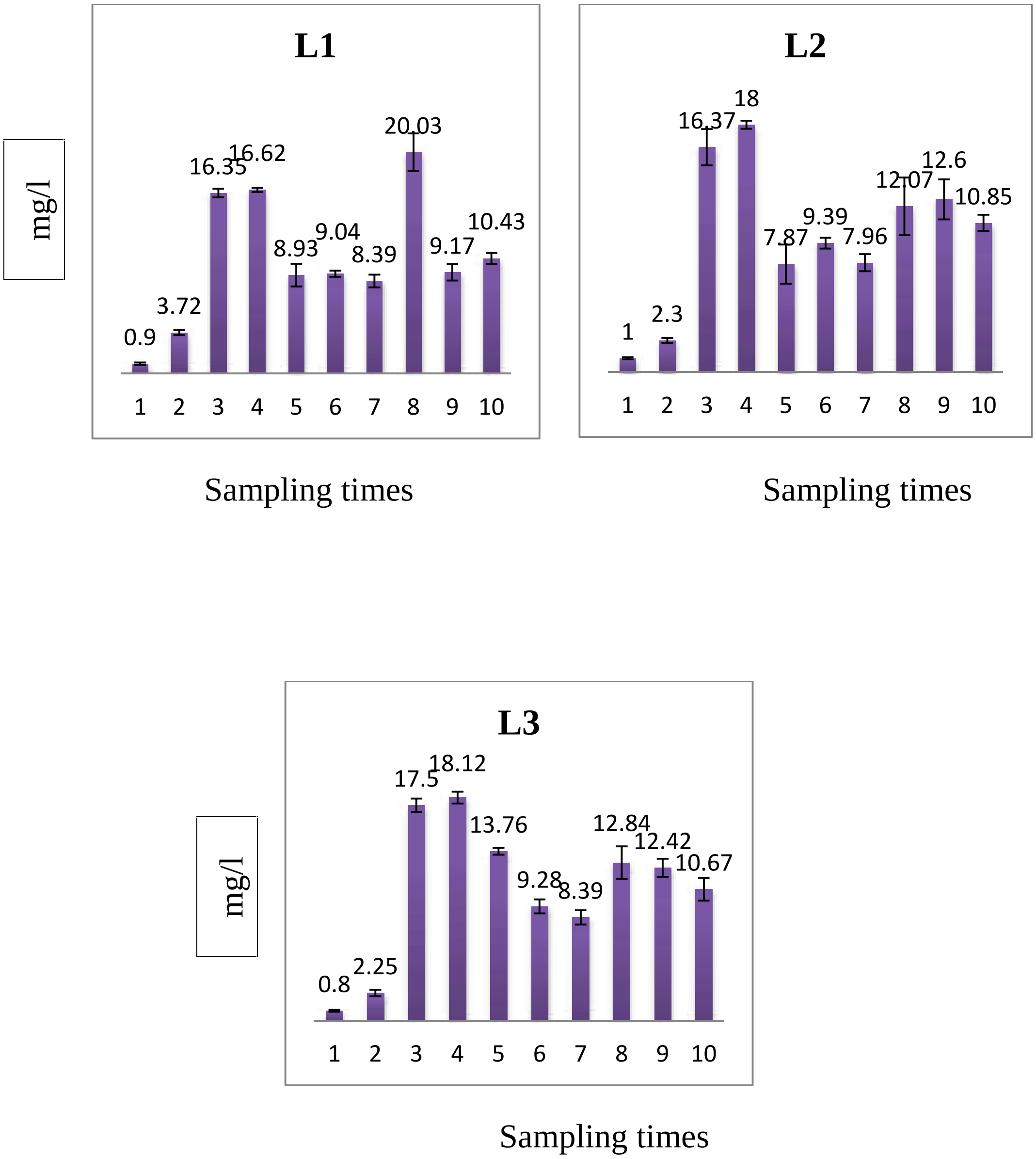


Fig. 3.2.6b: Location wise temporal variations of free CO_2 (mg/l) of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

The amount of free CO_2 in the water of Meghna ranged from 11.88 - 22.23 mg/l (Islam 2011). Thasneem *et al*. (2018) reported free CO_2 concentration in the Cochin estuary to vary from 7.31 ± 2.19 to 9.07 ± 1.24 mg/l. Free CO_2 concentration less than 10.00 mg/l are usually tolerated by fish if dissolved oxygen concentrations are near saturation (Michael 1992). However, values above 10.00 mg/l are known to cause mineral deposits within kidney tubules, collecting ducts and ureters of fishes (Michael 1992). Although, in the view of Landolt (1975), this condition rarely results in high mortality in fish unless other environmental conditions are marginal. In the present study, it was found that increase level of CO_2 in the estuary water concomitant with the slight acidification of the estuary water although an opposite trend was found in Cochin estuary where free CO_2 level was increased but pH was shifting towards alkaline scale (Thasneem *et al*. 2018).

3.2.7 Chloride Content in the Estuarine Water

The Chloride content of the water of the Buragauranga river estuary significantly varied among the locations except in 2017. Lowest values were observed in location 1 followed by location 2 and location 3. Similar pattern was observed in all sampling occasions except 2017 when the values were almost similar in all the three locations. The sampling occasion wise and location wise chloride values are shown in Fig. 3.2.7a, 3.2.7b and Table 3.2.2d where the mean, minimum and maximum values along with the coefficient of variation are also spresented. The minimum value of chloride during December 2003 (high tide) was 330 mg/l, maximum value was 4998 mg/l and the coefficient of variation was 88.82. The mean value was 1927 ± 1712 mg/l. The minimum value during February 2005 (high tide) was 1416 mg/l, maximum value was 8253 mg/l and the coefficient of variation was 54.73. The mean value was 5505 ± 3013 mg/l. The minimum value during May 2005 (high tide) was 532 mg/l, maximum value was 7338 mg/l and the coefficient of variation was 59.24. The mean value was 4662 ± 2762 mg/l. The minimum value during May 2005 (low tide) was 425 mg/l, maximum value was 6026 mg/l and the coefficient of variation was 63.86. The mean value was 3395 ± 2168 mg/l. The minimum value during February 2008 (low tide) was 461 mg/l, maximum value was 5318 mg/l and the coefficient of variation was 61.21. The mean value was 3185 ± 1949 mg/l. The minimum value during May 2009 (High tide) was 213 mg/l, maximum value was 2730 mg/l and the coefficient of variation was 77.78. The mean value was 1359 ± 1057 mg/l. The minimum value during May 2009 (low tide) was 389 mg/l, maximum value was 2268 mg/l and the coefficient of variation was 60.91. The mean value was 1020 ± 621 mg/l. The minimum value during December 2010 (high tide) was 578 mg/l, maximum value was 2548 mg/l and the coefficient of variation was 55.13. The mean value was 1298 ± 715 mg/l. The minimum value during December 2016 (low tide) was 427 mg/l, maximum value was 1891 mg/l and the coefficient of variation was 58.80. The mean value was 977± 574 mg/l. The minimum value during May 2017 (high tide) was 358 mg/l, maximum value was 591 mg/l and the coefficient of variation was 15.14. The mean value was 492.9 ± 74.6 mg/l.

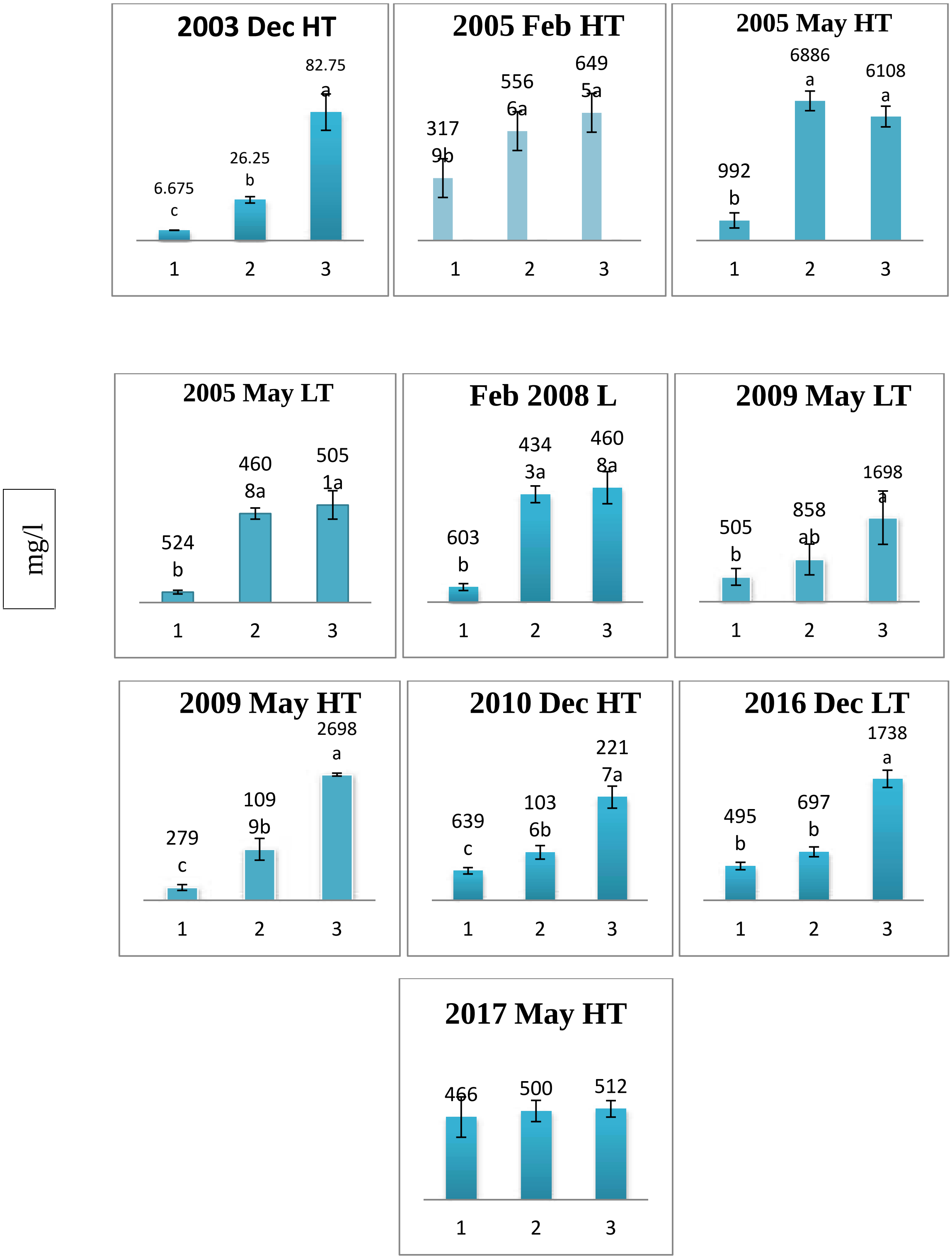


Fig. 3.2.7a: Spatio-temporal dynamics of chloride content (mg/l) of the water of the three locations of Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

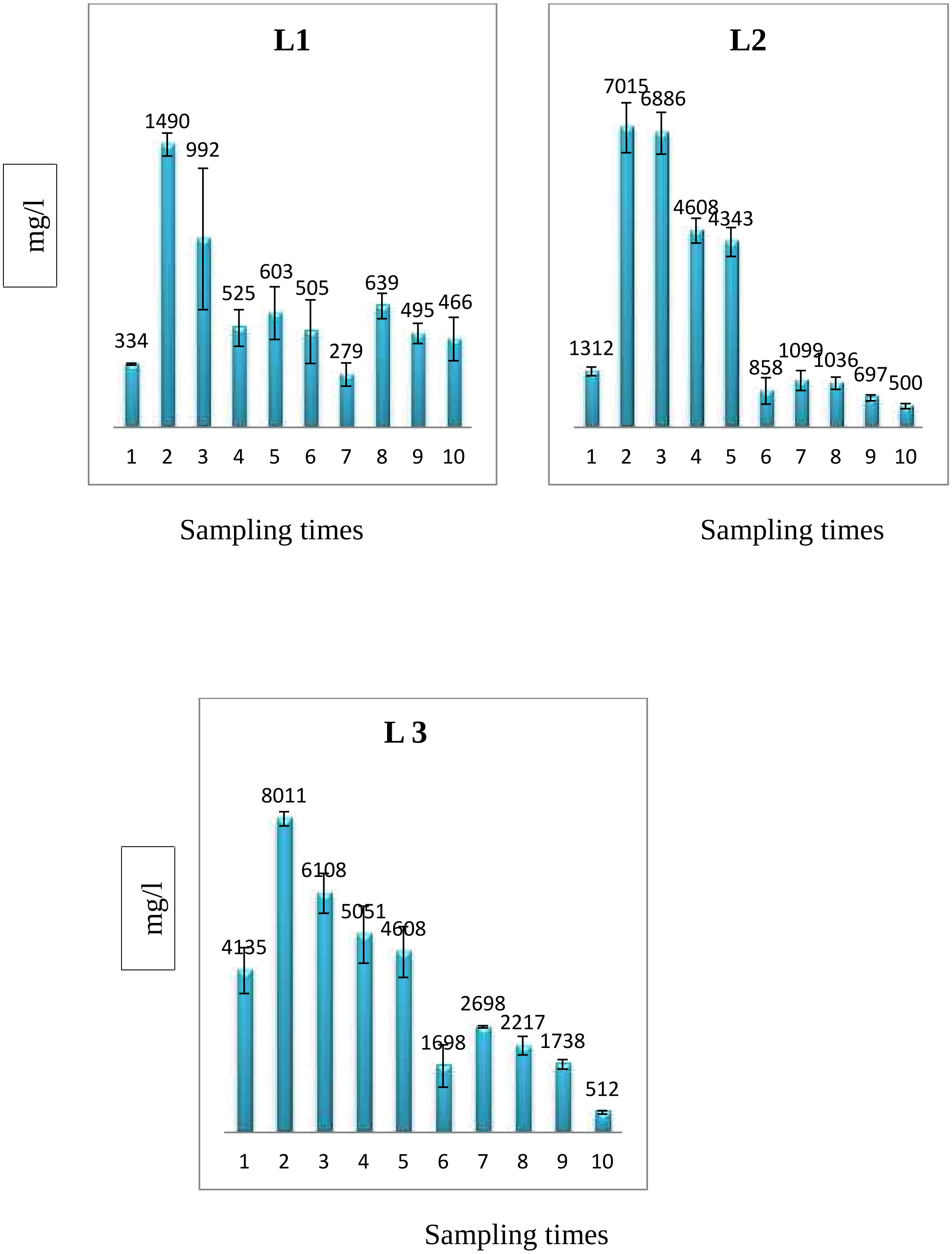


Fig. 3.2.7b: Location wise variations of chloride (mg/l) of water of the Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

3.2.8 Filtrable Residue in the Estuarine Water

Location 1 showed the lowest amount of filtrable residue of the water of the studied estuary in all sampling occasions except the sampling years of 2008, 2010 and 2016 when location 3 had the lowest values. The amount of filtrable residue was lower in comparison to non-filtrable residues in all sampling occasions except December 2010 (high tide condition) when filtrable residue was the major constitute of the total residue in the estuarine water (Table 3.2.3a and Table 3.2.3b). The sampling occasion wise and location wise filtrable residue values are shown in Fig. 3.2.8a, 3.2.8b and Table 3.2.3a where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value of filtrable residue during December 2003 (high tide) was 34.0 mg/l, maximum value was 284.0 mg/l and the coefficient of variation was 40.55. The mean value was 169.6 ± 68.8 mg/l. The minimum value during February 2005 (high tide) was 70.0 mg/l, maximum value was 300.0 mg/l and the coefficient of variation was 38.40. The mean value was 182.5 ± 70.1 mg/l. Very high amounts of filtrable residue were observed during the both high and low tide conditions in 2005. The values were almost similar to non-filtrable residues. The minimum value during May 2005 (high tide) was 760.0 mg/l, maximum value was 8750.0 mg/l and the coefficient of variation was 61.37. The mean value was 5488 ± 3368 mg/l. The minimum value during May 2005 (low tide) was 780.0 mg/l, maximum value was 9620 mg/l and the coefficient of variation was 62.11. The mean value was 6210.0 ± 3857.0 mg/l.

Table 3.2.3. Descriptive statistics of different variables of three different locations of Buragauranga river estuary, Rangabali, Patuakhali (HT stands for high tide, LT stands for low tide)

a. Filtrable residue (mg/l)						
Sampling time	Mean	StDev	CoefVar	Minimum	Median	Maximum
2003 Dec HT	169.6	68.8	40.55	34.0	182.5	284.0
2005 Feb HT	182.5	70.1	38.40	70.0	185.0	300.0
2005 May HT	5488.0	3368.0	61.37	760.0	7250.0	8750.0
2005 May LT	6210.0	3857.0	62.11	780.0	8485.0	9620.0
2008 Feb LT	480.0	74.1	15.44	310.0	485.0	590.0
2009May HT	1817.0	1044.0	57.47	787.0	1484.0	3278.0
2009May LT	1643.0	957.0	58.23	502.0	1558.0	2853.0
2010Dec HT	543.3	114.5	21.08	419.0	523.5	720.0
2016 Dec LT	85.0	29.7	34.94	60.0	80.0	160.0
2017May HT	273.3	247.5	90.55	60.0	150.0	760.0
b. Non-filtrable residue (mg/l)						
2003 Dec HT	1617	1147	70.90	257	1716	3547
2005 Feb HT	7352	3736	50.82	980	8395	11170
2005 May HT	5394	3372	62.51	630	7175	8700
2005 May LT	6217	3790	60.96	730	8450	9610
2008 Feb LT	6288	3791	60.29	960	8530	9660
2009May HT	3162	1786	56.49	1417	2474	5638
2009May LT	2406	1464	60.86	1254	1580	4521
2010Dec HT	100	32	32.73	63	91	168
2016 Dec LT	1188	1377	115.88	20.0	1290	4880
2017May HT	829	935	112.78	200	350	3140
c. **Total residue (mg/l)**						
2003 Dec HT	1787	1187	66.41	398	1899	3789
2005 Feb HT	7534	3744	49.70	1060	8595	11240
2005 May HT	10882	6739	61.93	1390	14425	17450
2005 May LT	12427	7645	61.52	1510	16935	19230
2008 Feb LT	6768	3776	55.79	1470	9005	10140
2009May HT	4978	2827	56.78	2231	4015	8777
2009May LT	4048	2379	58.75	1803	3101	7374
2010Dec HT	643	127	19.83	492	622	857
2016 Dec LT	1273	1375	108.00	120	1410	4960
2017May HT	1102	1150	104.38	300	430	3680

The minimum value during February 2008 (low tide) was 310.0 mg/l, maximum value was 590.0 mg/l and the coefficient of variation was 15.44. The mean value was 480.0 ± 74.1 mg/l. Relatively higher amount of filtrable residue were found during May 2009 at both low and high tide conditions in comparison to 2003, 2005 (February), 2008, 2010, 2016 and 2017 sampling occasions. The minimum value during May 2009 (high tide) was 787.0 mg/l, maximum value was 3278.0 mg/l and the coefficient of variation was 57.47. The mean value was 1817.0 ± 1044.0 mg/l. The mean value was 1643.0 ± 957.0 mg/l during May 2009 (low tide). The minimum value was 502 mg/l, maximum value was 2853.0 mg/l and the coefficient of variation was 58.23. The minimum value during December 2010 (high tide) was 419.0 mg/l, maximum value was 720.0 mg/l and the coefficient of variation was 21.08. The mean value was 543.3 ± 114.5 mg/l. The minimum value during December 2016 (low tide) was 60.00 mg/l, maximum value was 160.00 mg/l and the coefficient of variation was 34.94. The mean value was 85.00 ± 29.70 mg/l. The minimum value during May 2017 (high tide) was 60.0 mg/l, maximum value was 760.0 mg/l and the coefficient of variation was 90.55. The mean value was 273.3 ± 247.5 mg/l. Islam (2011) found the mean value of filtrable residue of Meghna estuary was 4.89 mg/l where maximum value was 7.00 mg/l and minimum value was 4.10 mg/l which indicated that filtrable residue of Buragauranga estuary were high.

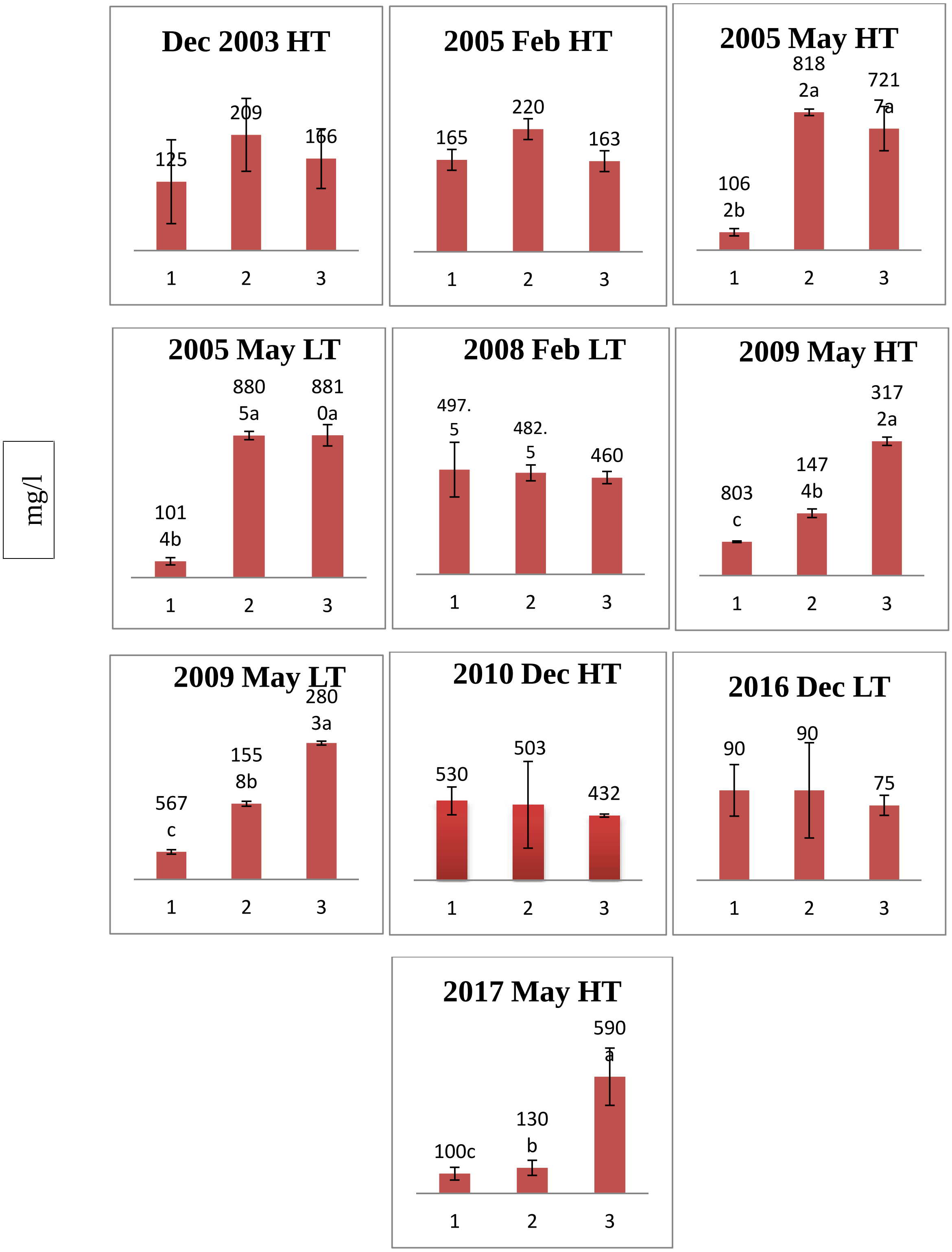


Fig. 3.2.8a: Spatio-temporal dynamics of filtrable residue (mg/l) of the water of three locations of Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

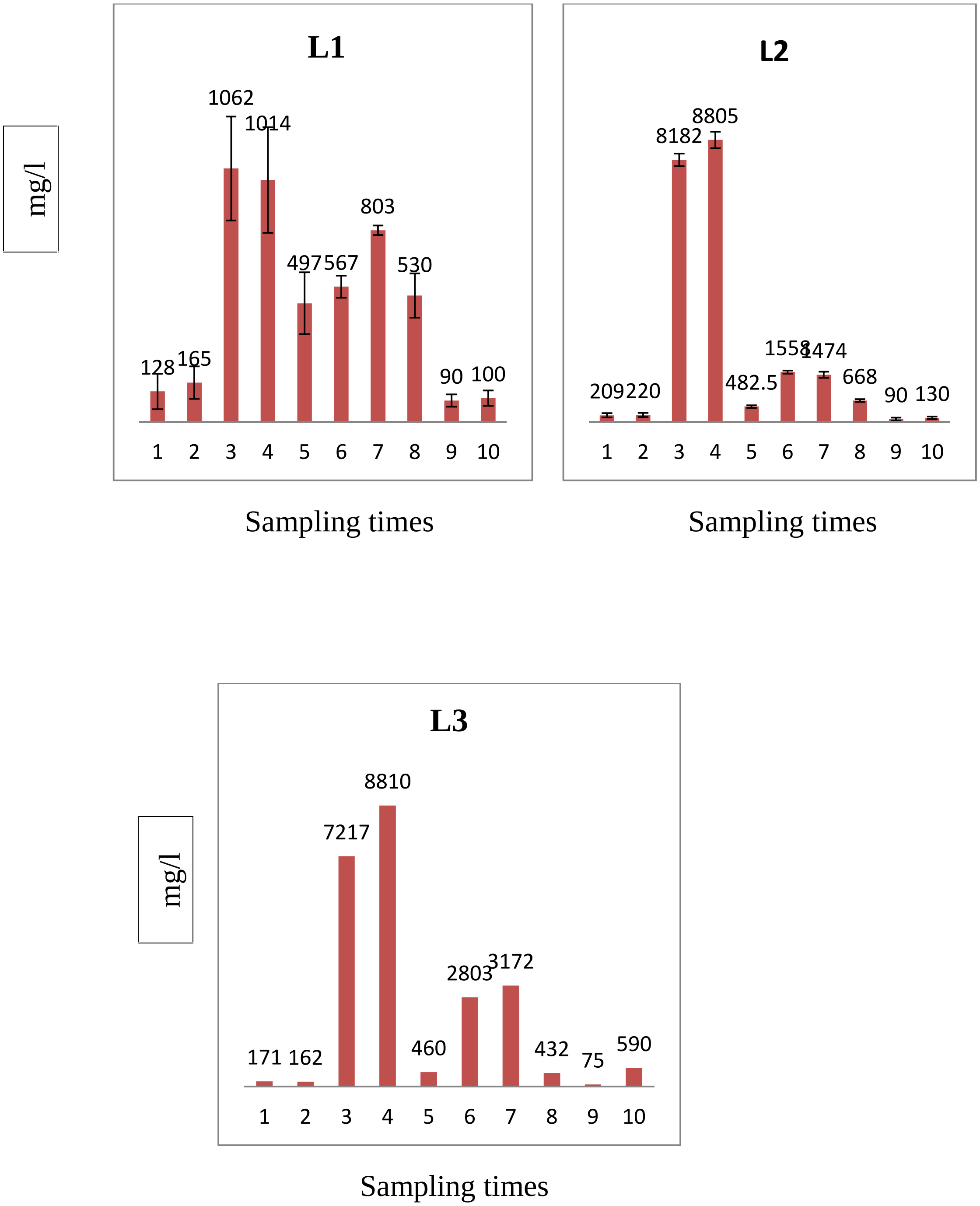


Fig. 3.2.8b: Spatial dynamics of filtrable residue (mg/l) of the water of Buragauranga river estuary of (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

3.2.9 Non-filtrable Residue in Estuarine Water

Non-filtrable residue was the major constitute of the total residue of the water in the Buragauranga estuary except December 2010. The sampling occasion wise and location wise non-filtrable residue values are shown in Fig. 3.2.9a, 3.2.9b and Table 3.2.3b where the mean, minimum and maximum values along with the coefficient of variation are also shown. Location 1 had the lowest non-filtrable residue in all sampling occasions. The minimum value of non-filtrable residue during December 2003 (high tide) was 257 mg/l, maximum value was 3547 mg/l and the coefficient of variation was 70.90. The mean value was 1617 ± 1147 mg/l. The minimum value during February 2005 (high tide) was 980 mg/l, maximum value was 11170 mg/l and the coefficient of variation was50.82. The mean value was 7352 ± 3736 mg/l. The minimum value during May 2005 (high tide) was 630 mg/l, maximum value was 8700 mg/l and the coefficient of variation was 62.51. The mean value was 5394 ± 3372 mg/l. The minimum value during May 2005 (low tide) was 730 mg/l, maximum value was 9610 mg/l and the coefficient of variation was 60.96. The mean value was 6217 ± 3790 mg/l. The minimum value during February 2008 (low tide) was 960 mg/l, maximum value was 9660 mg/l and the coefficient of variation was 60.29. The mean value was 6288 ± 3791 mg/l. The minimum value during May 2009 (high tide) was 1417 mg/l, maximum value was 5638 mg/l and the coefficient of variation was 56.49. The mean value was 3162 ± 1786 mg/l. The minimum value during May 2009 (low tide) was 1254 mg/l, maximum value was 4521 mg/l and the coefficient of variation was 60.86.

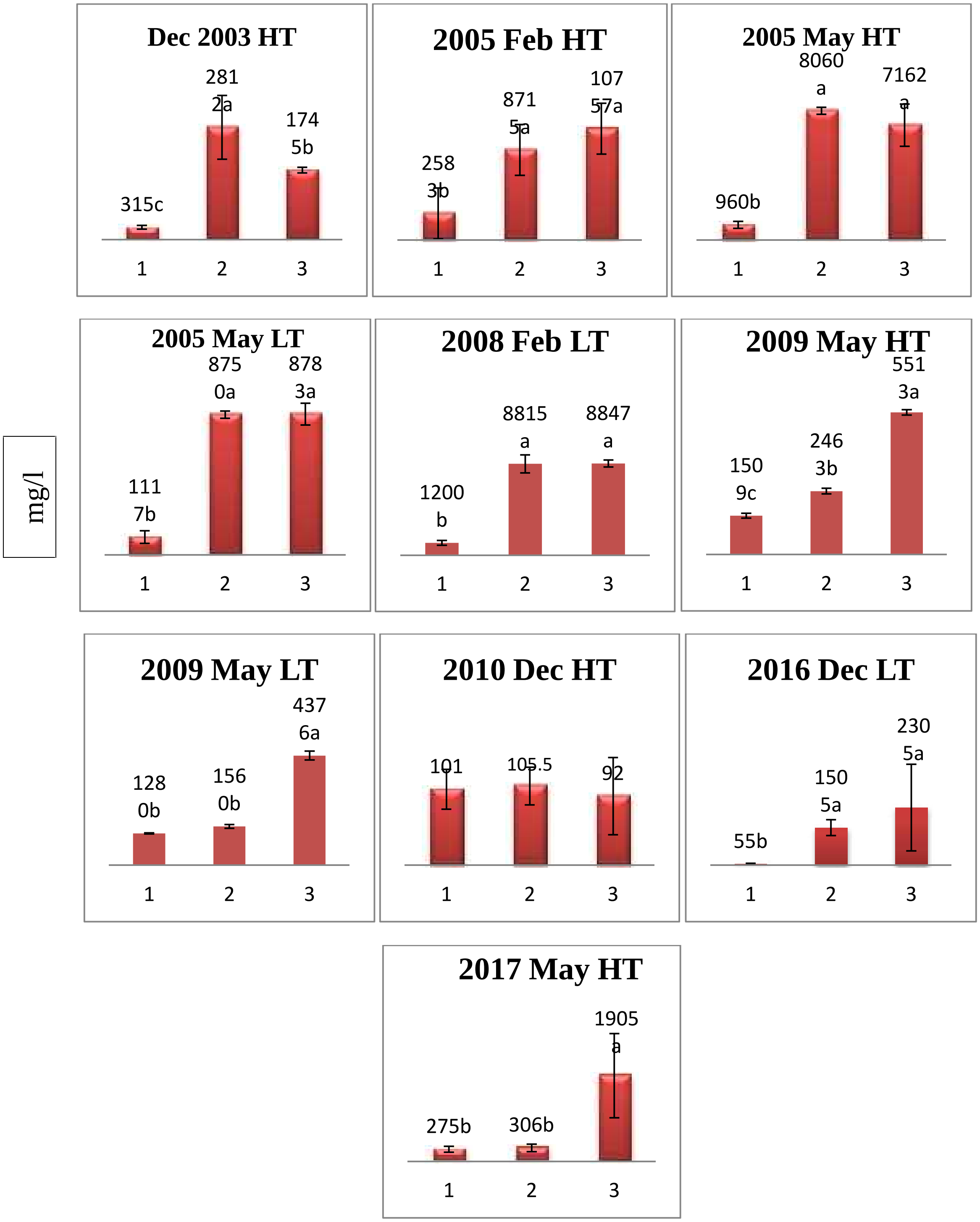


Fig. 3.2.9a: Spatio-temporal dynamics of non-filtrable residue (mg/l) of the water of three locations of the Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

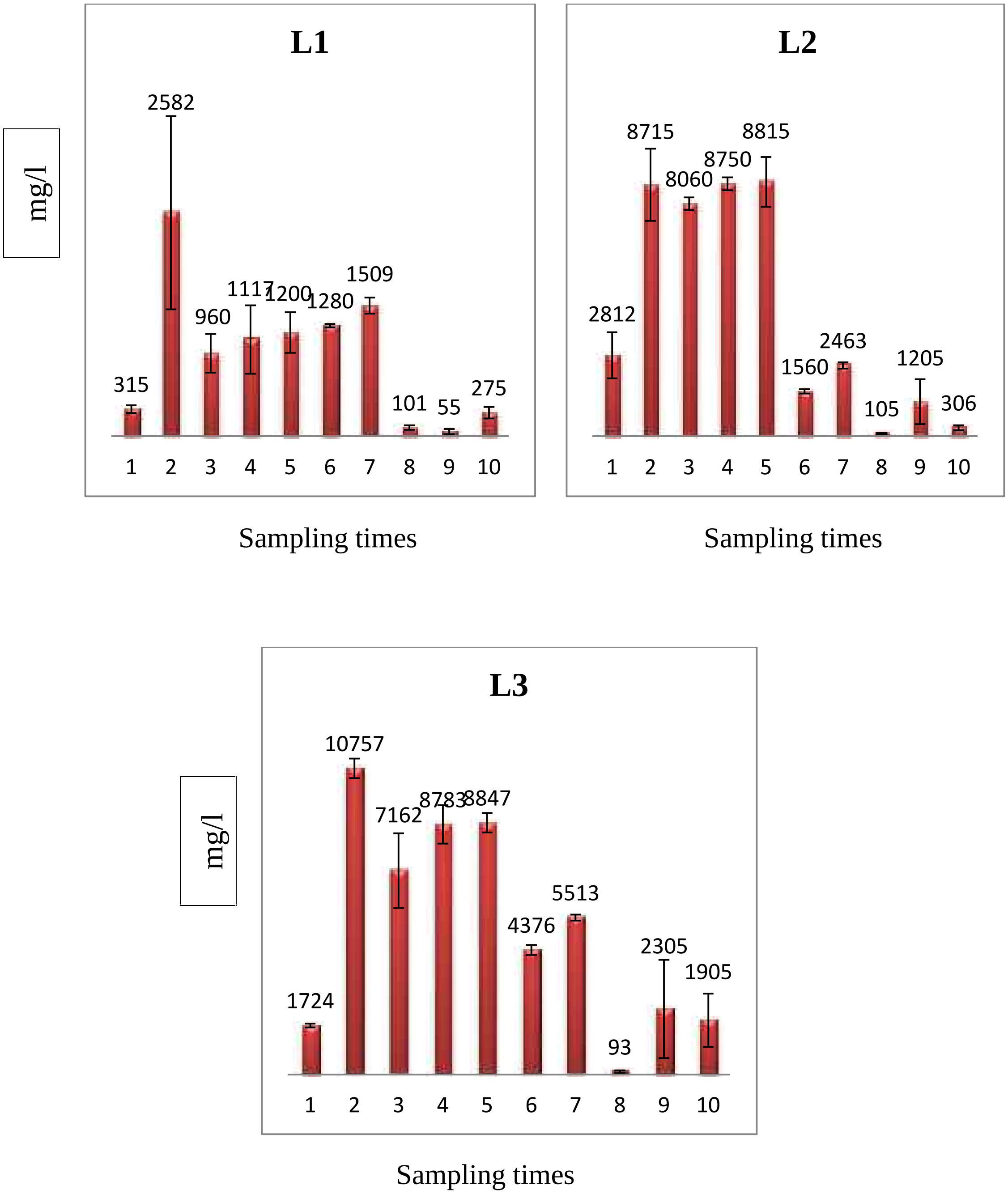


Fig. 3.2.9b: Location wise variation of Non-filtrable residue (mg/l) of the water of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

The mean value was 2406 ± 1464 mg/l. The minimum value during December 2010 (high tide) was 63 mg/l, maximum value was 168 mg/l and the coefficient of variation was 32.73. The mean value was 100 ± 33 mg/l. The minimum value during December 2016 (low tide) was 20 mg/l, maximum value was 4880 mg/l and the coefficient of variation was 115.88. The mean value was 1188 ± 1377 mg/l. The minimum value during May 2017 (high tide) was 200 mg/l, maximum value was 3140 mg/l and the coefficient of variation was 112.78. The mean value was 829 ± 935 mg/l.

Islam (2011) found the mean value of non-filtrable residue of Meghna estuary was 0.81 mg/l where maximum value was 1.58 mg/l and minimum value was 0.40 mg/l which indicated that the water of Buragauranga estuary contained much higher amount of non-filtrable residue. The very low amount of non-filtrable residue of Meghna estuary might be due to huge fresh water supply of the mighty Meghna river. Filtrable residue was found to constitute the major portion of the total solids in the Meghna estuary.

3.2.10 Total Residue of the Estuarine Water

The sampling occasion and location wise total residue values are shown in Fig. 3.2.10a, 3.2.10b and Table 3.2.3c where the mean, minimum and maximum values along with the coefficient of variation are also presented. The minimum value of total residue during December 2003 (high tide) was 398 mg/l, maximum value was 3789 mg/l and the coefficient of variation was 66.41. The mean value was 1787 ± 1187 mg/l. The minimum value during February 2005 (high tide) was 1060 mg/l, maximum value was 11240 mg/l and the coefficient of variation was 49.70. The mean value was 7534 ± 3744 mg/l. The minimum value during May 2005 (high tide) was 1390 mg/l, maximum value was 17450 mg/l and the coefficient of variation was 61.93. The mean value was 10882 ± 6739 mg/l. The minimum value during May 2005 (low tide) was 1510 mg/l, maximum value was 19230 mg/l and the coefficient of variation was 61.52. The mean value was 12427 ± 7645 mg/l. The minimum value during February 2008 (low tide) was 1470 mg/l, maximum value was 10140 mg/l and the coefficient of variation was 55.79. The mean value was 6768 ± 3776 mg/l. The minimum value during May 2009 (high tide) was 2231 mg/l, maximum value was 8777 mg/l and the coefficient of variation was 56.78. The mean value was 4978 ± 2827. The minimum value during May 2009 (low tide) was 1803 mg/l, maximum value was 7374 mg/l and the coefficient of variation was 58.75. The mean value was 4048 ± 2379 mg/l. The minimum value during December 2010 (high tide) was 492 mg/l, maximum value was 857 mg/l and the coefficient of variation was 19.83. The mean value was 643 ± 127 mg/l. The minimum value during December 2016 (low tide) was 120 mg/l, maximum value was 4960 mg/l and the coefficient of variation was 108.00. The mean value was 1273 ± 1375 mg/l. The minimum value during May 2017 (high tide) was 300 mg/l, maximum value was 3680 mg/l and the coefficient of variation was 104.38. The mean value was 1102 ± 1150 mg/l. Islam (2011) found the mean value of total residue of Meghna estuary was 4.50 mg/l where maximum value was 8.24 mg/l and minimum value was 4.50 mg/l.

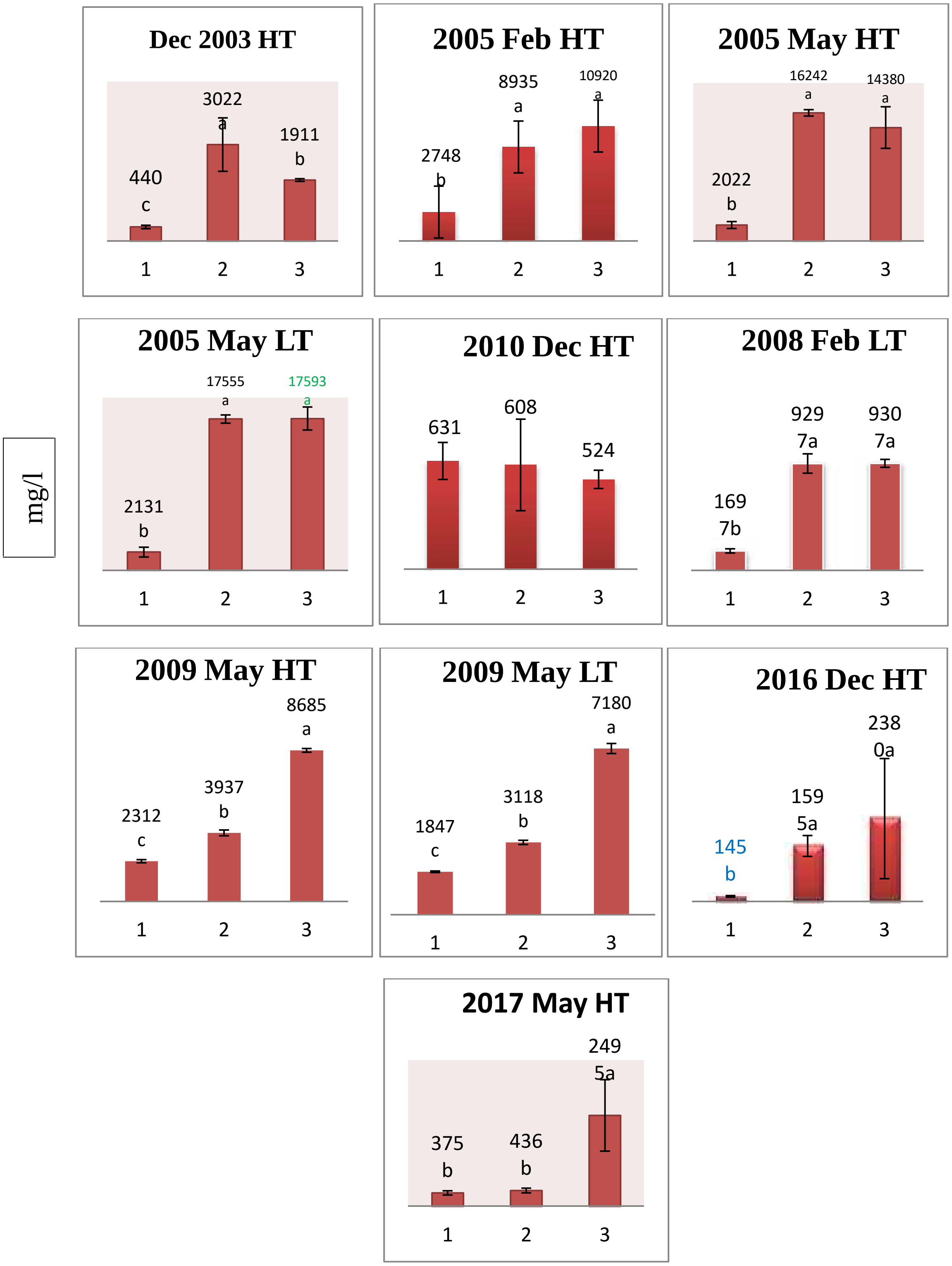


Fig. 3.2.10a: Spatio-temporal dynamics of total residue (mg/l) of the water of three locations of the Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

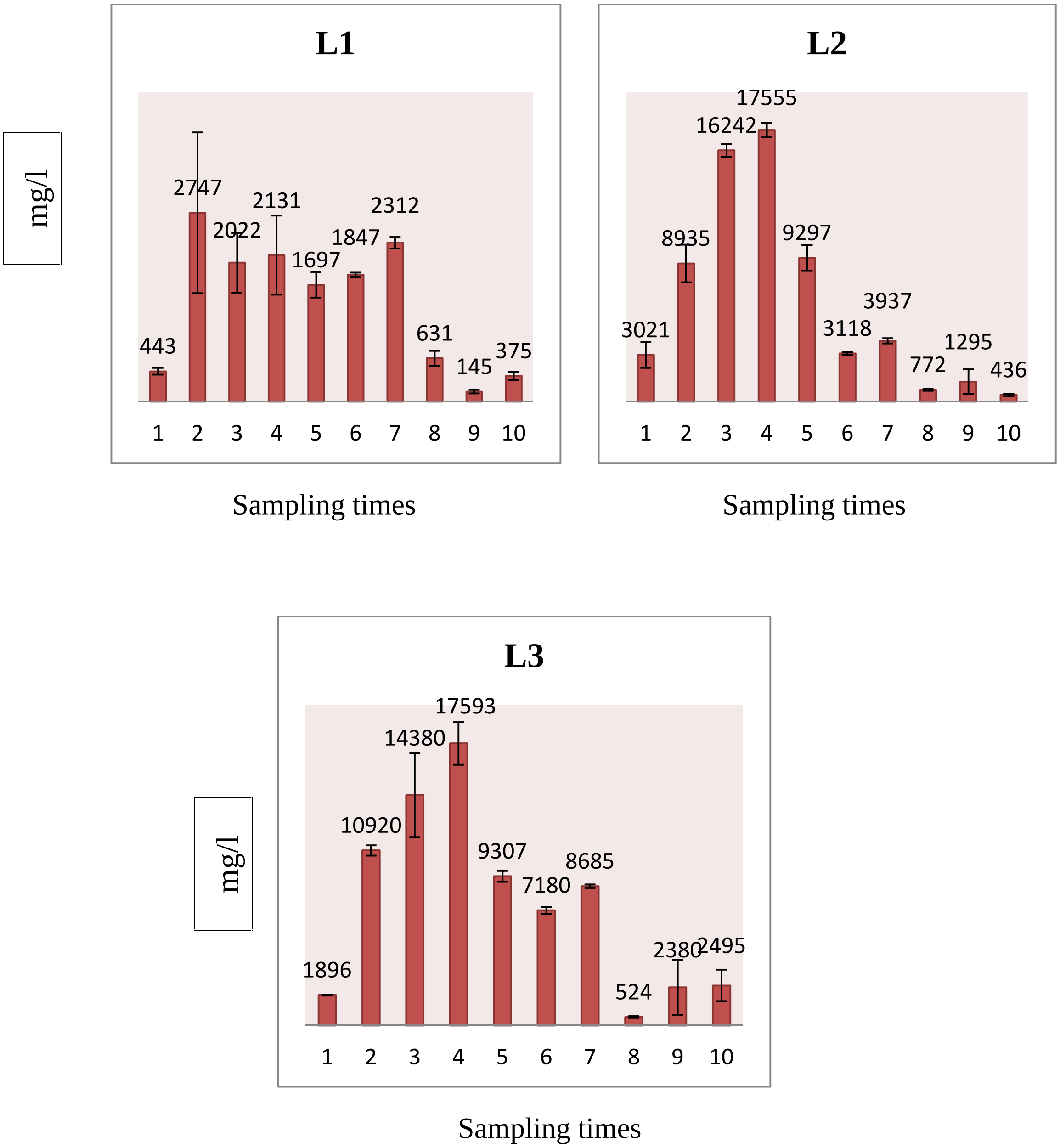


Fig. 3.2.10b: Location wise temporal variations Total residue (mg/l) of the water of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

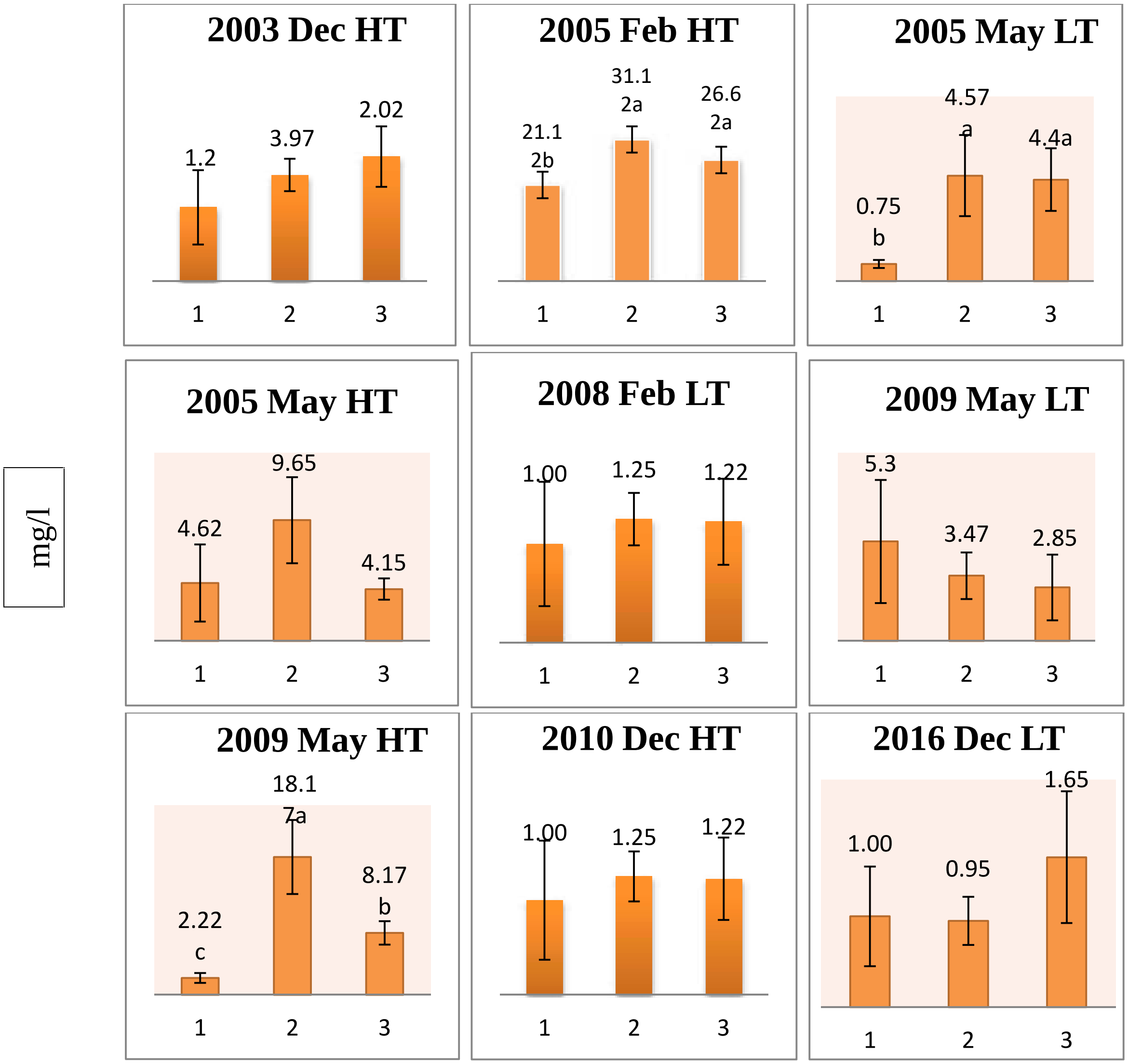
3. 2.11 Temporary Hardness of the Estuarine Water

The sampling occasion and location wise temporary hardness values are shown in Fig. 3.2.11a, 3.2.11b and Table 3.2.4a where the mean, minimum and maximum values along with the coefficient of variation are also shown. Lowest values of temporary hardness were found in all sampling occasion at location 1 except May 2009 during low tide. The minimum value of temporary hardness during December 2003 (high tide) was 0.60 mg/l, maximum value was 2.60 mg/l and the coefficient of variation was 33.84. The mean value was 1.65 ± 0.56 mg/l. The minimum value during February 2005 (high tide) was 20.00 mg/l, maximum value was 32.50 mg/l and the coefficient of variation was 16.61. The mean value was 26.29 ± 4.37 mg/l. The minimum value during May 2005 (high tide) was 1.60 mg/l, maximum value was 14.80 mg/l and the coefficient of variation was 58.18. The mean value was 6.14 ± 3.57 mg/l. The minimum value during May 2005 (low tide) was 0.50 mg/l, maximum value was 6.40 and the coefficient of variation was was 67.18. The mean value was 3.24 ± 2.18 mg/l. The minimum value during February 2008 (low tide) was 0.20 mg/l, maximum value was 1.80 mg/l and the coefficient of variation was 37.80. The mean value was 1.16 ± 0.44 mg/l. The minimum value during May 2009 (high tide) was 1.30 mg/l, maximum value was 23.40 mg/l and the coefficient of variation was 77.53. The mean value was 9.53 ± 7.39 mg/l. The minimum value during May 2009 (low tide) was 0.60 mg/l, maximum value was 9.10 mg/l and the coefficient of variation was 59.73. The mean value was 3.87 ± 2.31 mg/l. The minimum value during December 2010

Table 3.2.4. Descriptive statistics of different variables of three different locations of Buragauranga river estuary, Rangabali, Patuakhali (HT stands for high tide, LT stands for low tide)

a. Temporary hardness (mg/l)						
Time	Mean	StDev	CoefVar	Minimum	Median	Maximum
2003 Dec HT	1.65	0.56	33.84	0.60	1.65	2.60
2005 Feb HT	26.29	4.37	16.61	20.00	26.75	32.50
2005 May HT	6.14	3.57	58.18	1.60	4.90	14.80
2005 May LT	3.24	2.18	67.18	0.50	3.30	6.40
2008 Feb LT	1.16	0.44	37.80	0.20	1.20	1.80
2009May HT	9.53	7.39	77.53	1.30	8.80	23.40
2009May LT	3.87	2.31	59.73	0.60	3.90	9.10
2010Dec HT	1.16	0.44	37.80	0.20	1.20	1.80
2016 Dec LT	1.20	0.59	49.62	0.40	1.10	2.30
2017May HT	12.13	6.29	51.87	2.80	12.90	21.00
b. Permanent hardness (mg/l)						
2003 Dec HT	10.44	7.98	76.44	1.30	9.75	22.20
2005 Feb HT	37.54	10.57	28.16	23.00	41.20	48.50
2005 May HT	27.64	11.66	42.19	7.50	33.25	39.30
2005 May LT	25.03	13.29	53.10	7.70	29.70	42.00
2008 Feb LT	30.22	14.20	46.98	10.80	37.85	48.50
2009May HT	27.30	11.91	43.62	10.20	33.25	39.30
2009May LT	29.03	12.03	41.42	11.10	33.95	43.80
2010Dec HT	31.38	14.32	45.64	11.80	39.35	50.00
2016 Dec LT	19.38	10.98	56.70	7.20	17.45	39.10
2017May HT	9.55	9.66	101.14	1.90	4.35	32.30
c. Total hardness (mg/l)						
2003 Dec HT	12.05	8.08	67.06	2.10	11.45	24.30
2005 Feb HT	63.83	14.11	22.10	44.50	71.90	76.00
2005 May HT	33.78	12.96	38.37	11.10	38.35	47.30
2005 May LT	28.28	15.04	53.19	8.20	34.05	48.00
2008 Feb LT	31.38	14.32	45.64	11.80	39.35	50.00

2009May HT	36.83	17.60	47.80	12.90	43.85	55.80
2009May LT	32.91	11.14	33.87	15.90	36.80	48.60
2010Dec HT	32.53	14.46	44.43	12.00	40.45	51.50
2016 Dec LT	20.12	10.63	52.83	8.60	18.45	40.40
2017May HT	19.38	10.98	56.70	7.20	17.45	39.10



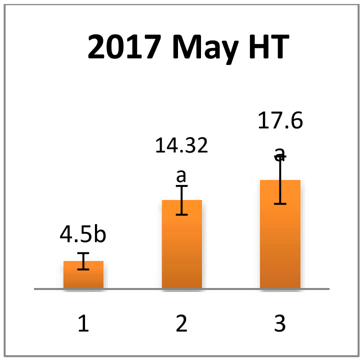
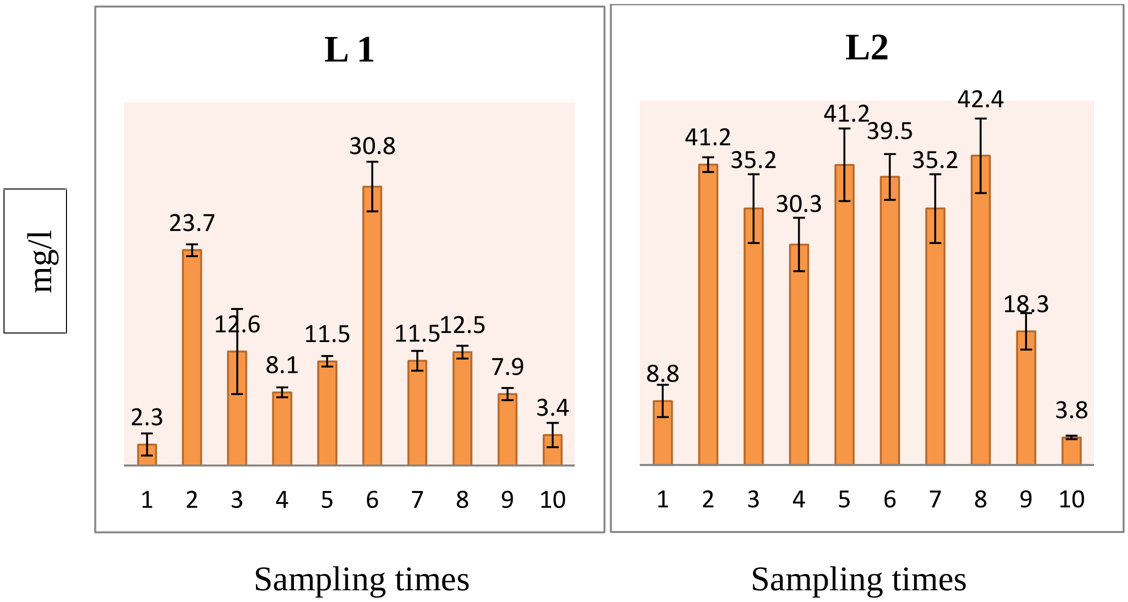


Fig. 3.2.11a: Spatio-temporal dynamics of temporary hardness (mg/l) of the water of the three locations of Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)



mg/l

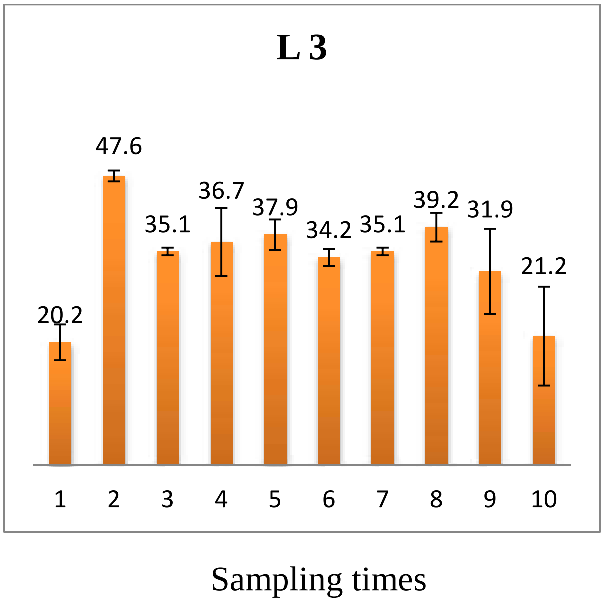


Fig. 3.2.12b: Location wise temporal variation of temporary hardness (mg/l) of the water of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

(high tide) was 0.20 mg/l, maximum value was 1.80 mg/l and the coefficient of variation was 37.80. The mean value was 1.16 ± 0.44 mg/l. The minimum value during December 2016 (low tide) was 0.40 mg/l, maximum value was 2.30 mg/l and the coefficient of variation was 49.62. The mean value was 1.20 ± 0.59 mg/l. The minimum value during May 2017 (high tide) was 2.80 mg/l, maximum value was 21.00 mg/l and the coefficient of variation was 51.87. The mean value was 12.13 ± 6.29 mg/l.

3.2.12 Permanent Hardness of the Estuarine Water

The sampling occasion and location wise permanent hardness values are shown in Fig. 3.2.12a, 3.2.12b and Table 3.2.4b where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value of permanent hardness during December 2003 (high tide) was 1.30, maximum value was 22.20 mg/l and the coefficient of variation was 76.44. The mean value was 10.44 ± 7.98 mg/l. The minimum value during February 2005 (high tide) was 23.00, maximum value was 48.50 mg/l and the coefficient of variation was 28.16. The mean value was 37.54 ± 10.57 mg/l. The minimum value during May 2005 (high tide) was 7.50, maximum value was 39.30 mg/l and the coefficient of variation was 42.19. The mean value was 27.64 ± 11.66 mg/l. The minimum value during May 2005 (low tide) was 7.70, maximum value was 42.00 mg/l and the coefficient of variation was 53.10. The mean value was 25.03 ± 13.29 mg/l. The minimum value during February 2008 (low tide) was 10.80, maximum value was 48.50 mg/l and the coefficient of variation was 46.98. The mean value was 30.22 ±

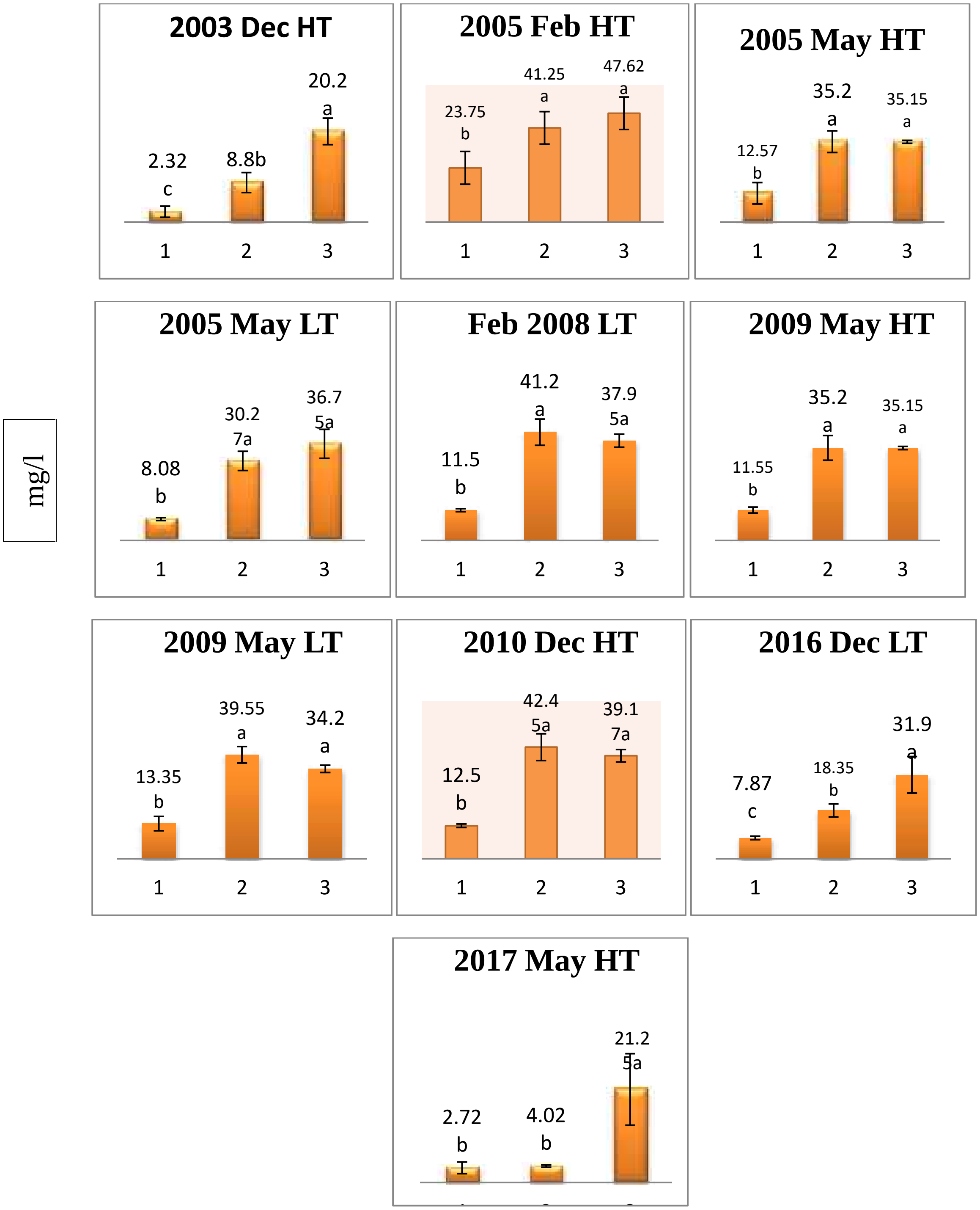


Fig. 3.2.12a: Spatio-temporal dynamics of permanent hardness (mg/l) of the water of three locations of the Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

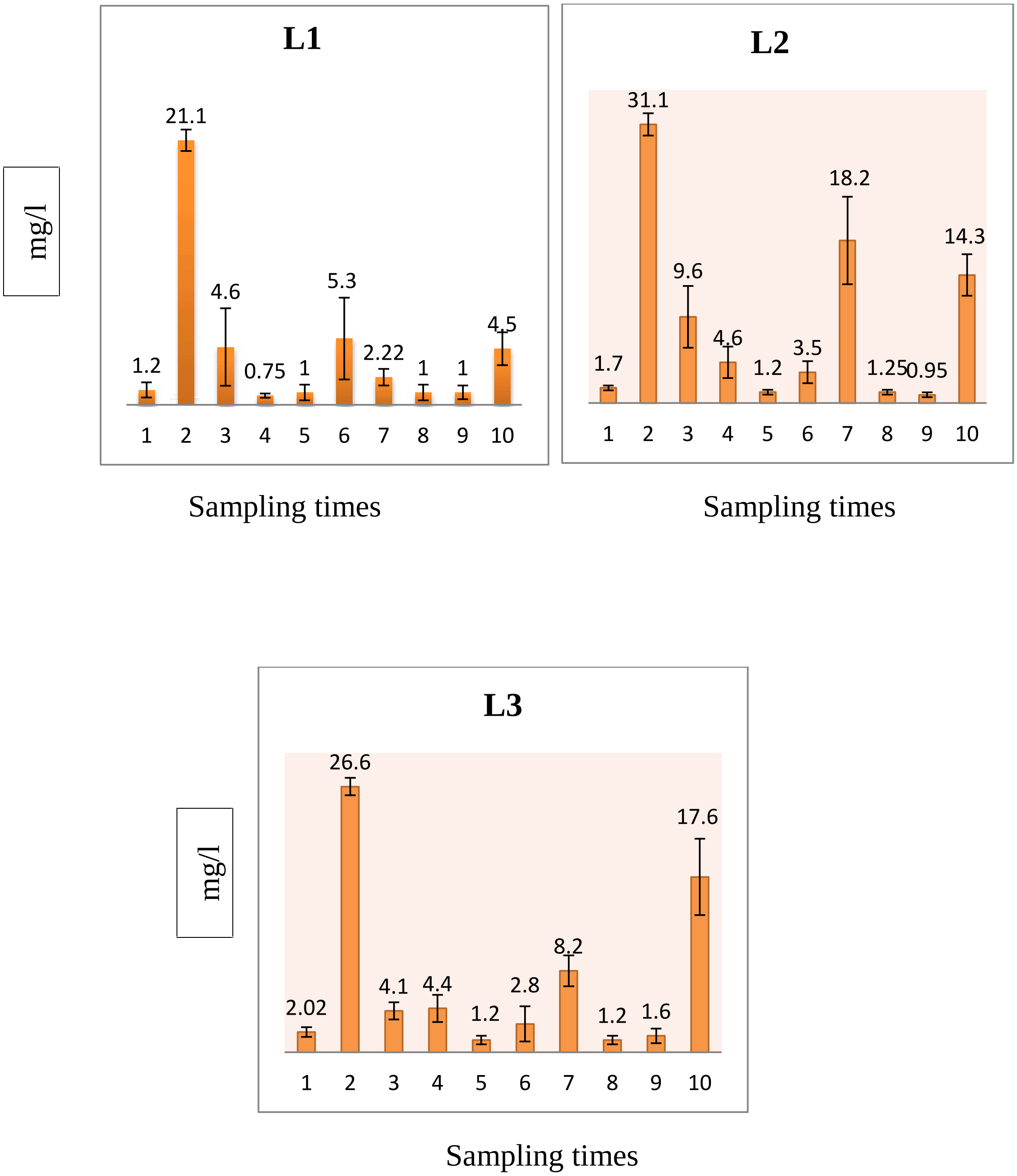


Fig. 3.2.12b: Location wise temporal dynamics of Permanent hardness (mg/l) of the water of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

14.20 mg/l. The minimum value during May 2009 (high tide) was 10.20, maximum value was 39.30 mg/l and the coefficient of variation was 43.62. The mean value was 27.30 ± 11.91 mg/l. The minimum value during May 2009 (low tide) was 11.10, maximum value was 43.80 mg/l and the coefficient of variation was 41.42. The mean value was 29.03 ± 12.03 mg/l. The minimum value during December 2010 (high tide) was 11.80, maximum value was 50.00 mg/l and the coefficient of variation was 45.64. The mean value was 31.38 ± 14.32 mg/l. The minimum value during December 2016 (low tide) was 7.20, maximum value was 39.10 mg/l and the coefficient of variation was 56.70. The mean value was 19.38 ± 10.98 mg/l. The minimum value during May 2017 (high tide) was 1.90, maximum value was 32.30 mg/l and the coefficient of variation was 101.14. The mean value was 9.55 ± 9.66 mg/l.

3.2.13 Total hardness of the Estuarine Water

The sampling occasion and location wise total hardness values are shown in Fig. 3.2.13a, 3.2.13b and Table 3.2.4c where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value of total hardness during December 2003 (high tide) was 2.10 mg/l, maximum value was 24.30 mg/l and the coefficient of variation was 67.06. The mean value was 12.05 ± 8.08 mg/l. The minimum value during February 2005 (high tide) was 44.50 mg/l, maximum value was 76.00 mg/l and the coefficient of variation was 22.10. The mean value was 63.83 ± 14.11 mg/l. The minimum value during May 2005 (high tide) was 11.10 mg/l, maximum value was 47.30 mg/l and the coefficient of variation was 38.37. The mean value was 33.78 ± 12.96 mg/l. The minimum value during May 2005 (low tide) was 8.20 mg/l, maximum value was 48.00 mg/l and the coefficient of variation was 53.19. The mean value was 28.28 ± 15.04 mg/l. The minimum value during February 2008 (low tide) was 11.80 mg/l, maximum value was 50.00 mg/l and the coefficient of variation was 45.64. The mean value was 31.38 ± 14.32 mg/l. The minimum value during May 2009 (high tide) was 12.90 mg/l, maximum value was 55.80 mg/l and the coefficient of variation was 47.80. The mean value was 36.83 ± 17.60. The minimum value during May 2009 (low tide) was 15.90 mg/l, maximum value was 48.60 mg/l and the coefficient of variation was 33.87. The mean value was 32.91 ± 11.14 mg/l. The minimum value during December 2010 (high tide) was 12.00 mg/l, maximum value was 51.50 mg/l and the coefficient of variation was 44.43. The mean value was 32.53 ± 14.46 mg/l. The minimum value during December 2016 (low tide) was 8.60 mg/l, maximum value was 40.40 mg/l and the coefficient of variation was 52.83. The mean value was 20.12 ± 10.63 mg/l. The minimum value during May 2017 (high tide) was 7.20 mg/l, maximum value was 39.10 mg/l and the coefficient of variation was 56.70. The mean value was 19.38 ± 10.98 mg/l.

Prasanna and Ranjan (2010) found that the hardness ranged from 969.68 to 5655.24 mg/l at Dhamra estuary, India. The higher values might be due to the dissolution of the land derived carbonates and bicarbonates in the water and this hardness may affect the photosynthesis and aquatic ecosystem (Gaspar and Lakshman 2014). Gaspar and Lakshman (2014) in their study found that the value

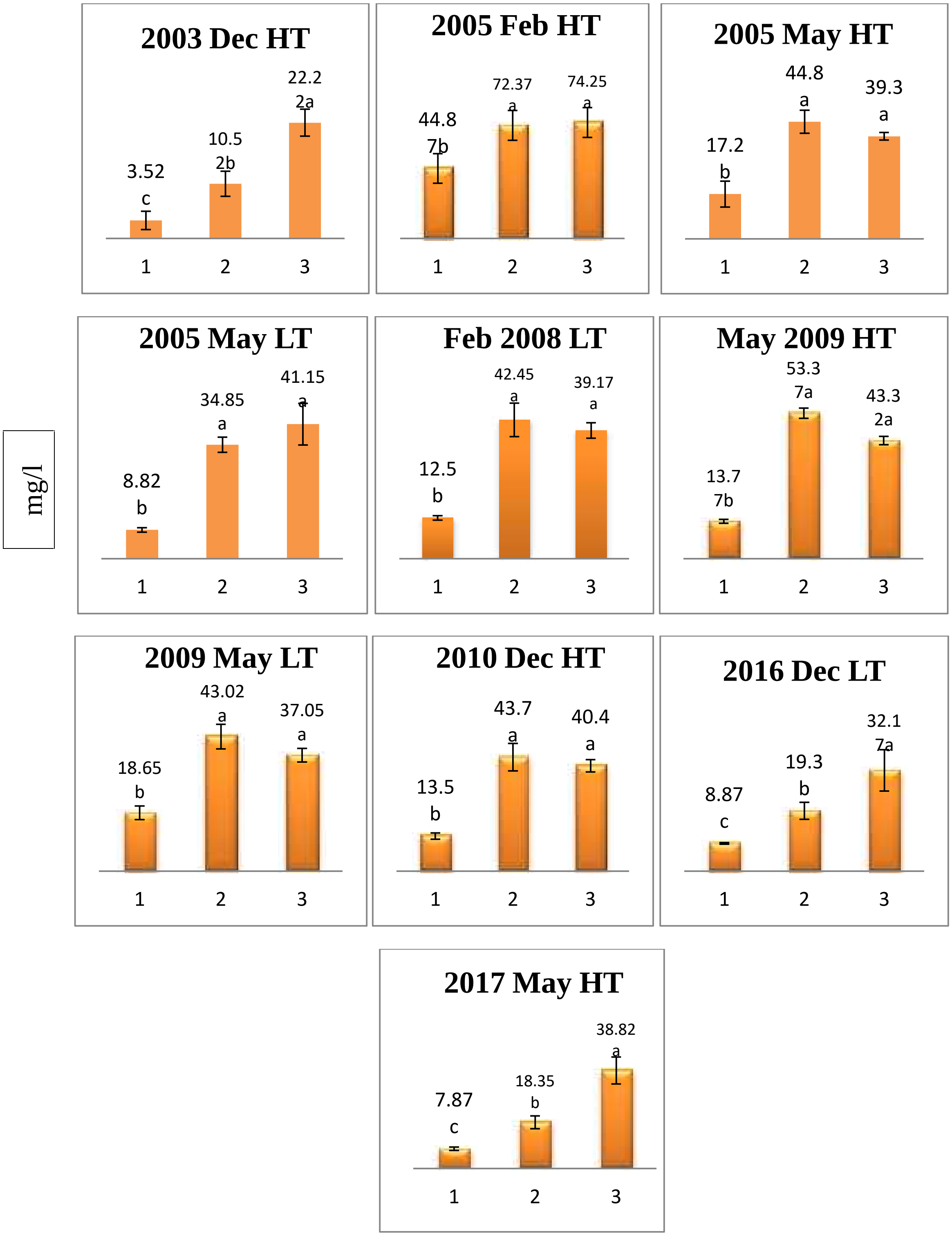


Fig. 3.2.13a: Spatio-temporal dynamics of total hardness (mg/l) of the water of three locations of the Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

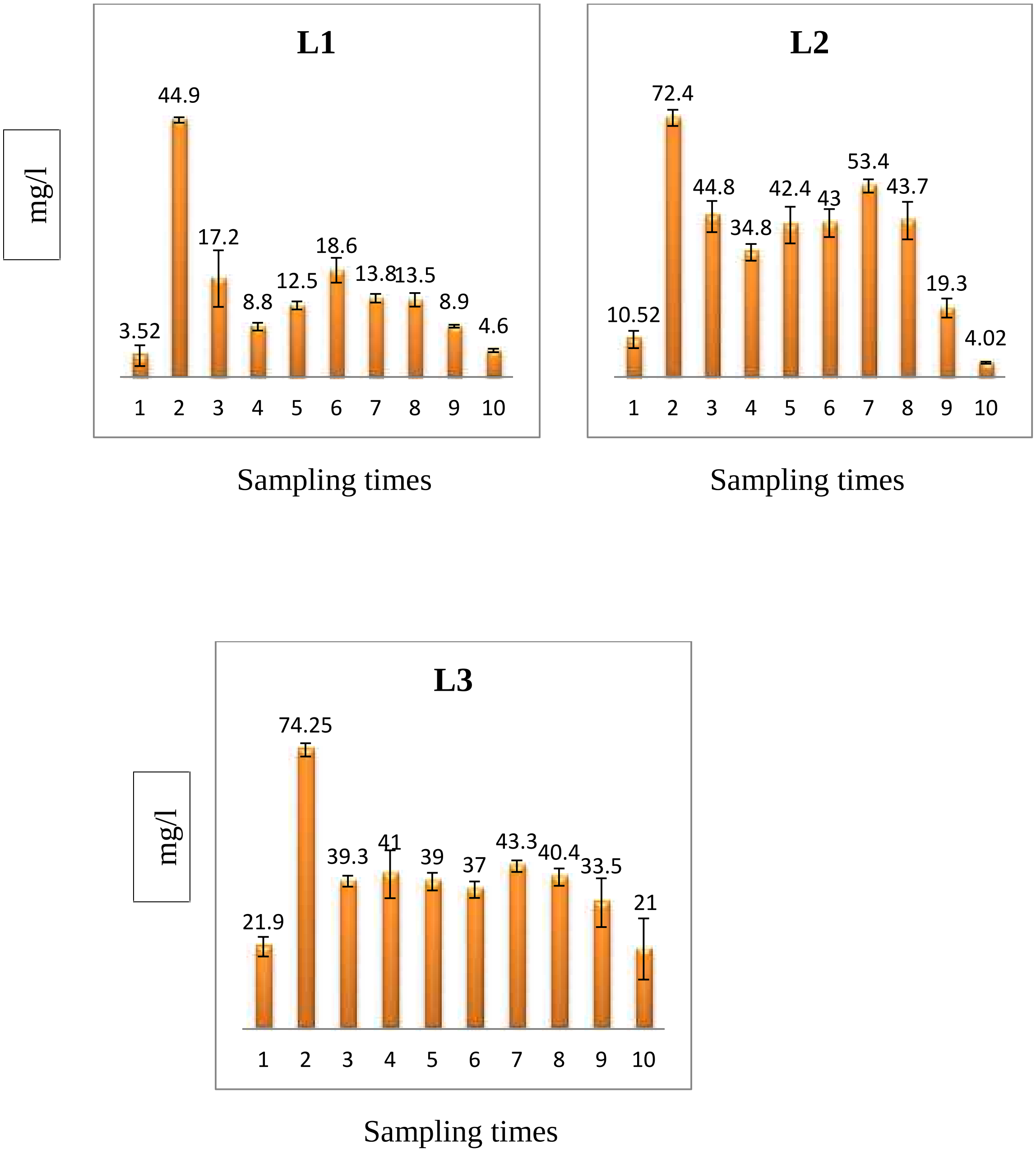


Fig. 3.2.13b: Location wise temporal variation of Total hardness (mg/l) of the water of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

of hardness ranged from 59 to 7070 mg/l in Thamirabarani estuary. Thasneem *et al*. (2018) reported the average total hardness in the Cochin estuary, India was 1823.29 ± 1596.76 mg/l. High level of hardness is present in the water during summer because of dry weather and absence of water flow whereas in monsoon, hardness is very low due to rainfall and water flowing (Gaspar and Lakshman 2014).

3.2.14 Elemental analysis of Estuarine Water

3.2.14.1 Sodium

The sampling occasion and location wise sodium (Na) values are shown in Fig. 3.2.14.1a, 3.2.14.1b and Table 3.2.5a where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value of sodium during December 2003 (high tide) was 2261 mg/l, maximum value was 14709 mg/l and the coefficient of variation was 56.43. The mean value was 7594 ± 4285 mg/l. The minimum value during February 2005 (high tide) was 8012 mg/l, maximum value was 15580 mg/l and the coefficient of variation was 21.79. The mean value was 12040 ± 2624 mg/l. The minimum value during May 2005 (high tide) was 422 mg/l, maximum value was 22278 mg/l and the coefficient of variation was 72.41. The mean value was 11166 ± 8085 mg/l. The minimum value during May 2005 (low tide) was 674 mg/l, maximum value was 20205 mg/l and the coefficient of variation was 73.85. The mean value was 9971± 7364 mg/l. The minimum value during February 2008 (low tide) was 655 mg/l, maximum value was 8790 mg/l and the coefficient of variation was 68.98. The mean value was

Table 3.2.5 Elemental analysis of the Buragauranga estuarine water

Time	Mean	StDev	CoefVar	Minimum	Median	Maximum
a. Sodium (mg/l)						
2003 Dec HT	7594	4285.0	56.43	2261	7447	14709
2005 Feb HT	12040	2624.0	21.79	8012	12912	15580
2005 May HT	11166	8085.0	72.41	422	14657	22278
2005 May LT	9971	7364.0	73.85	674	11786	20205
2008 Feb LT	4495	3100.0	68.98	655	4958	8790
2009 May HT	4639	3020.0	65.10	894	4896	8780
2009 May LT	3390	3178.0	93.76	691	1796	8121
2010 Dec HT	4732	3465.0	73.23	712	4761	10820
2016 Dec LT	4323	1962.0	45.37	1082	4420	7513
2017 May HT	72.8	65.8	90.31	12.3	48	202
b. Potassium (mg/l)						
2003 Dec HT	ND	ND	ND	ND	ND	Nd
2005 Feb HT	15.58	6.17	39.58	8.00	13.55	26.87
2005 May HT	249.60	191.90	76.87	15.00	250.00	550.00
2005 May LT	146.80	105.40	71.80	13.60	159.30	273.00
2008 Feb LT	66.70	39.90	59.86	9.20	92.30	99.90
2009 May HT	42.23	28.54	67.58	8.00	46.00	88.00
2009 May LT	24.62	11.65	47.33	12.40	23.40	45.60
2010 Dec HT	46.83	6.48	13.84	37.50	46.50	60.00
2016 Dec LT	51.88	25.97	50.05	18.43	50.18	90.11
2017 May HT	29.03	32.42	111.69	5.07	11.84	106.54
c. Calcium (mg/l)						
2010Dec HT	59.52	7.26	12.20	52.90	56.60	73.50
2016 Dec LT	58.50	7.42	12.68	51.10	55.25	71.50
2017May HT	70.50	26.19	37.14	43.00	66.50	128.00
d. Magnesium (mg/l)						
2010Dec HT	173.9	48.5	27.86	98.0	166.5	269.0
2016 Dec LT	172.9	49.8	28.82	97.5	160.8	271.0
2017May HT	73.6	43.6	59.26	20.5	65.0	156.0

ND = not detected

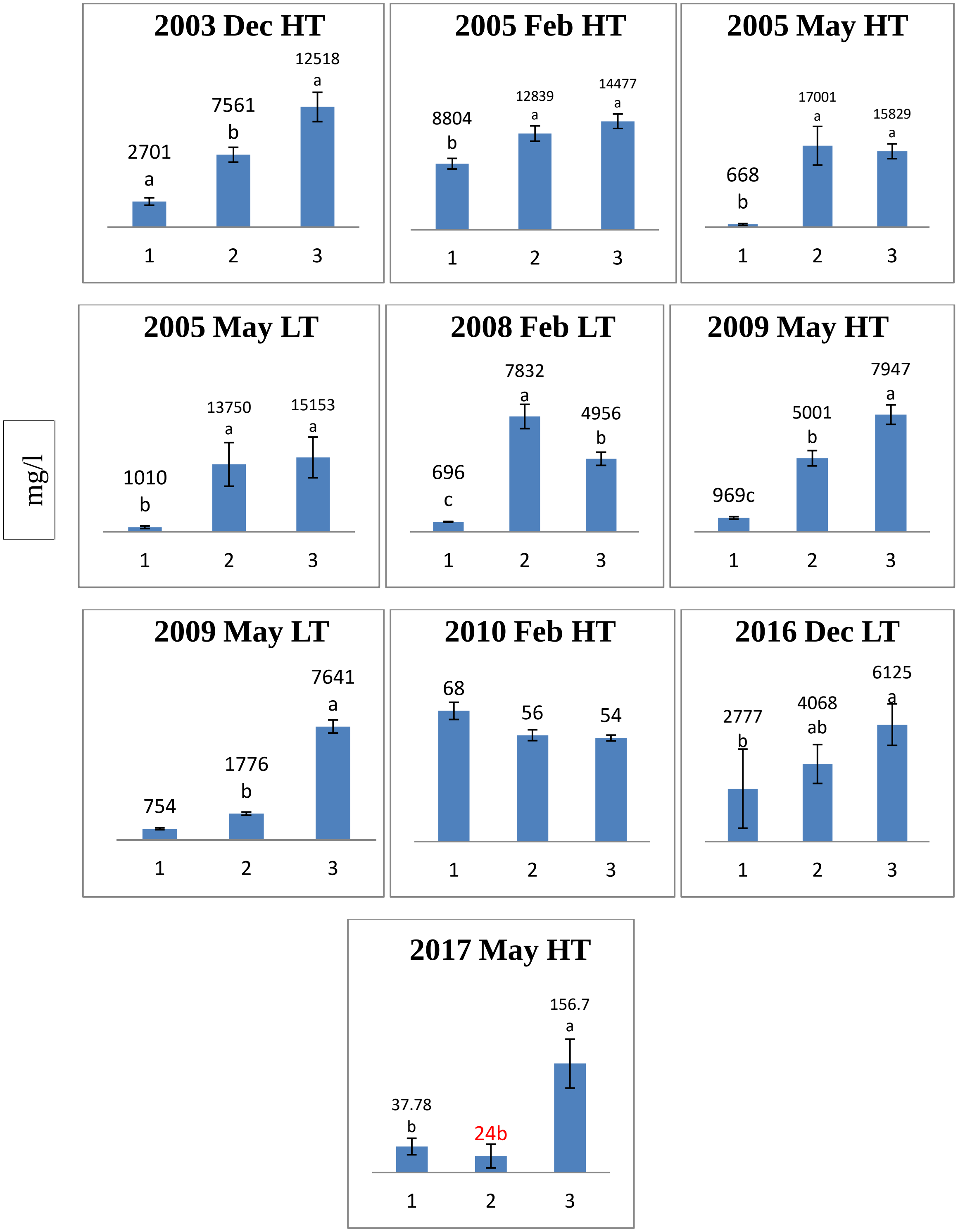


Fig. 3.2.14.1a: Spaito-temporal dynamics of Na (mg/l) of the water of the three locations Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

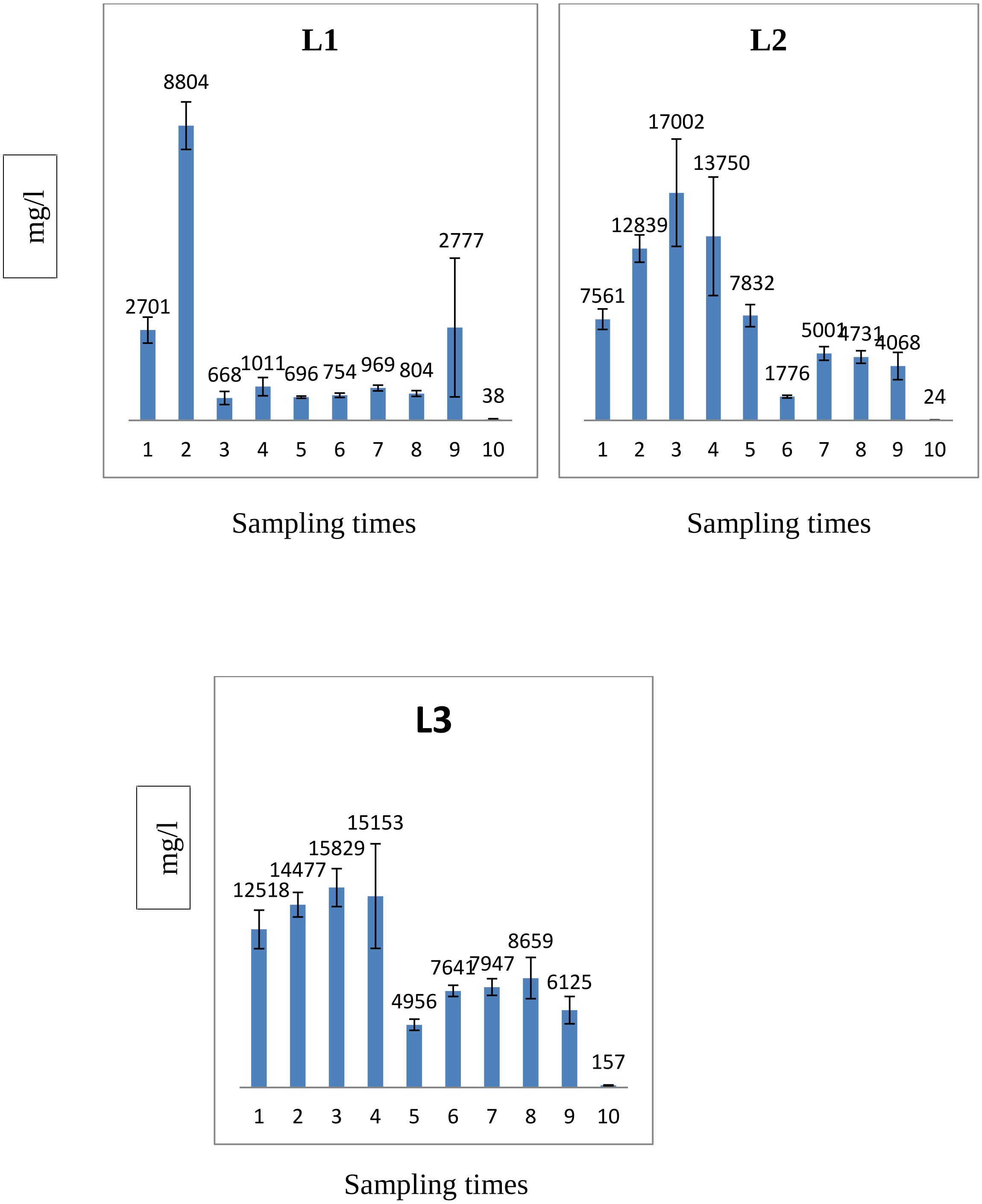


Fig. 3.2.14.1b: Location wise temporal variation of Na (mg/l) of the water of the three location of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

4495 ± 3100 mg/l. The minimum value during May 2009 (high tide) was 894 mg/l, maximum value was 8780 mg/l and the coefficient of variation was 65.10. The mean value was 4639 ± 3020 mg/l. The minimum value during May 2009 (low tide) was 691 mg/l, maximum value was 8121 mg/l and the coefficient of variation was 93.76. The mean value was 3390 ± 3178 mg/l. The minimum value during December 2010 (high tide) was 712 mg/l, maximum value was 10820 mg/l and the coefficient of variation was 73.23. The mean value was 4732 ± 3465 mg/l. The minimum value during December 2016 (low tide) was 1082 mg/l, maximum value was 7513 mg/l and the coefficient of variation was 45.37. The mean value was 4323 ± 1962 mg/l. The minimum value during May 2017 (high tide) was 12.3 mg/l, maximum value was 202.1 mg/l and the coefficient of variation was 90.31. The mean value was 72.8 ± 65.8 mg/l. The concentration of Na of water samples in different rivers flowing inside the SMF in April 2015 was found to vary 600 to 4300 mg/l and 4683.5 to13465.1 mg/l in March 2016 (Akter 2016).

3.2.14.2 Potassium

Potassium is required for all cells principally as an enzyme activator and stored in the plant tissues than in surrounding medium (Hornes and Goldman 1983). The sampling occasion and location wise potassium values are shown in Fig. 3.2.14.2a, 3.2.14.2b and Table 3.2.5.b where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value of potassium during February 2005 (high tide) was 8.00 mg/l, maximum value was 26.87 mg/l and the coefficient of variation was 39.58. The mean value was 15.58 ± 6.17 mg/l.

The minimum value during May 2005 (high tide) was 15.0 mg/l, maximum value was 550.00 mg/l and the coefficient of variation was 76.87. The mean value was 249.60 ± 191.90 mg/l. The minimum value during May 2005 (low tide) was 13.60 mg/l, maximum value was 273.00 mg/l and the coefficient of variation was 71.80. The mean value was 146.80 ± 105.40 mg/l. The minimum value during February 2008 (low tide) was 9.20 mg/l, maximum value was 99.90 mg/l and the coefficient of variation was 59.86. The mean value was 66.70 ± 39.90 mg/l. The minimum value during May 2009 (High tide) was 8.00 mg/l, maximum value was 88.00 mg/l and the coefficient of variation was 67.58. The mean value was 42.23 ± 28.54 mg/l. The minimum value during May 2009 (low tide) was 12.40 mg/l, maximum value was 45.60 mg/l and the coefficient of variation was 47.33. The mean value was 24.62 ± 11.65 mg/l. The minimum value during December 2010 (high tide) was 37.50 mg/l, maximum value was 60.00 mg/l and the coefficient of variation was 13.84. The mean value was 46.83 ± 6.48 mg/l. The minimum value during December 2016 (low tide) was 18.43 mg/l, maximum value was 90.11 mg/l and the coefficient of variation was 50.05. The mean value was 51.88 ± 25.97 mg/l. The minimum value during May 2017 (high tide) was 5.07 mg/l, maximum value was 106.54 ppm and the coefficient of variation was 111.69. The mean value was 29.03± 32.42 mg/l. Values of potassium in different rivers flowing inside the SMF in April 2015 was maximum 630.0 mg/l and minimum 125.0 mg/l where mean value was 344.4 mg/l and 110 to 670 mg/l in March 2016 (Akter 2016). The values of K in the present studies were more than the Manipur river system (2-9 mg/l,

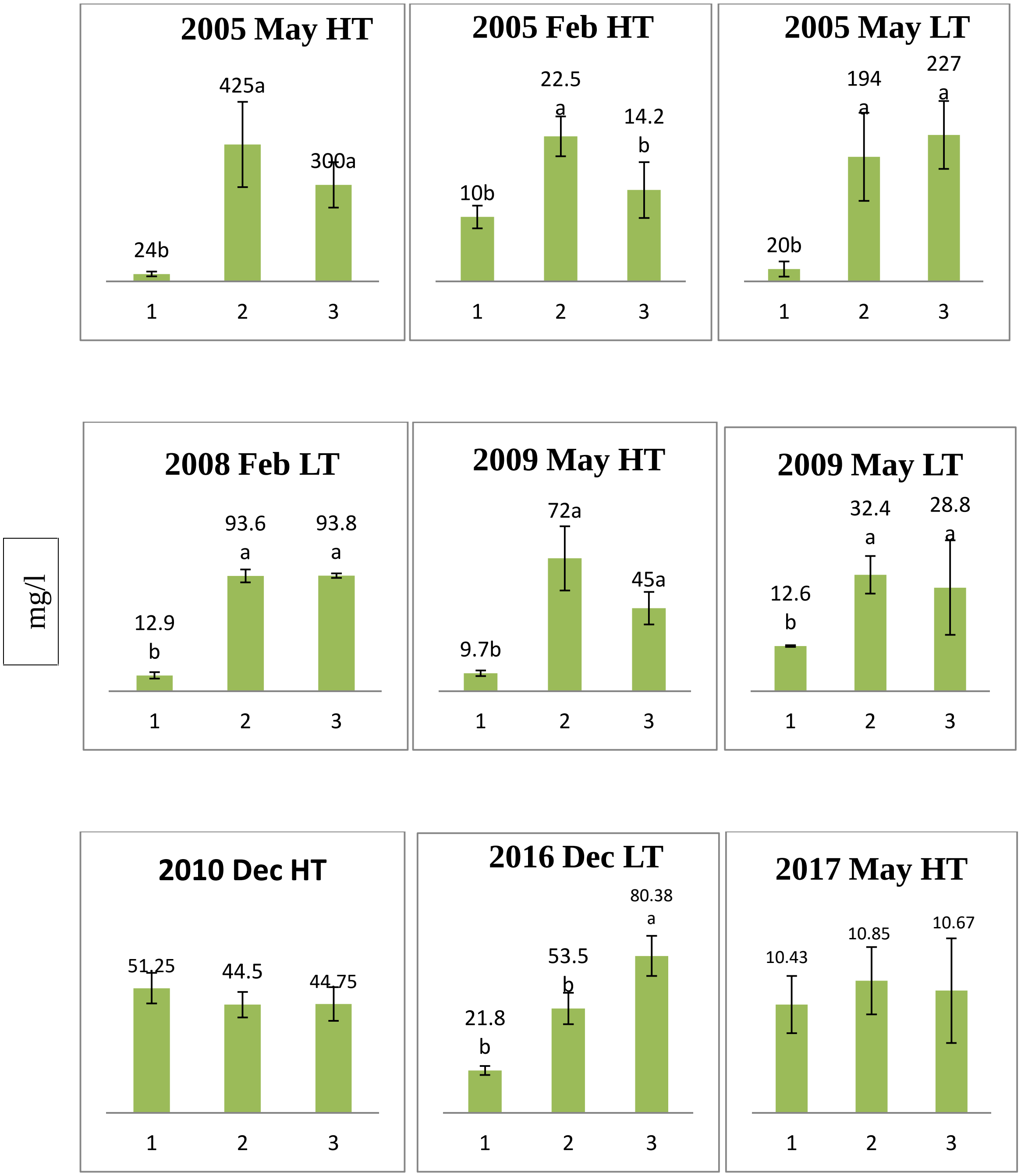


Fig. 3.2.14.2a: Spatio-temporal dynamics of K (mg/l) of the water of three locations of the Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

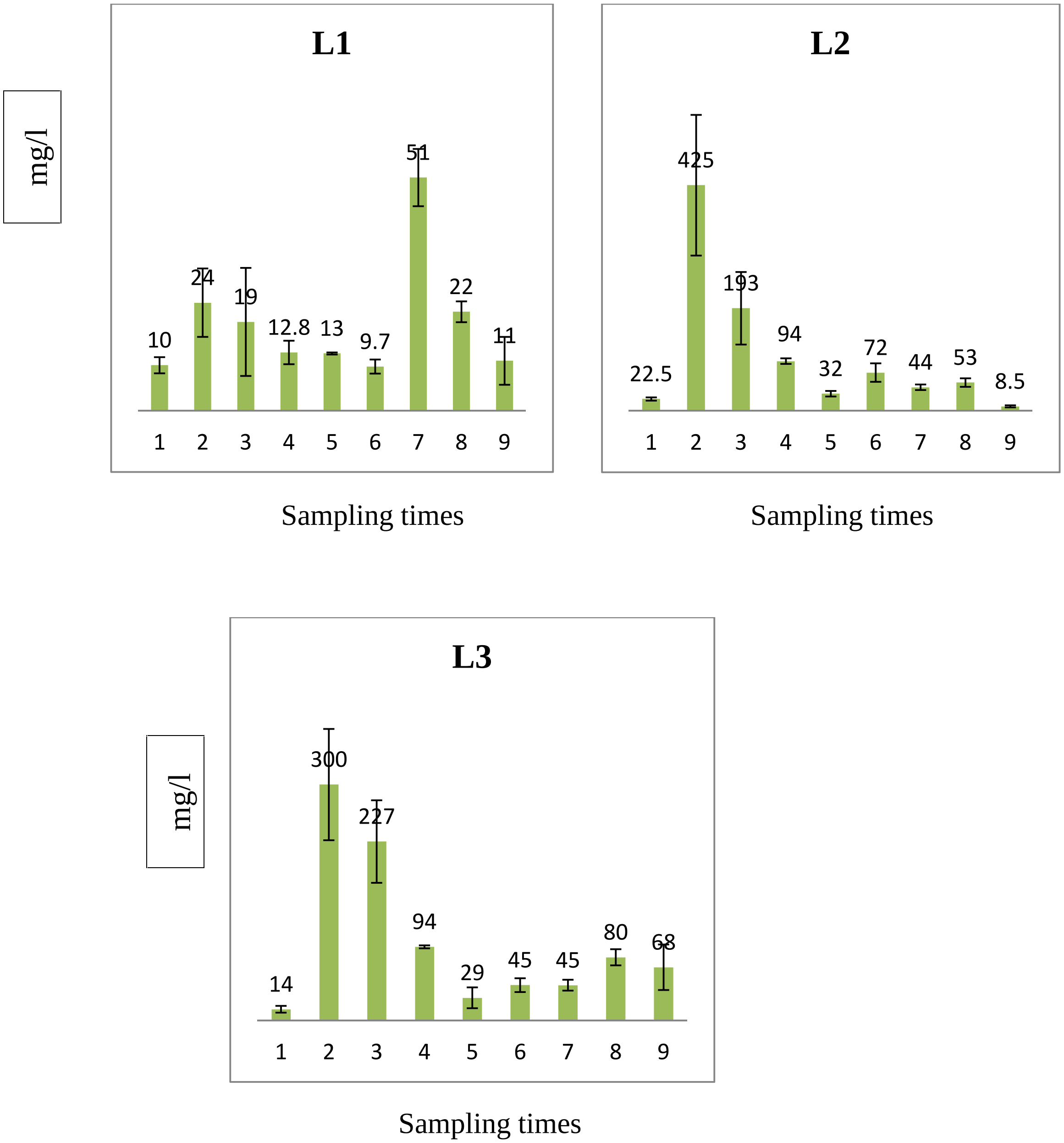


Fig. 3.2.14.2b: Location wise temporal variation of K (mg/l) of the water of Buragauranga river estuary (1 – 10 and L1, L2 and L3 as in Fig. 3.2.1b)

Singh *et al.* 2010). The mean value was within the standard limit of K in the water 50 mg/l as given by WHO (1995).

3.2.14.3 Calcium

The sampling occasion and location wise calcium (Ca) values are shown in Fig. 3.2.14.3 and Table 3.2.5.c where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value during December 2010 (high tide) was 52.90 mg/l, maximum value was 73.50 mg/l and the coefficient of variation was 12.20. The mean value was 59.52 ± 7.26 mg/l. The minimum value during December 2016 (low tide) was 51.10 mg/l, maximum value was 71.50 mg/l and the coefficient of variation was 12.68. The mean value was 58.50 ± 7.42 mg/l. The minimum value during May 2017 (high tide) was 43.00 mg/l, maximum value was 128.00 mg/l and the coefficient of variation was 37.14. The mean value was 70.50 ± 26.19 mg/l.

Islam (2011) found that the amount of Ca ranged from 44.40 - 73.50 mg/l where mean value was 57.38 mg/l in the Meghna estuary. The concentration of Ca in water sample samples of different rivers flowing inside the SMF in April 2015 was found to vary 210 to 500 mg/l (Akter 2016). The calcium content has been found to be high in Arabian Sea and Mandovi and Zuari estuaries (Gupta and Sugandhini 1981), west coast of India (Sugandhini and Dias 1982) and Vellar estuary (Palanichamy and Balasubramanian 1989). Naik (1978) reported that the lowering of the Ca level in the near shore water of Goa during monsoon months was due to dilution effect. According to WHO (1995), the recommended amount of Ca for drinking purpose is below 100 mg/l in the water. The values of the present study were less than the WHO limits except one sampling occasion.

3.2.14.4 Magnesium

The sampling occasion and location wise magnesium (Mg) values are shown in Fig. 3.2.14.4 and Table 3.2.14.d where the mean, minimum and maximum values along with the coefficient of variation are also shown. The minimum value during December 2010 (high tide) was 98.0 mg/l, maximum value was 269.0 mg/l and the coefficient of variation was 27.86 mg/l. The mean value was 173.9 ± 48.5 mg/l. The minimum value during December 2016 (low tide) was 97.5 mg/l, maximum value was 271.0 mg/l and the coefficient of variation was 28.82. The mean value was 172.9 ± 49.8 mg/l. The minimum value during May 2017 (high tide) was 20.5 mg/l, maximum value was 156.0 mg/l and the coefficient of variation was 59.26. The mean value was 73.6 ± 43.6 mg/l. The mean value of Mg of the Meghna estuary was 162.60 mg/l where maximum value was 262.0 mg/l and minimum value was 92.0 mg/l (Islam 2011). The mean value of Mg in different rivers flowing inside the SMF in April 2015 was 611.3 ± 190.5 mg/l where minimum value was 320.0 mg/l and maximum value was 892.0 mg/l (Akter 2016). The higher Mg content was found (average 1243 mg/l) in the Vellar estuary (Palanichamy and Balasubramanian 1989) than the present studies. The standard limit for Mg in the water is 150 mg/l (WHO 1995). The mean values of Mg during different sampling occasion of the present study were little higher than the WHO

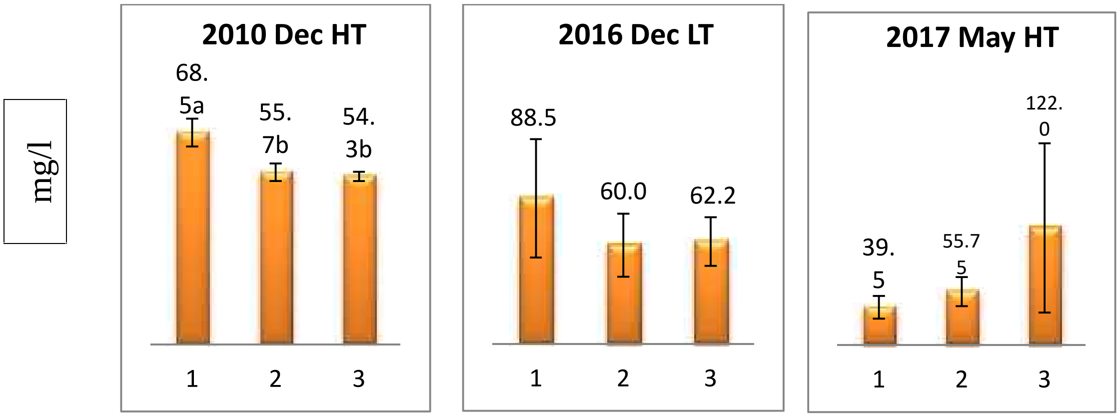


Fig. 3.2.14.3: Spatio-temporal dynamics of Ca (mg/l) of the water of three locations of the Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

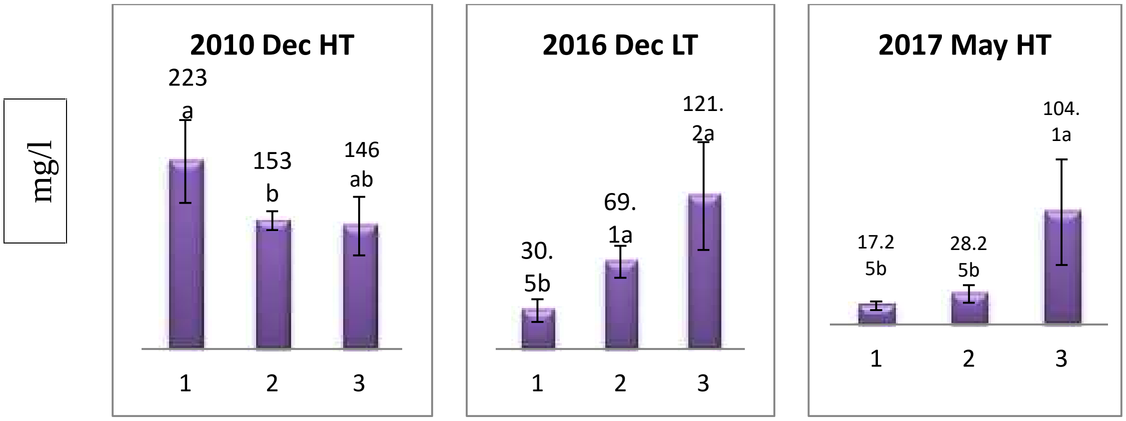


Fig. 3.2.14.4: Spatio-temporal dynamics of Mg (mg/l) of the water of three locations of the Buragauranga river estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

limit but the mean value was comparatively lower than the standard value in 2017.

3.2.14.5 Zinc

The sampling occasion and location wise zinc (Zn) values are shown in Fig. 3.2.14.5. The values of zinc in the study area during May 2010 (high tide) were found to be below detection level. The minimum value during December 2016 (low tide) was 0.02 mg/l, maximum value was 0.05 mg/l. The minimum and maximum values during May 2017 (high tide) were the same as 2016 i.e. the minimum value was 0.02 and the maximum was 0.05 mg/l. Islam (2011) had found the mean values of the Zn in the Meghna estuary were under below detection limit (lowest detection limits for Zn was 0.05 mg/l).

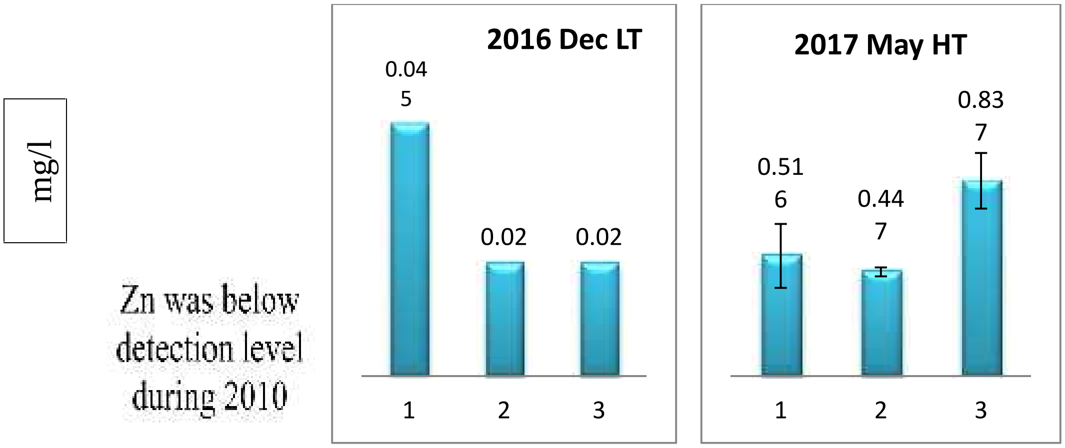


Fig. 3.2.14.5: Spatio-temporal dynamics of Zn (mg/l) of the water of three locations of Buragauranga river Estuary (1, 2 and 3; and LT and HT as in Fig. 3.2.1a)

3.2.14.6 Manganese, Iron and Lead

It was found that Manganese (Mn), iron (Fe) and lead (Pb) content of the water of the Buragauranga River estuary were below the detection level of the machine (the level of detection for Mn was 0.02 mg/l, for Fe was 0.04 mg/l and for Pb 0.20 mg/l). Islam (2011) found that the mean values of the Mn in the Meghna estuary were under below detection limit (lowest detection limits for Mn was 0.02 mg/l). The mean value of Fe of Meghna estuary was 0.092 mg/l where maximum value was 0.23 mg/l and minimum value was 0.04 mg/l (Islam 2011).

The ecology of coastal area of Bangladesh is regulated by tidal impact from Bay of Bengal. But the present study revealed that fresh water supply from the Meghna River also plays a vital role in the ecology of this area. The tidal action of the sea inundates the whole coastal zones of Bangladesh to varying depths, pushing back silt to the river, channels and creeks. The central coastal zone is the most dynamic estuarine deltas of the country. Estuaries provide habitat and breeding locations for a great number of aquatic species and thus are critically important ecosystems. Although human civilizations have historically depended on and benefited from estuarine resources, only recently have we recognized the effects of habitat disturbances (NOAA 2016).

3.3 Soil quality

Soils of the chars were found less heterogeneous especially during each sampling occasions with few exceptions such as iron (Fe) showed high variability during all sampling occasion. The values ranged from 268 – 4815, 211 - 5245, 6 – 16200 and 3 – 26050 µg/g (Table 3.3.1, 3.3.2, 3.3.3 and 3.3.4 respectively). The Na and K contents of soil also showed very high variability during 2016 (CoVar were 252.6 and 233.5% respectively) (Table 3.3.3). Das (2012) has also found that the Char Tamaruddin at Hatia, Noakhali to be rather homogenous in respect to soil quality.

3.3.1. Moisture content

Total nutrient masses and their redistribution in the soil profile are greatly influenced by soil moisture content. For the growth of vegetation water storage capacity in topsoil layers has also been found to be of great importance. The variations of moisture content in both layers of soil of the three chars during the study period are shown in Fig. 3.3.1. The moisture content of the study area varied from 22.57 to 40.24 % during May 2009 with the mean value was 33.0 ± 0.97 % (Table 3.3.1). Some variation of moisture content of soil was found and the co-efficient of variation was 5.26 (Table 3.3.1). The moisture content of the study area varied from 21.56 to 44.84 % during December 2010 with the mean value of 30.13 ± 1.95 % (Table 3.3.2). Some variations in moisture content of soil was found and the co-efficient of variation was 24.5 (Table 3.3.2). The moisture content of the study area varied from 18.27 % to 50.12 % during December 2016 with the mean value was 30.56 ±8.65% (Table 3.3.3). Some variations of moisture

Fig 3.3.1: Spatio-temporal variation of soil moisture (%) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

content of soil was found and the co-efficient of variation was 28.29 (Table 3.3.3). The moisture content of the study area varied from 20.60 to 35.30 % during May 2017 with the mean value of 26.09 ± 3.358 % (Table 3.3.4). The co-efficient of variation was low, 12.87 i.e. the moisture content of soil from chars did not vary much (Table 3.3.4). Das (2012) also found that the mean value of soil moisture in the Char Tamaruddin at Hatia, Noakhali was 28.97% where the minimum value was 19.10 % and maximum value was 40.50 %. Ataullah *et al.* (2017) have found that the overall mean of the soil moisture of Bangladesh Sundarbans was 25.701% with minimum value 11.23 % and maximum 44.9 %.

3.3.2. pH

The overall values of pH during study periods ranged from 6.0 (Char Kashem in 2017) to 7.9 (Char Motherbunia in 2017). The variations of pH in both layers of soils of the three Chars during the study period are shown in Fig. 3.3.2, where the mean values showed that all the three chars were slightly acidic to moderately alkaline. The mean values of pH ranged from 6.74 (in 2016) to 7.78 (in 2017), 6.24 (in 2017) to 7.7 (in 2010) and 6.72 (in 2016) to 7.43 (in 2009) in Char Motherbunia, Char Taposhi and Char Kashem, respectively. During May 2009, soil pH of the study area varied from 7.20 to 7.80 with the mean value of 7.5 ± 0.13 indicating that the soil was slightly alkaline in nature (Table 3.3.1). The co-efficient of variation was low, 1.80 i.e. the char’s soil did not vary much in respect to pH values (Table 3.3.1). During December 2010 the soil pH of the study area varied from 7.10 to 7.80 with the mean value was 7.47 ± 0.20 indicating that the

Table 3.3.1: Descriptive statistics of different variables of soil of the three chars (May 2009) (Cond. = conductivity, Sal. = salinity, Avl.= available, OC = organic carbon, OM = Organic matter, StDev = standard deviation, CoefVar = coefficient of variation)

Variable	Mean	StDev	CoefVar	Minimum	Median	Maximum
Moisture %	33.0	0.97	5.26	22.57	29.5	40.24
pH	7.5	0.13	1.80	7.20	7.50	7.80
Cond. mS/cm	9.4	4.39	47.07	4.05	9.70	18.95
Sal. ‰	5.97	2.81	47.08	2.59	6.21	12.13
OC %	0.471	0.089	19.02	0.310	0.485	0.590
OM %	0.810	0.154	19.02	0.533	0.834	1.015
Avl. N ppm	1.721	0.530	30.83	0.430	1.570	2.420
P %	0.0292	0.0072	24.75	0.0121	0.0314	0.0372
Na µg/g	947	303	32.08	588	837	1584
K µg/g	55.66	27.62	49.62	19.22	48.05	105.71
Ca µg/g	4240	1354	31.94	2186	3969	6908
Mg µg/g	6071	1806	29.75	3122	6027	8995
Mn µg/g	166.42	26.30	15.80	108.00	174.50	210.00
Fe µg/g	1422	1591	111.83	268	399	4815
Zn µg/g	35.50	10.58	29.81	18.00	32.50	60.00

soil was slightly alkaline in nature (Table 3.3.2). The co-efficient of variation was low, 2.69 i.e. the soil pH of chars did not vary much (Table 3.3.2). The pH of the study area decreased in 2016 and varied from 6.10 to 7.50 during December 2016 with the mean value was 6.67 ± 0.308 indicating that the soil was slightly acidic although the higher value was alkaline in nature (Table 3.3.3). The co-efficient of variation was low, 4.56 (Table 3.3.3). The pH of the study area varied from 6.00 to 7.900 during May 2017 with the mean value of 6.99 ± 0.604 indicating that the soil was neutral in nature although slightly acidic condition was also found (pH = 6.0) (Table 3.3.4). The co-efficient of variation was low, 8.64 i.e. the chars do not vary much (Table 3.3.4).

Das (2012) has found that the studied char at Tamaruddin at the coastal area of Noakhali district, Bangladesh and soils were alkaline in nature. Mean of the soil pH was 7.22 with minimum value of 7.00 and maximum 7.50. The pH of the soils of Bangladesh Sundarbans did not show much variations among the different locations where the overall mean was 7.34 with minimum value of 6.2 and maximum of 8.6 indicating the slightly alkaline nature although minimum value was acidic (Ataullah *et al*. 2017). Soil pH of other mangrove ecosystems located in Southeast coast of China was found to vary from 2.6 - 6.9 (Lin *et al*. 1987). This acidity might be partly due to oxidation of FeS_2 to H_2SO_4 (Holmer *et al.* 1994) and resulted from decomposition of mangrove litter (Lacerda *et al.* 1995). Various kinds of organic acids are derived from hydrolysis of tannin in mangrove plants and breakdown of organic matter.

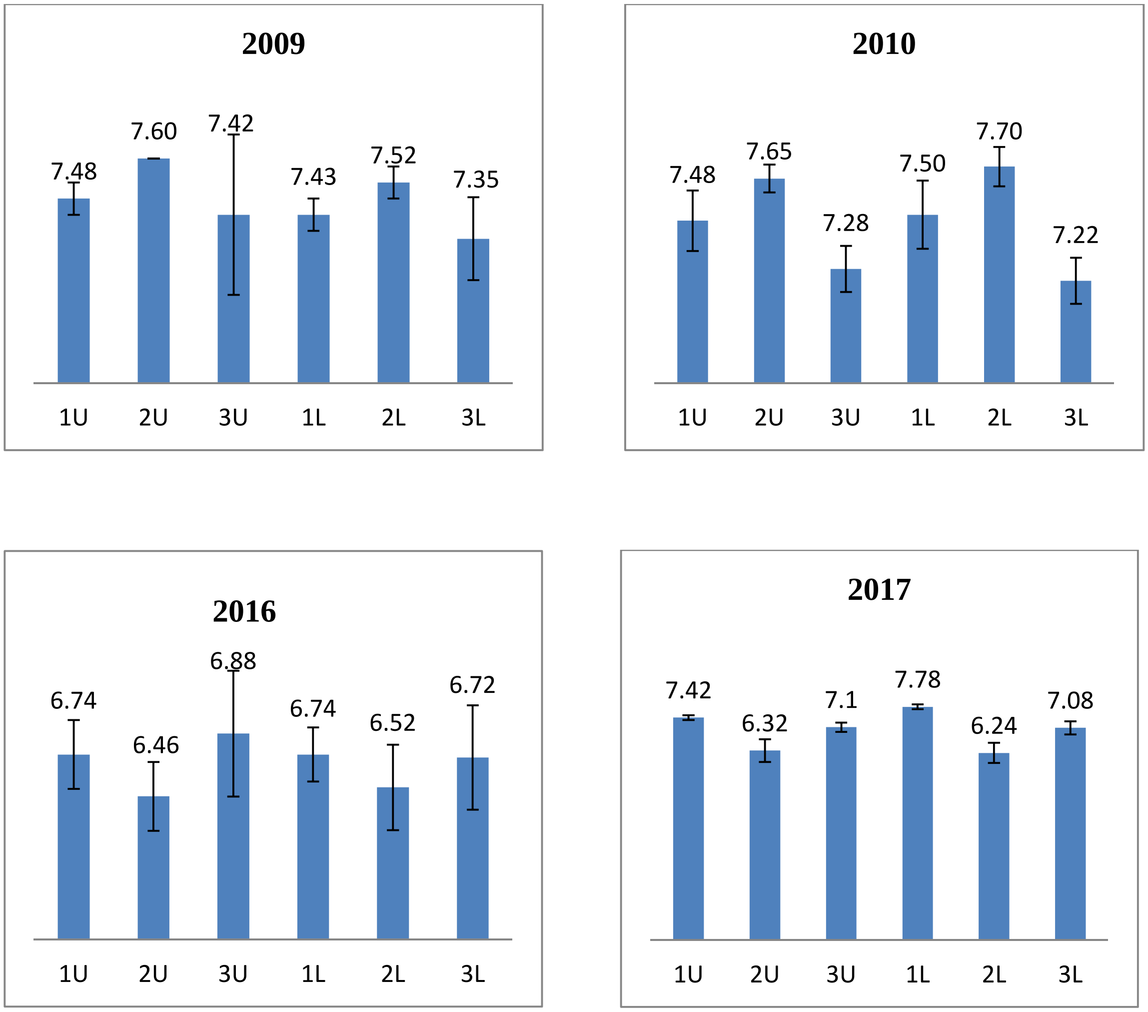


Fig 3.3.2: Spatio-temporal variation of soil pH of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

Table 3.3.2: Descriptive statistics of different variables of soil of three chars (December 2010) (abbreviated forms are same as Table 3.3.1)

Variable	Mean	StDev	CoefVar	Minimum	Median	Maximum
Moisture %	30.13	1.95	24.5	21.56	29.61	44.84
pH	7.47	0.20	2.69	7.10	7.50	7.80
Cond. mS/cm	9.69	5.29	54.54	2.50	9.80	24.10
Sal. ‰	6.203	3.383	54.54	1.60	6.27	15.42
OC%	0.406	0.094	23.24	0.28	0.38	0.59
OM %	0.698	0.162	23.24	0.482	0.654	1.015
P%	0.0308	0.0075	24.35	0.0171	0.0314	0.0526
Avl. N ppm	1.583	0.403	25.44	0.71 0	1.710	2.420
Na µg/g	888.1	305.4	34.39	498.0	769.0	1448.0
K µg/g	49.25	26.93	54.68	19.22	38.44	96.10
Ca µg/g	5241	1145	21.84	3198	5544	7101
Mg µg/g	5829	1666	28.59	3448	5657	9342
Mn µg/g	265.2	53.2	20.08	168.0	267.0	383.0
Fe µg/g	1549	1774	114.49	211	421	5245
Zn µg/g	36.67	8.47	23.11	22.00	36.50	57.00

Seawater has a strong buffering capacity which helps to neutralize acidic pH (Wakushima *et al.* 1994). Therefore, pH changes along tidal gradients directly reflected the tidal regime and degree of litter production and decomposition.

3.3.3. Electrical Conductivity of Soils

The variations of conductivity in both layers of soil of the three Chars during the study period are shown in Fig. 3.3.3. The conductivity of the studied soils of the area varied from 4.05 to 18.95 mS/cm during May 2009 with a mean value of 9.4 ± 4.39 mS/cm (Table 3.3.1). The co-efficient of variation was 47.07 i.e. there were variation within the chars in terms of conductivity (Table 3.3.1). During December 2010 the conductivity of the study area increased little bit and varied between 2.50 to 24.10 mS/cm with a mean value of 9.69 ± 5.29 mS/cm (Table 3.3.2). The co-efficient of variation was low, 54.54 i.e. the conductivity of chars showed some variation (Table 3.3.2). The conductivity of the soils varied from 1.01 to 2.99 mS/cm during December 2016 with a mean value of 1.83 ± 0.48 mS/cm (Table 3.3.3). The co-efficient of variation was 26.54 i.e. there were some variation within the chars in terms of electrical conductivity of soil (Table 3.3.3). Low conductivity was found during May 2017 in the soil of the study area. The conductivity varied between 1.615 to 8.39 mS/cm with a mean value of 4.17 ± 1.92 mS/cm (Table 3.3.4). The co-efficient of variation was 46.13 which indicated some variation within the chars in terms of conductivity of soil (Table 3.3.4).

Table 3.3.3: Descriptive statistics of different variables of soil of three chars (December 2016) (abbreviated forms are same as Table 3.3.1)

Variable	Mean	StDev	CoefVar	Minimum	Median	Maximum
Moisture %	30.56	8.65	28.29	18.27	28.99	50.12
pH	6.67	0.308	4.56	6.10	6.7000	7.50
Cond. mS/cm	1.83	0.485	26.54	1.01	1.72	2.99
Sal ‰	1.17	0.31	26.53	0.65	1.10	1.91
OC%	0.472	0.136	28.92	0.195	0.480	0.690
OM %	0.812	0.235	28.92	0.335	0.826	1.187
P%	0.0482	0.008	16.58	0.0374	0.0465	0.0767
Avl N ppm	1.727	0.731	42.34	0.854	1.637	4.269
Na µg/g	734.6	487.6	66.38	226.3	588.3	2036.3
K µg/g	83.8	211.7	252.62	13.7	34.4	1190.8
Ca µg/g	5330	2602	48.82	1550	4950	11900
Mg µg/g	6182	1115	18.03	3200	6175	8400
Mn µg/g	193.50	39.26	20.29	80.00	195	300
Fe µg/g	4642	5418	116.70	6.00	1750	16200
Zn µg/g	31.63	10.06	31.81	1.00	33.25	48.00

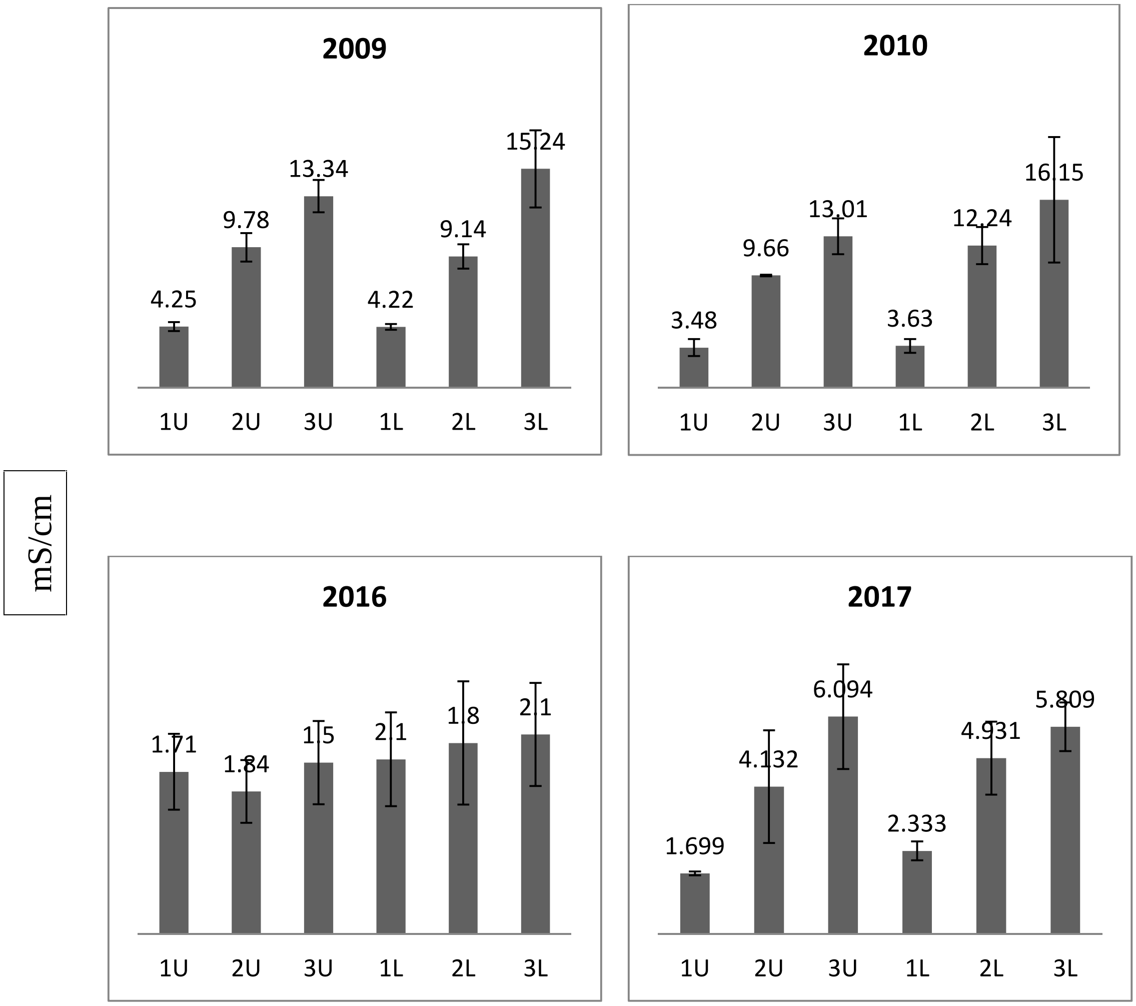


Fig 3.3.3: Spatio-temporal variation of soil conductivity (mS/cm) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

Das (2012) found that the mean value of the soil electrical conductivity was 1.65 mS/cm with minimum value was 1.2 mS/cm and maximum value was 2.26 mS/cm. Ataullah *et al*. (2017) found the mean soil conductivity of Bangladesh Sundarbans was 12.17 mS/cm with minimum value 3.22 mS/cm and maximum 37.9 mS/cm. The values of the electrical conductivity of this mangrove soils was higher than other mangrove forests (Sah *et al*. 1989, Tam *et al*. 1995, Tam and Wong 1998). High soil conductivity was due to the penetration of seawater during high tides, the evaporation of water and capillary rise of ground water during low tides, thus electrical conductivity in the top soil had a more complex spatial structure than that at a lower depth (Sylla *et al*. 1995).

3.3.4 Salinity

Salinity showed overall variation of 0.65 ‰ in 2016 to 15.42 ‰ in 2010 (Table 3.3.3 and 3.3.2).Very low salinity was observed during December 2016 (0.65 – 1.91 ‰). The variations of salinity in both layers of soils of the three chars during the study period are shown in Fig. 3.3.4. Both layers of soils of Char Motherbunia showed low salt content except 2009, indicating that the soils of this char were non-saline which might be attributed to flashing of the char with freshwater of the nearby river (Fig. 3.3.4). There was gradual decrease in soil salinity of the three chars till 2016 when all the three chars were in non-saline condition but in 2017 Char Taposhi and Char Kashem showed saline condition.

Table 3.3.4: Descriptive statistics of different variables of soil of three chars (May 2017) (abbreviated forms are same as Table 3.3.1)

Variable	Mean	StDev	CoefVar	Minimum	Median	Maximum
Moist. %	26.09	3.358	12.87	20.60	25.95	35.30
pH	6.99	0.604	8.64	6.00	7.05	7.90
Cond. mS/cm	4.17	1.922	46.13	1.615	4.51	8.39
Sal ‰	2.67	1.230	46.12	1.03	2.88	5.37
OC %	0.442	0.093	20.99	0.310	0.405	0.59
OM %	0.760	0.159	20.99	0.533	0.697	1.015
Avl N ppm	1.518	0.563	37.05	0.87	1.415	2.94
P %	0.0307	0.008	26.01	0.0139	0.0291	0.0566
Na µg/g	88.59	26.84	30.30	51.35	97.80	139.37
K µg/g	44.77	11.68	26.09	24.20	45.98	67.76
Ca µg/g	3892	1367	35.13	1800	3500	7900
Mg µg/g	8435	2264	26.84	4450	8425	12050
Mn µg/g	308.2	138.9	45.07	115.0	330.0	525.0
Fe µg/g	4931	9187	186.30	3.00	443	26050
Zn µg/g	42.85	19.91	46.47	10.50	41.50	85.00

The salinity of the soils of the three different chars of the study area varied between 2.59 and 12.13 ‰ during May 2009 with the mean value of 5.97 ± 2.81 ‰ indicating that the soil was moderately saline i.e. mesohaline condition was prevailing there (Walter 1935) (Table 3.3.1). The co-efficient of variation was 47.08 i.e. there were variations within the chars in terms of soil salinity (Table 3.3.1). During December 2010 the salinity of the soil of the three different chars of the study area varied from 1.60 to 15.42 ‰ with the mean value was 6.20 ± 3.38 ‰ indicating that the soil was moderately saline i.e. mesohaline condition was prevailing there (Walter 1935) (Table 3.3.2). The co-efficient of variation was 54.54 i.e. there were variation within the chars in terms of soil salinity (Table 3.3.2). During December 2016 the salinity of the soils of the three different chars of the study area decreased from the previous years and varied 0.65 to 1.91 ‰ with the mean value was 1.17 ± 0.31 ‰ indicating that the soil was slightly saline i.e. the condition of the chars turned from mesohaline to oligohaline condition (Walter 1935) (Table 3.3.3). The co-efficient of variation was 26.53 i.e. there were some variation within the chars in terms of salinity (Table 3.3.3). The salinity of the soil of the three different chars of the study area were found to decrease gradually and varied 1.03 to 5.37 ‰ during May 2017 with the mean value was 2.67 ± 1.23 ‰ indicating that the soil was moderately saline i.e. mesohaline condition was prevailing there (Walter 1935) (Table 3.3.4). The co-efficient of variation was 46.12 i.e. there were some variations within the chars in terms of soil salinity (Table 3.3.4).

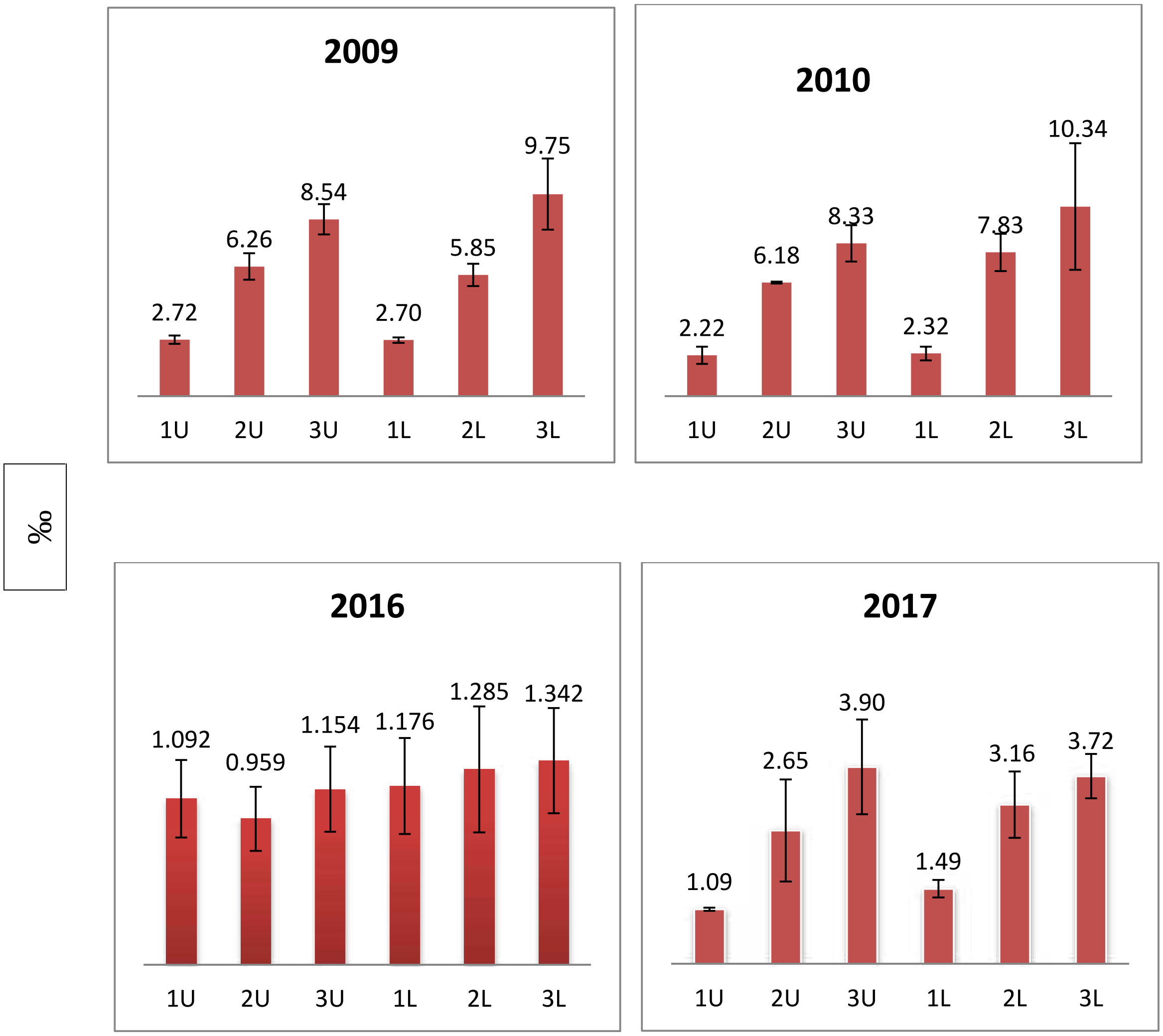


Fig 3.3.4: Spatio-temporal variation of soil salinity (‰) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

Das (2012) found that salinity of the char was comparatively little bit high which ranged from 6.0 - 9.0 ‰ and mean value was 6.83 ‰. Mean soil salinity of Bangladesh Sundarbans was 7.79 ‰ with minimum value 2.06 ‰ and maximum 24.26‰ (Ataullah *et al*. 2017). Boto and Wellington (1984) has found that in the Northern Australian Mangrove Forest, salinity was much higher than those of the present study and ranged from 30 - 50 ‰. Soil salinity decreased with increasing distance from the tidal coast. Naidoo and Raiman (1982) reported soil salinity to be related with extent of tidal inundation and seepage in the mangrove soils of Sipingo and Mgeni, South Africa. Salinization leads to a partial or total loss of the productive capacity of a soil, because of degradation of its chemical and physical properties. Due to soil salinity the variability of the mangrove forest all over the world is observed. In some forests the salinity values are obtained more than 30 ‰ (Sukardjo 1994; Moreno and Calderon 2011). However, the salinity value of 14.99 ‰ was also observed by Das *et al.* (2012). Mangrove vegetation is more luxuriant in lower salinities (Kathiresan *et al.* 1996) and there are evidence that indicated mangroves spend more energy to maintain water balance and ion concentration rather than for primary production and growth at high salinity. It is also evident that the vegetation in mangrove forest is influenced by high salinity levels that adversely affected mangrove biomass production and retention (Lin and Sternberg 1992; Suwa *et al.* 2009).

3.3.5. Organic Carbon content of Soil

The variations of organic carbon (OC) in both layers of soil of the three Chars during the study period are shown in Fig. 3.3.5. The OC of the soil of the three different chars of the study area varied 0.31 % to 0.59 % during May 2009 with the mean value was 0.47 ± 0.09 % (Table 3.3.1). The co-efficient of variation was 19.02 i.e. there were slight variation within the chars in terms of OC content of the soils (Table 3.3.1). During December 2010 the mean value of OC of the soil of the three different chars of the study area was slightly lower than that of first sampling. The mean value was 0.41 ± 0.09 % with the minimum value of 0.28 % and maximum of 0.59 % (Table 3.3.2). The co-efficient of variation was 23.24 i.e. there were slight variation within the chars in terms of OC content of the soils (Table 3.3.2). The OC of the soil of the three different chars of the study area varied from 0.20 % to 0.69 % during December 2016 with the mean value was 0.47 ± 0.14 % (Table 3.3.3). The co-efficient of variation was 28.92 i.e. there were slight variation within the chars in terms of OC content of the soils (Table 3.3.3). The OC of the soil of the three different chars of the study area varied from 0.31 % to 0.59 % during May 2017 with the mean value of 0.44 ± 0.09 % (Table 3.3.4). The co-efficient of variation was 20.99 i.e. there were slight variation within the chars in terms of OC content of the soils (Table 3.3.4).

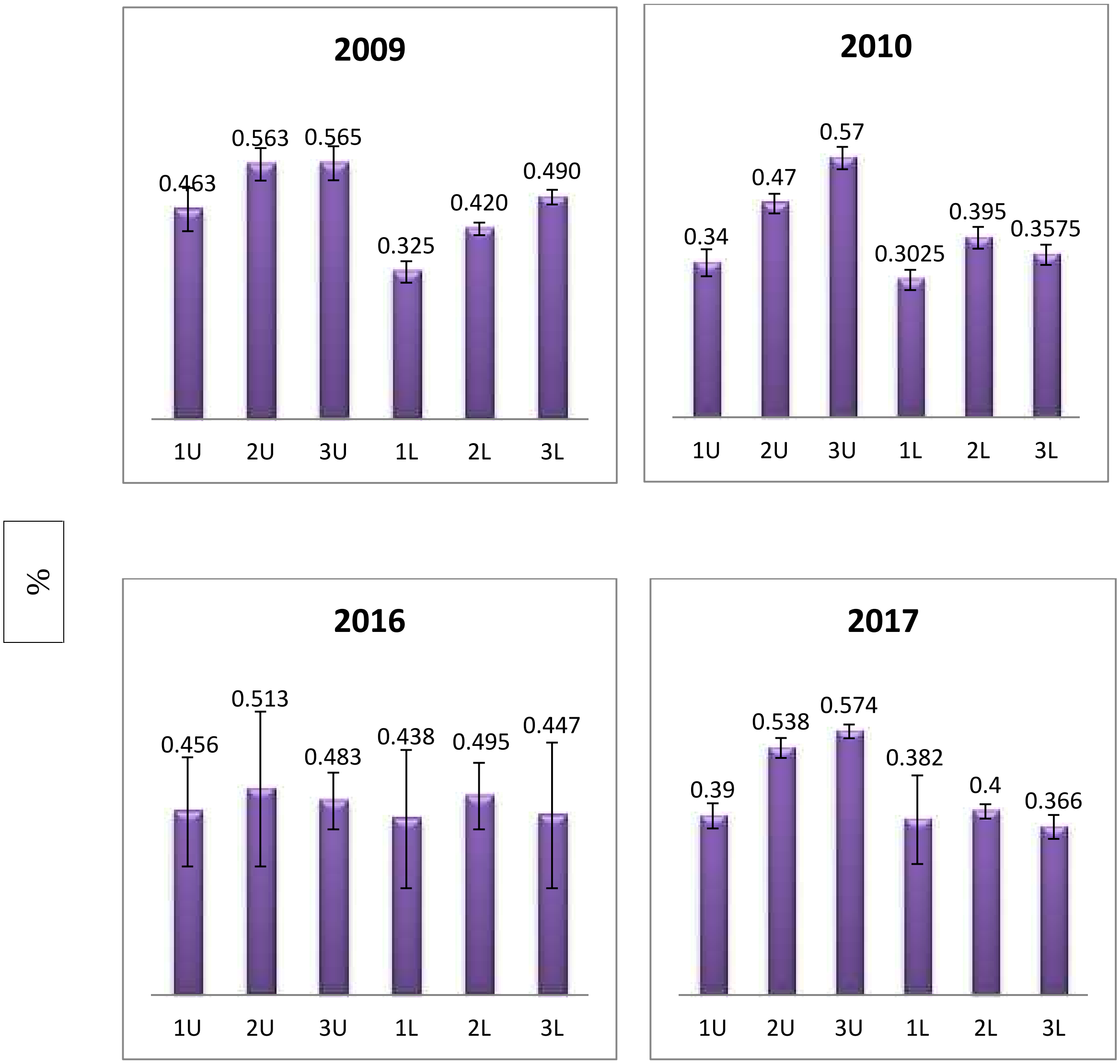


Fig 3.3.5: Spatio-temporal variation of soil organic carbon (%) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

Ataullah *et al*. (2017) have found that mean of the soil organic C of SMF was 0.83% with minimum value 0.29 % and maximum 1.54 %. Some other studies reported above 10 % organic carbon in mangrove forests (Sukardjo 1994; Rambok *et al*. 2010; Moreno and Calderon 2011), reflecting the peaty nature of the soils. However, Sah *et al.* (1989) reported less than one percent organic carbon reflecting the poor nutritional conditions of the soils of some mangrove forests.

3.3.6. Organic matter

The overall organic matter (OM) content varied between 0.33 and 1.19% where both the minimum and maximum values were found during 2016 (Table 3.3.1 – 3.3.4). A gradual decrease in OM content in the upper layer soil was found in Char Kashem. Sudden rise in OM content in the soil of other two chars during 2016 were noticed. The variations of OM in both layers of soil of the three chars during the study period are shown in Fig. 3.3.6.

The OM of the soil of the three different chars of the study area varied from 0.53% to 1.02 % during May 2009 with the mean value of 0.81 ± 0.15 % (Table 3.3.1). The co-efficient of variation was 19.02 i.e. there were slight variation within the chars in terms of OM content of the soils (Table 3.3.1). It was found that the OM of the soil of the three different chars of the study area during December 2010 varied from 0.48 % to 1.02 % with the mean value was 0.70 ± 0.16 % (Table 3.3.2). The co-efficient of variation was 23.24 i.e. there were slight variation within the chars in terms of OM content of the soils (Table 3.3.2). The organic matter (OM) of the soil of the three different chars of the study area varied 0.34 % to 1.19 % during December 2016 with the mean value was 0.81 ± 0.24 % (Table 3.3.3). The co-efficient of variation was 28.92 i.e. there were slight variation within the chars in terms of OM content of the soils (Table 3.3.3). The OM of the soil of the three different chars of the study area varied 0.53 % to 1.02 % during May 2017 with a mean value was 0.76 ± 0.16 % (Table 3.3.4). The co-efficient of variation was 20.99 i.e. there were slight variation within the chars in terms of OM content of the soils (Table 3.3.4).

Das (2012) found that content of organic matter in the soil was very low and the mean value was 0.71 % with minimum 0.60 % and maximum 0.96 %. Content of organic matter in the location-1 ranged from 0.60 - 0.86 % where mean value was 0.73% and at location-2 ranged from 0.65 - 0.67 % where mean value was 0.66 %. Islam (2011) found that content of organic matter in the soil was very low where mean value was 0.80 % with minimum 0.65 % and maximum 1.02 %. When compared with other mangrove ecosystems in Asia Pacific regions, organic matter concentrations (both average values and ranges) recorded in this mangrove were comparable to that of Shenzhen, People’s Republic of China (0.4 - 4.5 %, Tam *et al.* 1995). But the values were very low in comparison to the mangroves of Malaysia (5.2%, Sasekumar 1974) and Thailand (7–8 %, Frith *et al*. 1976), Malaysia (20 %, Thong *et al*. 1993). Low organic matter content was probably due to frequent tidal flushing which rapidly exports mangrove litter. Major source of organic matter were mangrove litter and water which is again indirectly related to tidal gradients. After falling and decomposition, mangrove stem and leaf litter

Fig 3.3.6: Spatio-temporal variation of soil organic matter (%) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

are incorporated into the soil surface, while death of roots adds organic matter to the soil at varying depths (Lacerda *et al*. 1995). Therefore the more the litter produced, the higher the organic matter would be incorporated into soils. Different plant species have different levels of effect on the amount of organic matter and nutrient released from litter decomposition. Due to differences in leaf composition organic matter and nitrogen contents were higher in *Avicennia* dominated soils than in *Rhizophora* soils because *Avicennia* litters have been found to contain more degradable organic matter and sustains a higher rate of microbial activity than *R. mangle* (rich in tannin and inhibits the activity of benthic organisms), and as a consequence, had more available nutrients in soils (Lacerda *et al*. 1995). The organic matter derived from litter decomposition would be exported to foreshore water by incoming and outgoing tides (Steinke *et al.* 1993, Khan and Brush 1994). Spatial variability is found due to changes in tidal amplitude and frequency (Ovalle *et al.* 1990). Organic matter of mangrove soils could also come from freshwater entering the ecosystem as well as from wastewater discharges. Previous study by Ovalle *et al*. (1990) stated that freshwater input as well as other terrestrial derived carbon and nutrients to the mangrove forests are mostly due to runoff, but they are insignificant when compared with tidal input. However, Jagtap (1987) found that terrestrial runoff contributed high levels of particulate and organic matter to the mangrove environment especially during monsoon months.

3.3.8. Available Nitrogen

The variations of available nitrogen in both layers of soil of the three Chars during the study period are shown in Fig. 3.3.8. The available nitrogen of the soil of the three different chars of the study area varied 0.430 to 2.420 ppm during May 2009 with the mean value was 1.721 ± 0.53 ppm (Table 3.3.1). The co-efficient of variation was 30.83 i.e. there were some variations within the chars in terms of available nitrogen content of the soils (Table 3.3.1). It was found that during 2010 the mean value of the available nitrogen of the soil of the three different chars of the study area the mean value was 1.583 ± 0.403 ppm where the minimum value was 0.710 ppm and maximum was 2.420 ppm (Table 3.3.2). The co-efficient of variation was 25.44 i.e. there were some variations within the chars in terms of available nitrogen content of the soils (Table 3.3.2). The available nitrogen of the soil of the three different chars of the study area varied from 0.854 to 4.269 ppm during December 2016 with the mean value was 1.727 ± 0.731 ppm (Table 3.3.3). The co-efficient of variation was 42.34 i.e. there were some variations within the chars in terms of available nitrogen content of the soils (Table 3.3.3). The available nitrogen of the soil of the three different chars of the study area varied 0.87 to 2.94 ppm during May 2017 with the mean value was 1.518 ± 0.563 ppm (Table 3.3.4). The co-efficient of variation was 37.05 i.e. there were some variations within the chars in terms of available nitrogen content of the soils (Table 3.3.4).

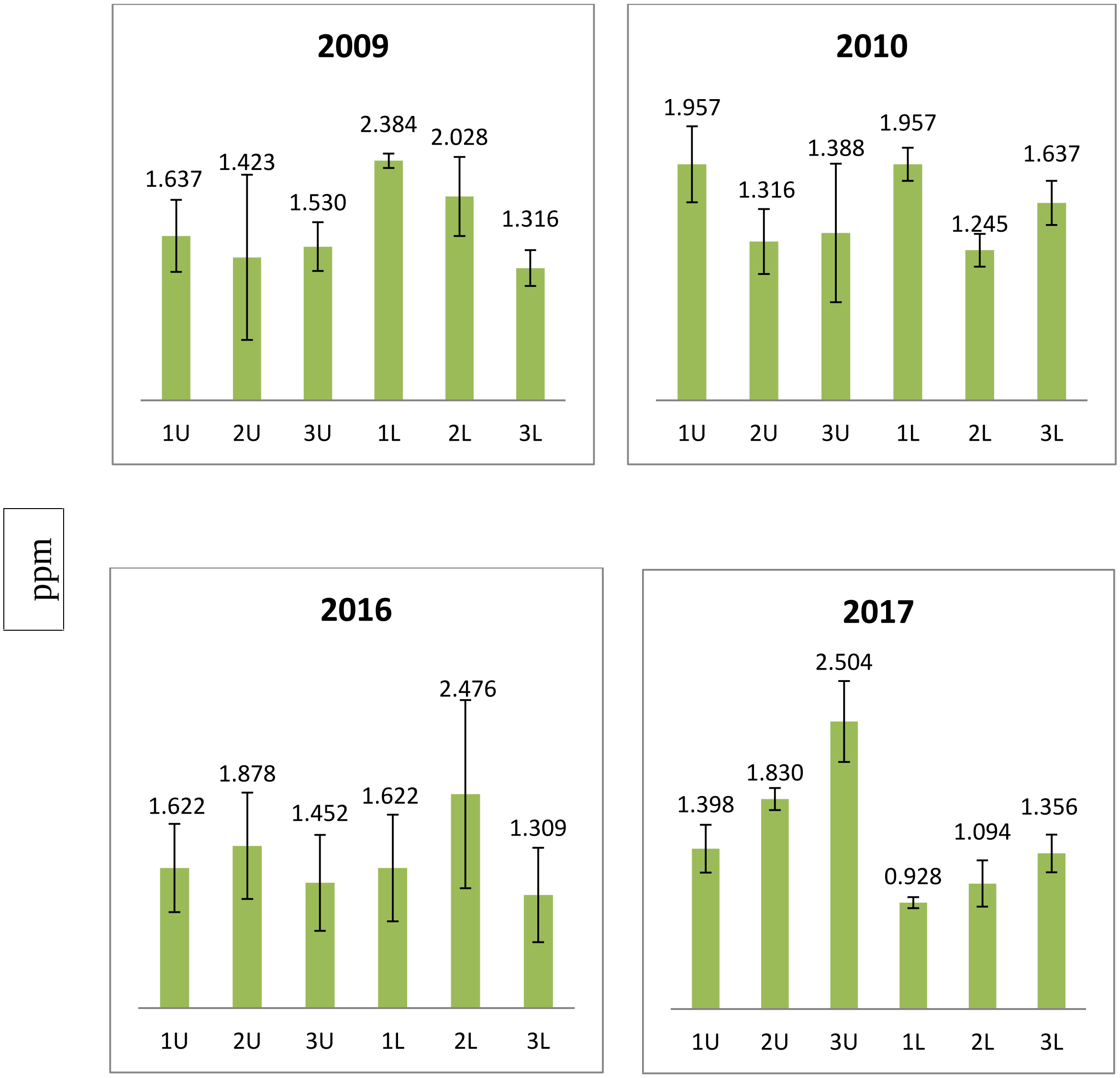


Fig 3.3.8: Spatio-temporal variation of soil available nitrogen (ppm) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

3.3.9. Total Phosphorus Content of the Soil

The variations of total phosphorus (P) in both layers of soil of the three chars during the study period are shown in Fig. 3.3.9. The total P of the soil of the three different chars of the study area varied from 0.012 to 0.037 % during May 2009 with the mean value was 0.029 ± 0.007 % (Table 3.3.1). The co-efficient of variation was 24.75 i.e. there were some variations within the chars in terms of P content of the soils (Table 3.3.1). During December 2010 the total P of the soil of the three different chars of the study area varied from 0.017 to 0.053 % with a mean value was 0.031 ± 0.008 % (Table 3.3.2). The co-efficient of variation was 24.35 i.e. there were some variations within the chars in terms of P content of the soils (Table 3.3.2). The total P of the soil of the three different chars of the study area ranged between 0.037 and 0.077 % during December 2016 with the mean value of 0.048 ± 0.008 % (Table 3.3.3). The co-efficient of variation was 16.58 i.e. there were some variations within the chars in terms of P content of the soils (Table 3.3.3). The total phosphorus (P) of the soil of the three different chars of the study area varied from 0.014 to 0.057 % during May 2017 with a mean value of 0.031 ± 0.008 % (Table 3.3.4). The co-efficient of variation was 26.01 i.e. there were some variations within the chars in terms of P content of the soils (Table 3.3.4).

Das (2012) reported almost similar amount of total P in Char Tamaruddin where the mean value was 0.050% with minimum value was 0.025% and maximum value was 0.056 %. Some other works also found almost similar results in different mangrove forest (Tam and Wong 1998; Boto and Wellington 1984).

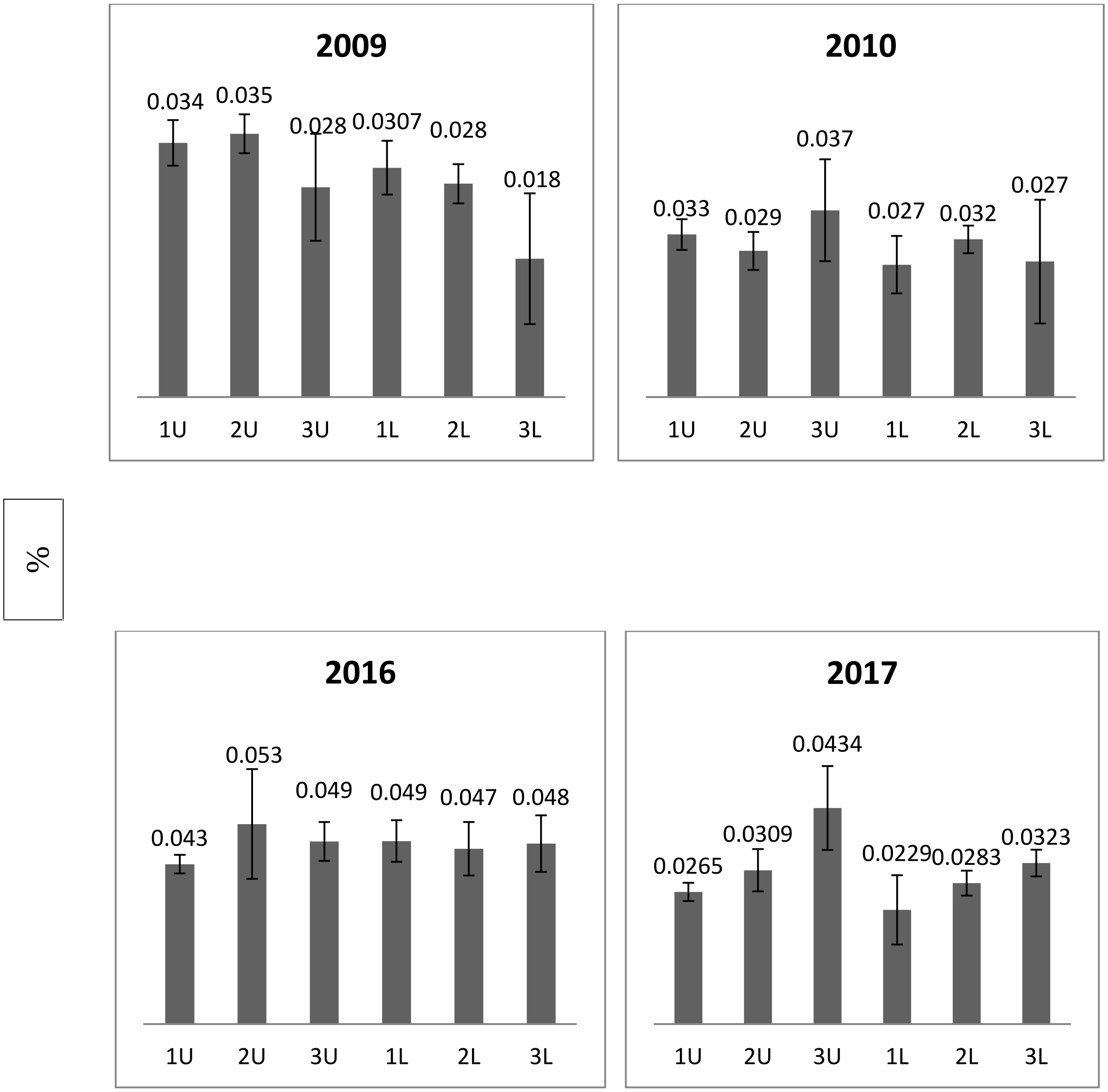


Fig 3.3.9: Spatio-temporal variation of total Phosphorus (%) of soil of different chars (1 = Char Motherbunia, 2 = Char Taposhi, 3 = Char Kashem, U = upper layer, L = lower layer)

Ataullah *et al*. (2017) have found that The P content of the soils of Bangladesh Sundarbans showed high variations among locations where the mean was 0.022 % and very low minimum value of 0.0052% and maximum 0.0956 %. But very high amount of phosphorus (25.27%) was reported by Rambok *et al.* (2010) in Sibuti mangrove, Sarawak, Malaysia. Although earlier reports suggested that N content of mangrove soils were the primary nutrient that control the species composition and structure of forest but more recent analysis found that P played approximately equal proportion influence on the structure and composition like that of N (Elser and Hamilton 2007).

3.3.10. Water Soluble Sodium Content of the Soil

In the aquatic environment sodium (Na) is considered as an active cation especially in the coastal zones. The variations of water soluble sodium (Na) in both layers of soil of the three chars during the study period are presented in Fig. 3.3.10. The water soluble Na of the soils of the three different chars of the study area varied between 588.0 µg/g and 1584.0 µg/g during May 2009 where the mean value was 947.0 ± 303.0 µg/g (Table 3.3.1). The co-efficient of variation was 32.08 i.e. there were some variations within the chars in terms of Na content of the soils (Table 3.3.1). The water soluble Na of the soils of the three different chars of the study area were slightly lower than the previous year and varied between 498.0 µg/g and 1448.0 µg/g during December 2010 where the mean value was 888.0 ± 305.0 µg/g (Table 3.3.2). The co-efficient of variation was 34.39 i.e. there were some variations within the chars in terms of Na content of the soils (Table 3.3.2).

The water soluble Na content of the soil of the three different chars of the study area showed a decreasing tendency although the variation was not significant and values varied between 226.3 and 2036.3 µg/g during December 2016 where the mean value were 734.6 ± 487.6 µg/g (Table 3.3.3). The co-efficient of variation was 66.38 i.e. there were higher variations within the chars in terms of water soluble Na content of the soils (Table 3.3.3). The water soluble Na of the soil of the three different chars of the study area were found to decrease gradually and varied between 51.35 and 139.37 µg/g during May 2017 where the mean value were 88.5 ± 26.84 µg/g (Table 3.3.4). The co-efficient of variation was 30.30 i.e. there were some variations within the chars in terms of Na content of the soils (Table 3.3.4).

The values of Sodium content of the soils of three different chars exceeded the standard guideline (278 mg/kg) of IAEA (1990) except the values of 2017. Ataullah *et al*. (2018) found that mean of the soil Na content of Bangladesh Sundarbans was 214.4 mg/kg where the minimum value was 3.5 mg/kg and maximum value was 2600 mg/kg and high variability of Na content was observed with the coefficient of variation 237.42. The slight variation in Na concentrations can be attributed to the minor changes of mineralogy or grain size of the sediments (Lerman 1978). Sodium concentration ranged from 2.21 - 4.13% in coastal sediment of Abu-Qir Bay (Ghani *et al.* 2013) which was comparatively higher than soil Na content of the studied area.

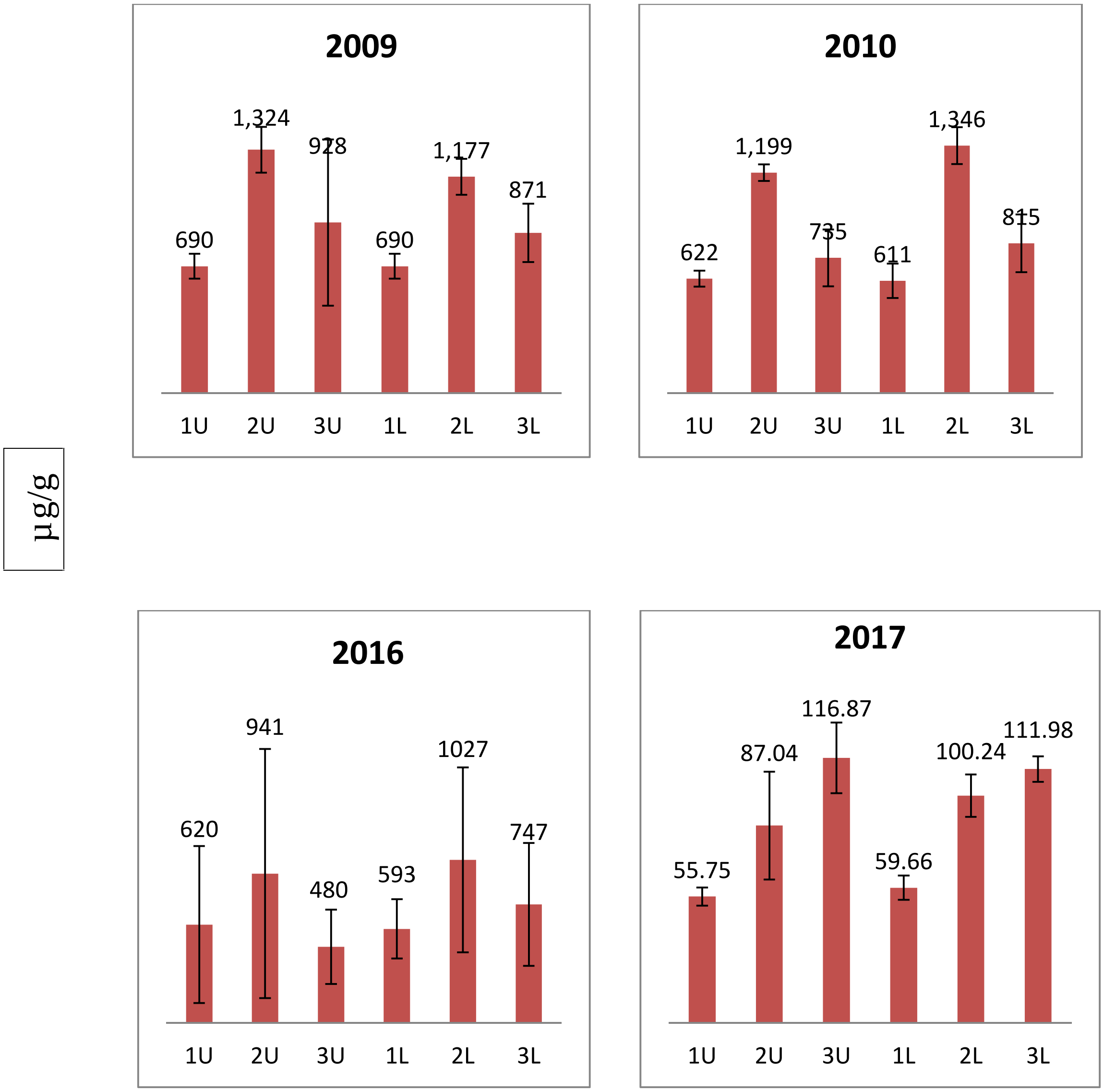


Fig 3.3.10: Spatio-temporal variation of soil Sodium (Na µg/g) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

3.3.11. Water Soluble Potassium Content of the Soil

In the aquatic environment potassium (K) has also been considered as an active cation and plays vital role for osmotic regulation in mangroves under high saline conditions (Downton 1982). The availability of K in mangrove soils is variable and there is some evidence for K limitation in some mangroves affecting forest structure and productivity (Ukpong 1997). The variations of water soluble potassium in both layers of soils of three chars during the study period are shown in Fig. 3.3.11.

The water soluble potassium (K) of the soil of the three different chars of the study area varied between 19.22 and 105.71 µg/g during May 2009 where the mean value were 55.66 ± 27.62 µg/g (Table 3.3.1). The co-efficient of variation was 49.62 i.e. soils varied moderately within the chars in terms of K content of the soils (Table 3.3.1). The water soluble K of the soil of the three different chars of the study area varied between 19.22 and 96.10 µg/g during December 2010 where the mean value were 49.25 ± 26.93 µg/g (Table 3.3.2). The co-efficient of variation was 54.68 i.e. soils varied moderately within the chars in terms of K content of the soils (Table 3.3.2). The water soluble K of the soil of the three different chars of the study area varied between 13.7 and 1190.8 µg/g during December 2016 where the mean value was 83.8 ± 211.7 µg/g (Table 3.3.3). The co-efficient of variation was 252.62 i.e. K content of the soils within the chars highly varied (Table 3.3.3). The water soluble K of the soil of the three different chars of the study area varied

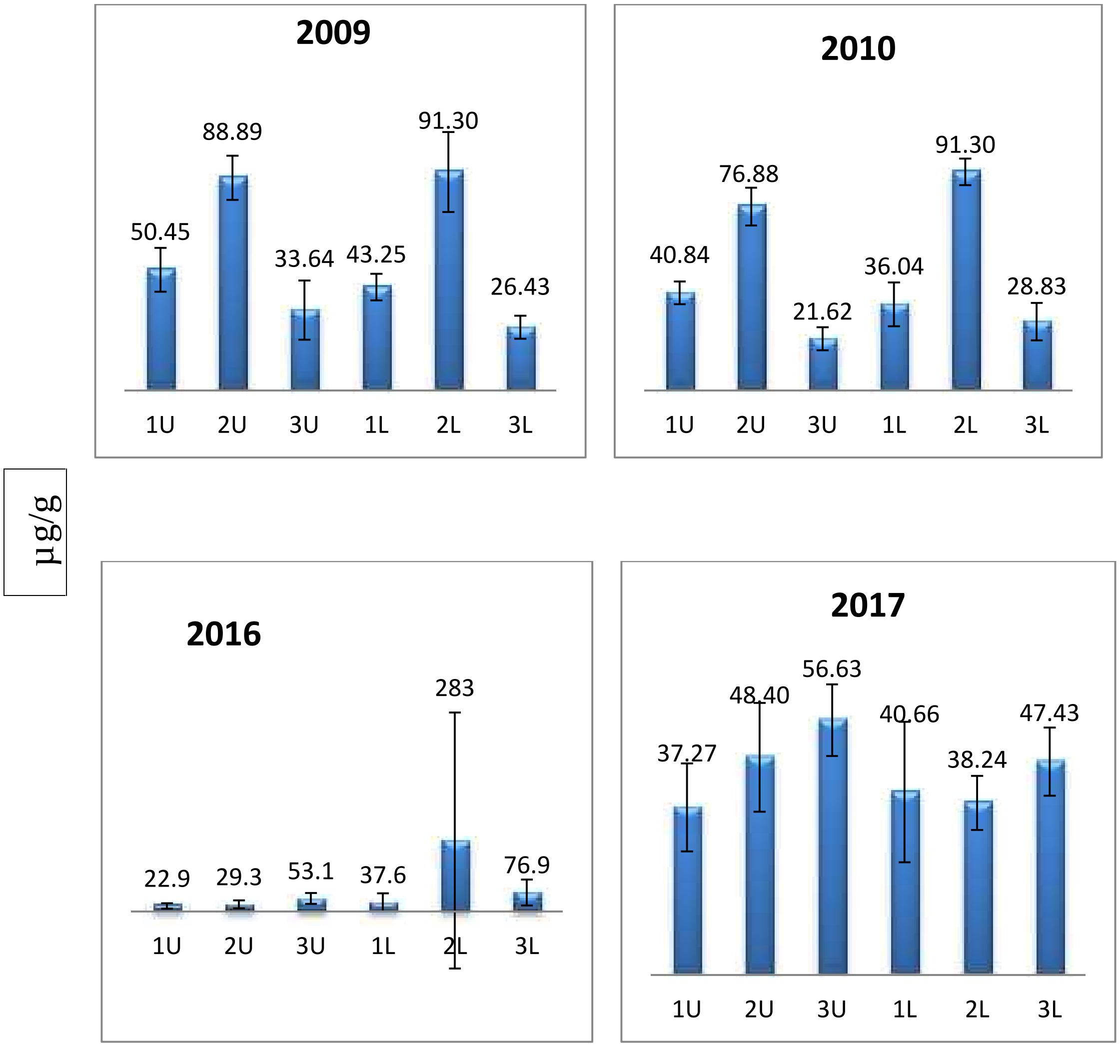


Fig 3.3.11: Spatio-temporal variation of soil Potassium (K µg/g) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

from 24.20 to 67.76 µg/g during May 2017 where the mean value was 44.77 ± 11.68 µg/g (Table 3.3.4). The co-efficient of variation was 26.09 i.e. soils varied moderately within the chars in terms of K content of the soils (Table 3.3.4).

Total K contents were reported 1.6 % in Shenzhen (Tam *et al*. 1995), 2.07 % in Fujian (Lin *et al*. 1987), 0.42 – 1.19 % in Hainan mangroves (Liao 1990) and 0.39 - 4.79 % in Hong Kong (Tam and Wong 1998). Mean of the water soluble soil K content of Bangladesh Sundarbans was found to be 22.17 mg/kg with minimum value 6.9 mg/kg and maximum 42.78 mg/kg (Ataullah *et al*. 2018). Das (2012) reported the amount of water soluble K content of the soil in Char Tamaruddin at Hatia, Noakhali ranged from 42.5 - 52.50 mg/kg.

3.3.12. Total Calcium Content of the Soil

The variations of total calcium (Ca) in both layers of soil of the three chars during the study period are shown in Fig. 3.3.12. The total Ca of the soil of the three different chars of the study area varied between 2186 and 6908 µg/g during May 2009 where the mean value was 4240 ± 1354 µg/g (Table 3.3.1). The co-efficient of variation was 31.94 i.e. there were some variations within the chars in terms of total Ca content of the soils (Table 3.3.1). During December 2010 the total calcium (Ca) of the soil of the three different chars of the study area were slightly higher than that of 2009 and ranged from 3198 to 7101 µg/g where the mean value was 5241 ± 1145 µg/g (Table 3.3.2). The co-efficient of variation was 21.84 i.e. there were some variations within the chars in terms of total Ca content of the soils (Table 3.3.2). The total Ca of the soil of the three different chars of the study area

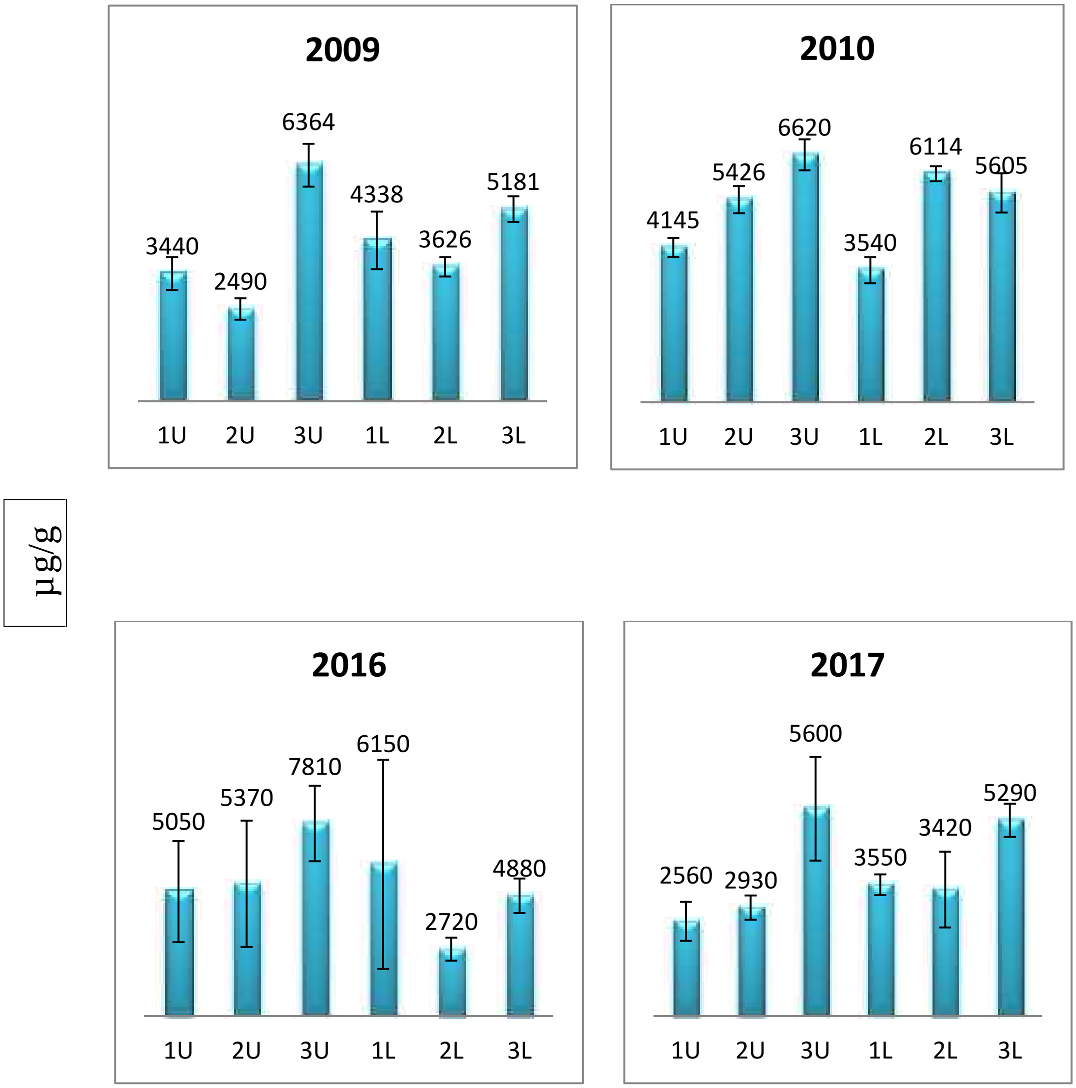


Fig 3.3.12: Spatio-temporal variation of soil Calcium (Ca µg/g) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

varied between 1550 and 11900 µg/g during December 2016 where the mean value was 5330 ± 2602 µg/g (Table 3.3.3). The co-efficient of variation was 48.82 i.e. Ca content of the soils within the chars highly varied (Table 3.3.3). The total calcium (Ca) of the soil of the three different chars of the study area varied from 1800 to 7900 µg/g during May 2017 where the mean value was 3892 ± 1367 µg/g (Table 3.3.4). The co-efficient of variation was 35.13 i.e. there were some variations within the chars in terms of total Ca content of the soils (Table 3.3.4).

Amount of Ca in the soil of Char Tamaruddin varied from 6.90 to 72.25 mg/kg with the mean value of 24.57 mg/kg (Das 2012). Mean of the Ca content of soil of Bangladesh Sundarbans was 1.02 mg/kg where the minimum value was 0.21 mg/kg and maximum value was 2.09 mg/kg (Ataullah *et al*. 2018). In the Nigerian mangroves, Ukpong (2000) found that the calcium content varied from 1.8 ± 0.2 - 15.5 ± 4.2 mg per 100 g (mean ± sd). Ruttner (1963) suggested that Ca and Mg might have some inhibitory role in the sorption of other cations especially trace metals such as Mn, Zn and Pb on metallic oxides.

3.3.13. Total Magnesium Content of the Soil

The variations of total magnesium (Mg) in both layers of soil of the three chars during the study period are shown in Fig. 3.3.13. The total Mg of the soil of the three different chars of the study area varied between 3122 µg/g and 8995 µg/g during May 2009 where the mean value was 6071 ± 1806 µg/g (Table 3.3.1). The co-efficient of variation was 29.75 i.e. there were some variations within the chars in terms of total Mg content of the soils (Table 3.3.1). The total Mg of the soil of three different chars of the study area varied between 3448 and 9342 µg/g during December 2010 where the mean value was 5829 ± 1666 µg/g (Table 3.3.2). The co-efficient of variation was 28.59 i.e. there were some variations within the chars in terms of total Mg content of the soils (Table 3.3.2). The total Mg of the soil of the three different chars of the study area varied from 3200 to 8400 µg/g during December 2016 where the mean value was 6182 ± 1115 µg/g (Table 3.3.3). The co-efficient of variation was 18.03 i.e. Mg content of the soils within the chars varied little bit (Table 3.3.3). The total Mg of the soil of the three different chars of the study area varied between 4450 and 12050 µg/g during May 2017 where the mean value was 8435 ± 2264 µg/g (Table 3.3.4). The co-efficient of variation was 26.84 i.e. there were some variations within the chars in terms of total Mg content of the soils (Table 3.3.4).

Das (2012) found that the mean value of Mg content in the soil of Char Tamaruddin was 177.3 mg/kg with minimum value 46.5 mg/kg and maximum value 271.1 mg/kg. Ukpong (2000) found 5.2 ± 0.1 - 24.6 ± 2.0 mg per 100 g (mean ± sd) magnesium in the Nigerian mangroves. Ataullah *et al*. (2018) reported the mean value of the soil Mg of Bangladesh Sundarbans was 2.74 mg/kg where the minimum value was 1.9 mg/kg and maximum value was 4.23 mg/kg.

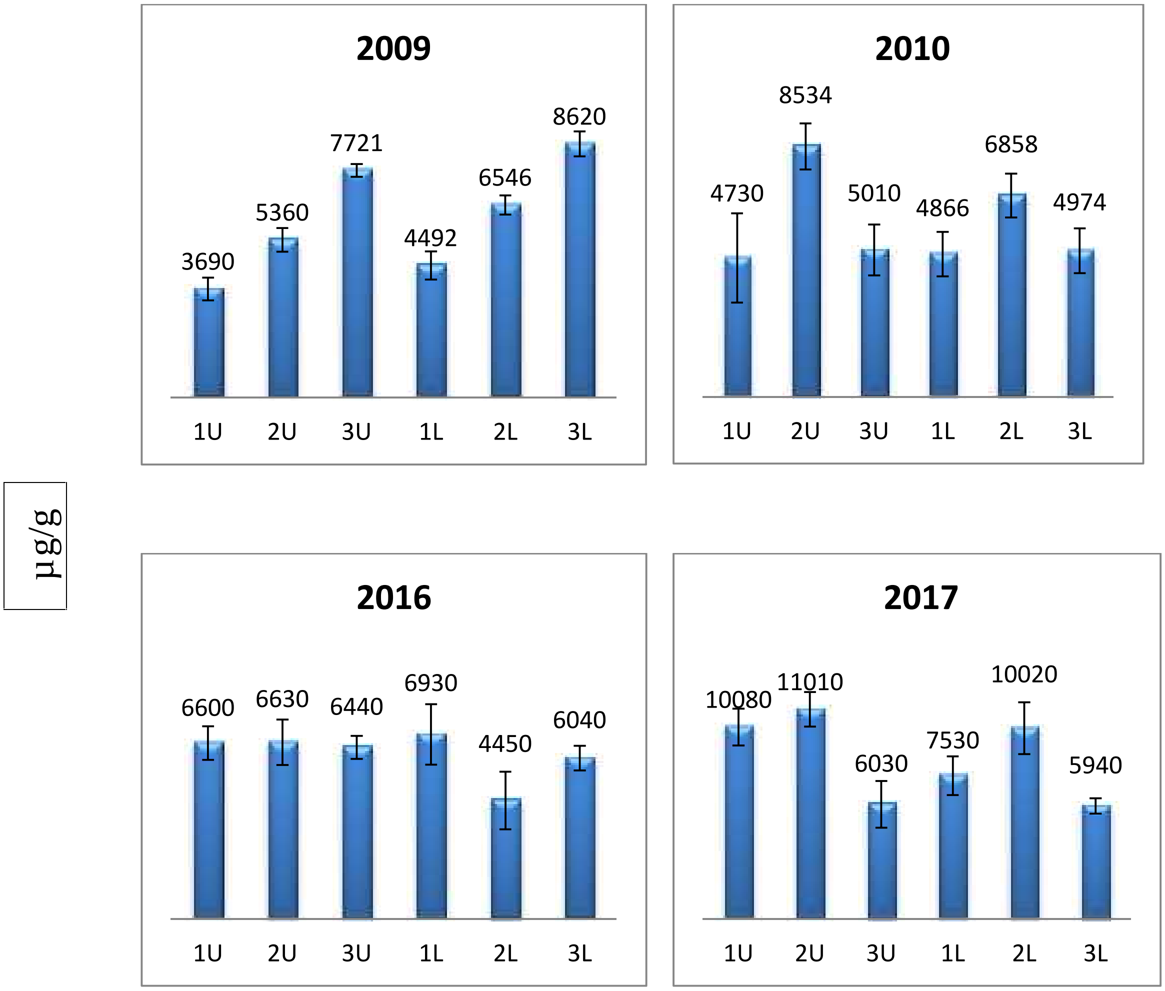


Fig 3.3.13: Spatio-temporal variation of soil Magnesium (µg/g) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

3.3.14. Total Manganese Content of the Soil

The variations of total manganese (Mn) in both layers of soil of the three chars during the study period are shown in Fig. 3.3.14.

The total Mn of the soil of the three different chars of the study area varied from 108.00 to 210.00 µg/g during May 2009 where the mean value was 166.42 ± 26.30 µg/g (Table 3.3.1). The co-efficient of variation was 15.80 i.e. there were slight variations within the chars in terms of total Mn content of the soils (Table 3.3.1). The total Mn of the soil of the three different chars of the study area varied between 168.0 and 383.0 µg/g during December 2010 where the mean value was 265.2 ± 53.2 µg/g (Table 3.3.2). The co-efficient of variation was 20.08 i.e. there were slight variations within the chars in terms of total Mn content of the soils (Table 3.3.2). The total Mn of the soil of the three different chars of the study area varied between 80.00 and 300.00 µg/g during December 2016 where the mean value was 193.50 ± 39.26 µg/g (Table 3.3.3). The co-efficient of variation was 20.29 i.e. little bit variation was found in Mn content of the soils within the chars (Table 3.3.3). The total manganese (Mn) of the soil of the three different chars of the study area varied from 115.0 to 525.0 µg/g during May 2017 where the mean value was 308.2 ± 138.9 µg/g (Table 3.3.4). The co-efficient of variation was 45.07 i.e. there were slight variations within the chars in terms of total Mn content of the soils (Table 3.3.4).

Manganese is an element of low toxicity having considerable biological significance. It is one of the most biogeochemical and active transition metals in

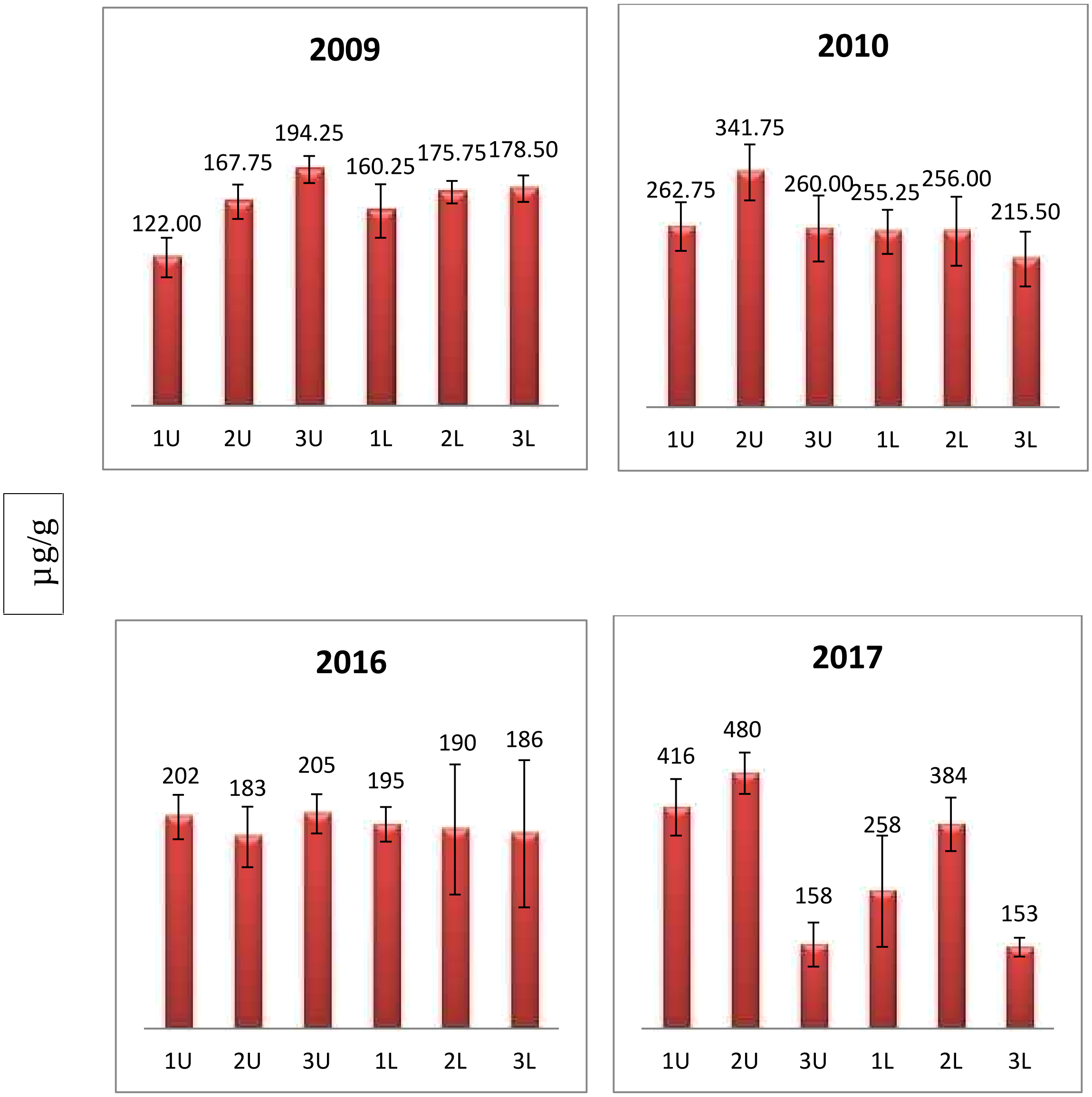


Fig 3.3.14: Spatio-temporal variation of soil Manganese (Mn µg/g) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

the aquatic environment (Evans *et al.* 1977). It is well established that iron and manganese oxides are excellent scavengers for trace metals (Tessier *et al.*1979). The amount of Mn content in soil of Char Tamaruddin varied between 6.30 - 15.5 mg/kg with the mean value was 12.62 mg/kg (Das 2012). Total Mn of 41.3 ± 9.4 µg/g found in The Sai Keng, Hong Kong, 509.2 ± 37.1 µg/g in the Shenzhen, People's Republic of China (Tam and Wong, 1996) were comparatively higher than the values found in the present study. Hasan *et al*. (2013) found 938.27 mg/g Mn in Chittagong coast of Bay of Bengal. Ahmed *et al.* (2002) reported that the amount of Mn in Bangladesh Sundarbans ranged from 95.8 – 1000.6 mg/g, whereas Kumar *et al.* (2016) reported the values ranged from 389.43 – 696.33 mg/g. Mean of the Mn content of soil of Bangladesh Sundarbans found by Ataullah *et al*. (2018) was 0.77 mg/kg where the minimum value was 0.45 mg/kg and maximum was 0.99 mg/kg.

3.3.15. Total Iron Content of the Soil

Total Iron (Fe) showed high variation during the study period and coefficient of variation (CoVar) were 111.83, 114.49, 116.70 and 186.30 % respectively during the four sampling occasions. The variations of total iron in both layers of soil of the three chars during the study period are shown in Fig. 3.3.15.

The total Fe content of the soil of the three different chars of the study area varied from 268 to 4815µg/g during May 2009 where the mean value was 1422 ± 1591µg/g (Table 3.3.1). The co-efficient of variation was 111.83 i.e. there were very high variations within the chars in terms of total Fe content of the soils (Table

3.3.1). The total Fe of the soil of the three different chars of the study area varied between 211 and 5245 µg/g during December 2010 where the mean value was 1549 ± 1774 µg/g (Table 3.3.2). The co-efficient of variation was 114.49 i.e. there were very high variations within the chars in terms of total Fe content of the soils (Table 3.3.2). The total Fe of the soil of the three different chars of the study area varied from 6.00 to 16200 µg/g during December 2016 where the mean value was 4642 ± 5418 µg/g (Table 3.3.3). The co-efficient of variation was 116.70 i.e. very high variations were found in Fe content of the soils within the chars (Table 3.3.3). The total Fe of the soil of the three different chars of the study area varied between 3.00 and 26050 µg/g during May 2017 where the mean value was 4931 ± 9187 µg/g (Table 3.3.4). The co-efficient of variation was 186.30 i.e. there were very high variations within the chars in terms of total Fe content of the soils (Table 3.3.4).

Das (2012) found the amount of total Fe of the soil of Char Tamaruddin ranged from 52.0 - 685 mg/kg with the mean value was 299.4 mg/kg. Mean Fe content of the soils of Bangladesh Sundarbans was recorded as 4.76 mg/kg with minimum value of 0.54 mg/kg and maximum 6.9 mg/kg and variation among locations were also observed (Ataullah *et al*. 2018). Ren *et al.* (2009) found that Fe content in the soil at the Zhaigang Mangrove Nature Reserve, China were 17.61 g/kg where the plantations of *Sonneratia apetala* were taken place. Hasan *et al.* (2013) found 58959.09 mg/g Fe in the soil of Chittagong coast of Bay of Bengal. Other authors found the amount of Fe in soil of Sundarban Mangrove Forests of Bangladesh

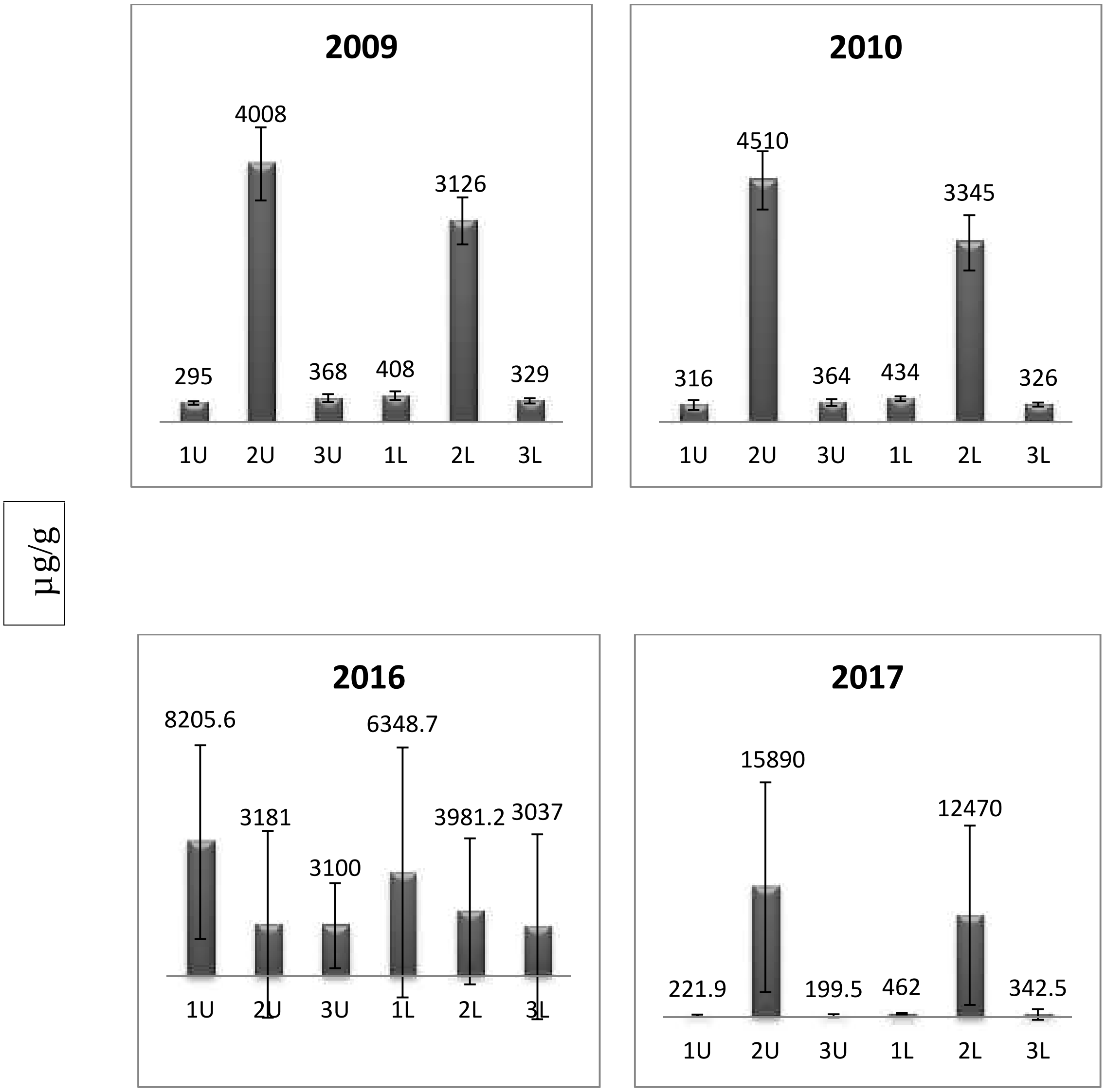


Fig 3.3.15: Spatio-temporal variation of soil Iron (Fe µg/g) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

ranged from 501.5 - 3985.2 mg/g (Ahmed *et al.* 2002) whereas Haque *et al.* (2004) found that values ranged from 1198.66 - 12984.35 mg/g and Kumar *et al.* (2016) found the values which were from 2.29 to 4.22 %.

3.3.16. Total Zinc Content of the Soil

The variations of total zinc (Zn) in both layers of soil of the three Chars during the study period are shown in Fig. 3.3.16. The total Zn of the soil of the three different chars of the study area varied between 18.00 and 60.00 µg/g during May 2009 where the mean value was 35.50 ± 10.58 µg/g (Table 3.3.1). The co-efficient of variation was 29.81 i.e. there were some variations within the chars in terms of total Zn content of the soils (Table 3.3.1). The total Zn of the soil of the three different chars of the study area varied from 22.00 to 57.00 µg/g during December 2009 where the mean value was 36.67 ± 8.47 µg/g (Table 3.3.2). The co-efficient of variation was 23.11 i.e. there were some variations within the chars in terms of total Zn content of the soils (Table 3.3.2). The total Zn of the soil of the three different chars of the study area varied between 1.00 and 48.00 µg/g during December 2016 where the mean value was 31.63 ± 10.06 µg/g (Table 3.3.3). The co-efficient of variation was 31.81 i.e. some variations were found in the content of Zn in the soils within the chars (Table 3.3.3). The total Zn of the soil of the three different chars of the study area varied from 10.50 to 85.00 µg/g during May 2017 where the mean value was 42.85 ± 19.91µg/g (Table 3.3.4). The co-efficient of variation was 46.47 i.e. there were some variations within the chars in terms of total Zn content of the soils (Table 3.3.4).

The amount of Zn in Char Tamaruddin ranged from 0.16 - 2.0 mg/kg where mean value was 1.30 mg/kg (Das, 2012). Ataullah *et al*. (2018) reported the mean of the soil Zn of Sundarban Mangrove Forests of Bangladesh of 0.4 mg/kg where the minimum value was 0.13 mg/kg and maximum value was 0.74 mg/kg with high variation among locations (Coefficient of variation was 52.22). Total Zn of 40.2 ± 3.3 µg/g found in the Sai Keng, Hong Kong which was almost similar to the present study whereas 143.3 ± 22.4 µg/g Zn was found in the Shenzhen, People's Republic of China (Tam and Wong, 1996) which were comparatively higher than those of the present study. Hasan *et al.* (2013) found 355 mg/g Zn in soil of Chittagong coast of Bay of Bengal which were also higher than those of the present study. The amount of Zn in the soil of Bangladesh Sundarbans by several other workers was found to be almost similar to the present study and the values ranged from 48.9 - 129.8 mg/g (Ahmed *et al.* 2002), from 26.22 - 53.39 mg/g (Haque *et al.* 2004) and from 38.83 – 74.09 mg/g (Kumar *et al.* 2016). Higher amount of Zn content in the marine sediment of Bangladesh than other parts of the world was reported by GESAMP (1982). It has been found that Zinc sulphate ($ZnSO_4$) and zinc chloride (Zn_2Cl) are widely used in textile industries like dyeing, printing, sizing and weighting of fabrics (ILO 2011) which might have contributed to the Zn content of the soils.

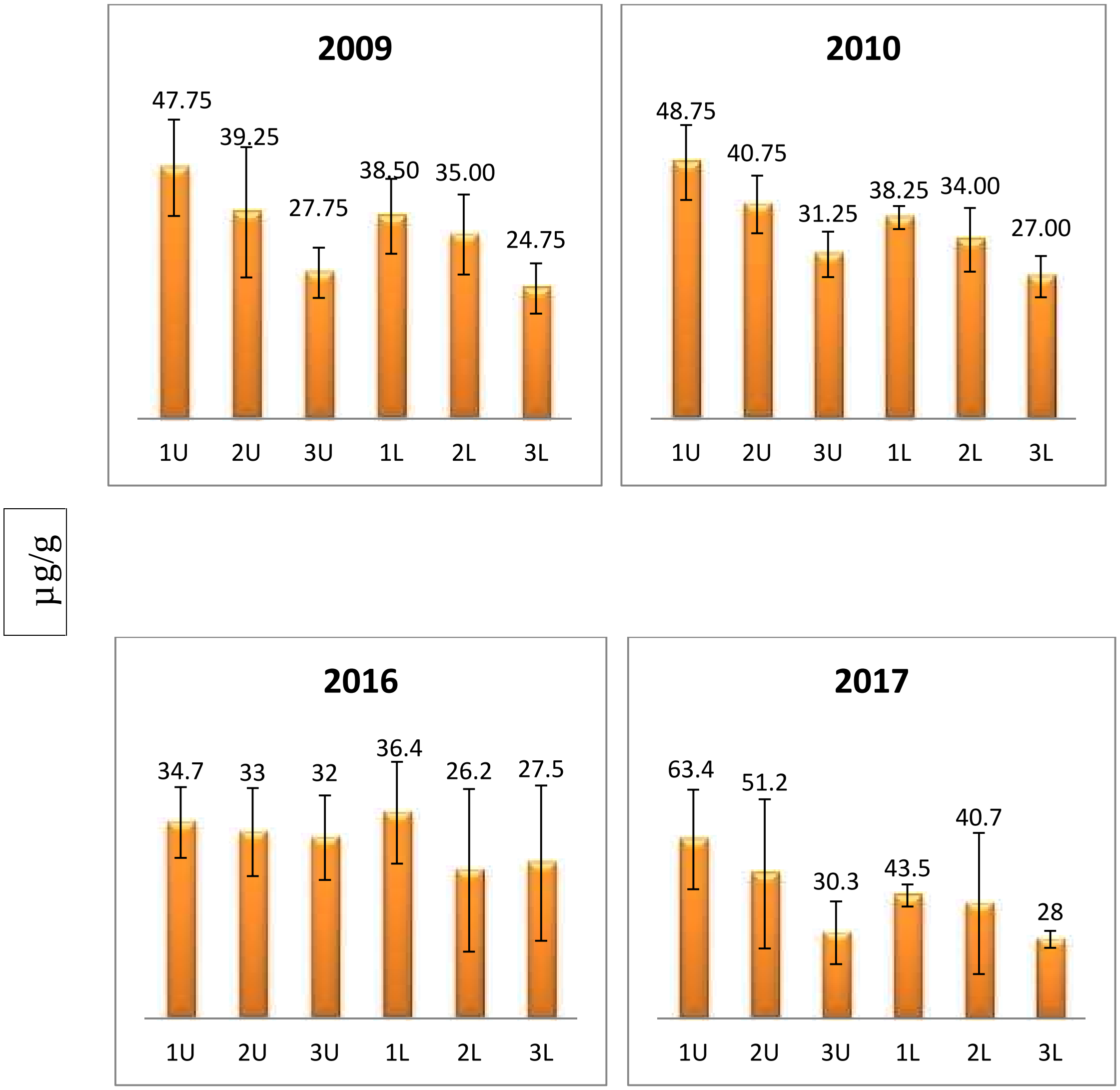


Fig 3.3.16: Spatio-temporal variation of soil Zinc (µg/g) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer)

3.3.17 Lead Content of the Soil

Lead (Pb) is a very important micro-element. The variations of total lead in both layers of soil of the three chars during the study period are shown in Fig. 3.3.17. In the soils of the three chars, Pb was found to be present in some soil samples. In Char Motherbunia the values ranged from 15 – 31 µg/g in 2009 and 11 to 24 µg/g in 2010. Lead was absent in Char Kashem during 2017 except in one sample. Das (2012) found that the range of Pb varied from 6.23 - 11.8 µg/g, with the mean value was 11.85 µg/g.

The values of the present studied exceeded the standard guideline (0.40 mg/kg) of GESAMP (1982). In the soil of Chittagong coast of Bay of Bengal, Hasan *et al.* (2013) found 18.09 mg/g Pb whereas Ahmed *et al.* (2002) found 10.96 - 61.66 mg/g, Haque *et al* (2004) found 1.88 - 45.53 mg/g and Kumar *et al.*(2016 have found 9.97 – 25.61 mg/g Pb content in the soils of Bangladesh Sundarbans in their works. But in a recent study, Ataullah *et al*. (2018) reported comparatively low amount of mean of the soil Pb content of Bangladesh Sundarbans and that was 0.53 mg/kg where the minimum value was 0.41 mg/kg and maximum value was 0.78 mg/kg.

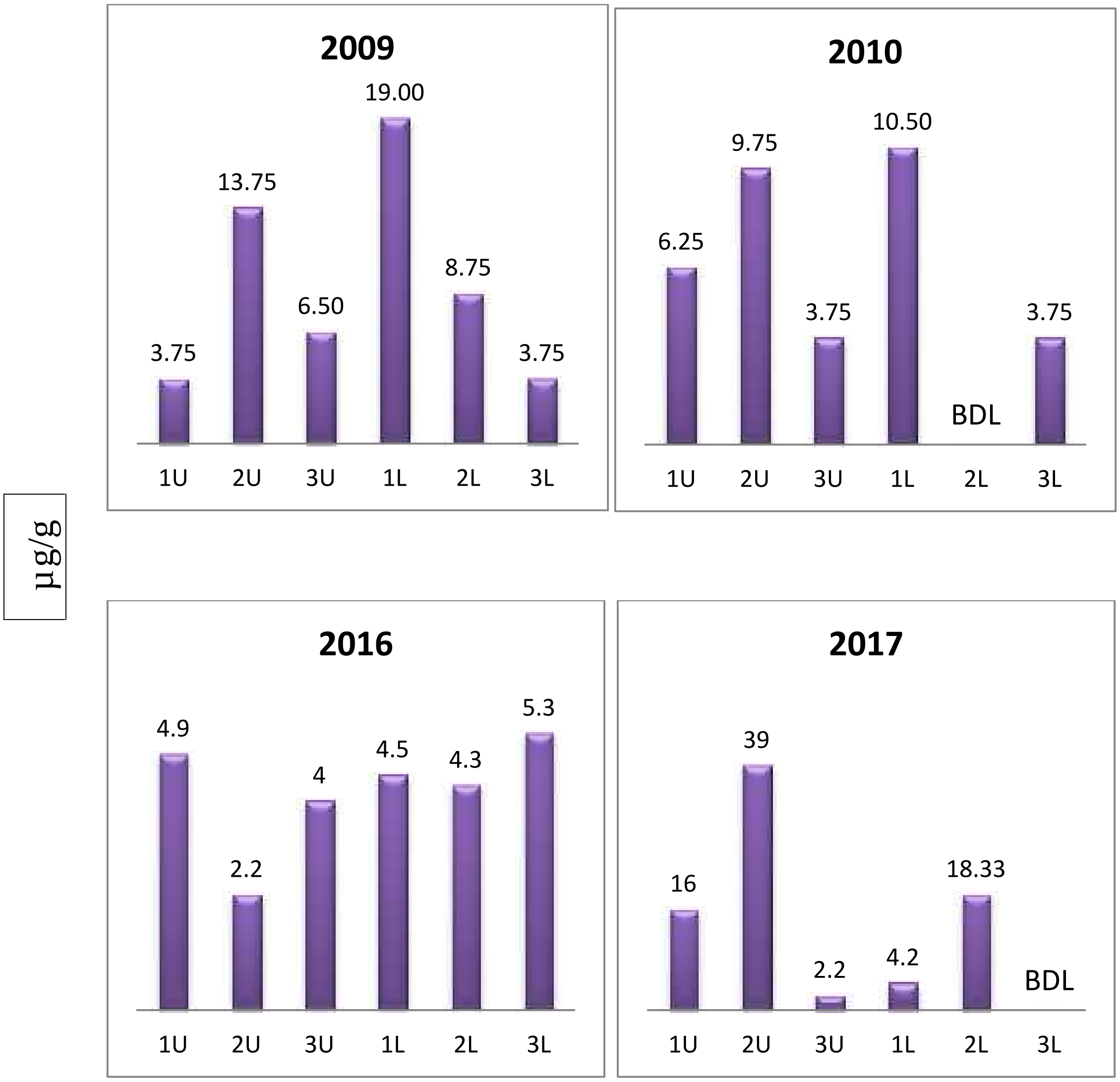


Fig 3.3.17: Spatio-temporal variation of soil Lead (µg/g) of different chars (1 = Char Motherbunia, 2 = Char Taposhi 3 = Char Kashem, U = upper layer, L = lower layer, As the Pb was present only in 1 or 2 samples, standard deviation was not calculated)

3.3.17. Enrichment factor, Contamination factor (C_f), Geoaccumulation index (I*geo*), ecological risk factors and index

For the examination of the anthropogenic contribution of metal in the sediments and differentiate the metal source whether anthropogenic or natural, usually enrichment factor (EF) has been used (Sohrabi *et al.* 2010) based on analyzed element against the background element. Enrichment factor has been found to be an effective method to estimate the anthropogenic impact on sediments (Huang *et al.* 2014) and it is a convenient measure of geochemical trends and is used for making comparisons between areas (Sinex and Helz 1981). The trace metal of interest and place of study play an important role and EF is highly variable depending upon them. The mean EF of trace metal provides fine finger prints of anthropogenic activities over a period of time (Banerjee *et al.* 2012). It is an essential part of geochemical studies to differentiate the sources of trace metals whether from human activities or from natural weathering (Banerjee *et al.* 2012). According to Taylor (1964), $EF < 1$ indicates no enrichment; $1 < EF < 3$ is minor enrichment; $3 < EF < 5$ is moderate enrichment; $5 < EF < 10$ is moderately severe enrichment; $10 < EF < 25$ is severe enrichment; $25 < EF < 50$ is very severe enrichment; and $EF > 50$ is extremely severe enrichment. Metals with EF values higher than 1 can be attributed to long term transportation from natural and/or anthropogenic sources to the studied locations (Nolting *et al.* 1999). Manganese, Zn and Pb showed very severe to extremely severe enrichment in Char Motherbunia (Table 3.3.5). In addition, Mn showed extremely severe enrichment in Char Taposhi and Char Kashem and Zn showed extremely severe enrichment in Char Kashem. Enrichment factor for Mn was very high during 2017 in upper layers of Char Motherbunia (172.2) and Char Kashem (126.4), and in lower layer of Char Kashem (998.3); for Pb in Char Motherbunia (251.7), for Zn the values were also very high in upper layers of Char Motherbunia (238.8) and Char Kashem (182.7), and in lower layer of Char Kashem (1658.5) indicating extremely severe enrichment of Mn.

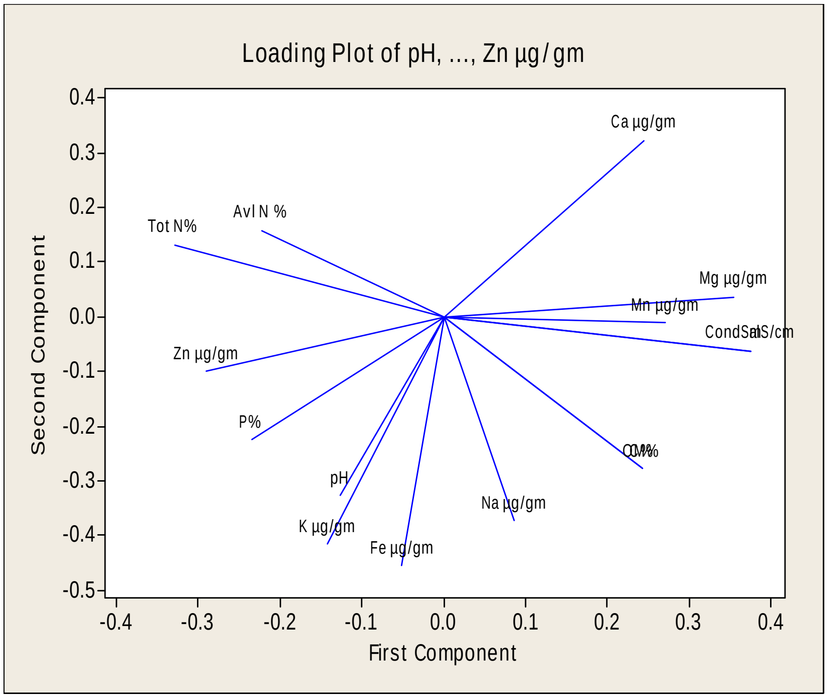
Ataullah *et al*. (2018) have found that EF value for Mn of overall Bangladesh Sundarbans was 8.51 and it showed moderately severe enrichment of Mn in SMF whereas severe enrichment of Mn in oligohaline zone and moderately severe enrichment of Mn in mesohaline and polyhaline zones of SMF were observed.

The contamination factor (C_f) is obtained from a ratio between the measured concentration of the heavy metals in rhizospheric sediment and the pre-industrial reference value for the same metal (Hakanson 1980; Rahman *et al*. 2014). The degree of contamination is defined as the sum of all contamination factors. Potential contamination index (Cp) of the studied metals namely Mn, Fe, Pb and Zn indicated that the metals are in low contamination level (Table 3.3.6). Contamination index indicated that Char Motherbunia is low contaminated in all sampling years. Char Taposhi was found to be also low contaminated during 2009 and moderately contaminated in 2010. Char Kashem has been found to be contamination free.

The geoaccumulation index (I*geo*) compares the contamination of a particular metal against a background value normalized by a factor of 1.5 to minimize the lithographic effect (Ruilian *et al*. 2008; Banerjee *et al*. 2016). The geo-accumulation index (I_{geo}) indicated uncontaminated state of all the three chars in respect to these four metal concentrations.

Although there are some enrichment of some metals namely Mn, Fe, Zn and Pb, the study also revealed that three chars were found to be still at low ecological risk in all sampling occasions i.e. the three chars are at low ecological risk in terms of potential ecological risk factors and hence ERI (Table3.3.7).

Principle component analyses (PCA) were carried out and the results are presented in the Fig 3.3.18 to Fig. 3.3.21. PC-1 of the different variables of soils of 2009 showed the positive loading of conductivity, salinity, OC, OM, Na, Ca, Mg and Mn; and with negative loading of pH, available N, total N, P, K, Fe and Zn (Fig 3.3.18). PC-2 showed positive loading of available N, total N , Ca and Mg; whereas negative loading of pH, conductivity, salinity, OC, OM, P, Na, K, Mn, Fe and Zn. PC-3 showed positive loading of conductivity, salinity, available N, total N , Na, K, Ca and Zn with negative loading of moisture, pH, OC, OM, P, Ca and Zn. PCA also showed the cluster form among the conductivity, salinity, Mg and Mn; and among pH, K and Fe. PC-1 of the different variables of soils of 2010 showed that it has negative loading with pH and Zn content and positive loading with the other variables (Fig 3.3.19). On the other hand, PC-2 has negative loading with pH, Na, K, Mg, Mn, Fe and Zn and positive loading with the other variables. There were two distinct clusters, one among the total N, OM (OC), conductivity,



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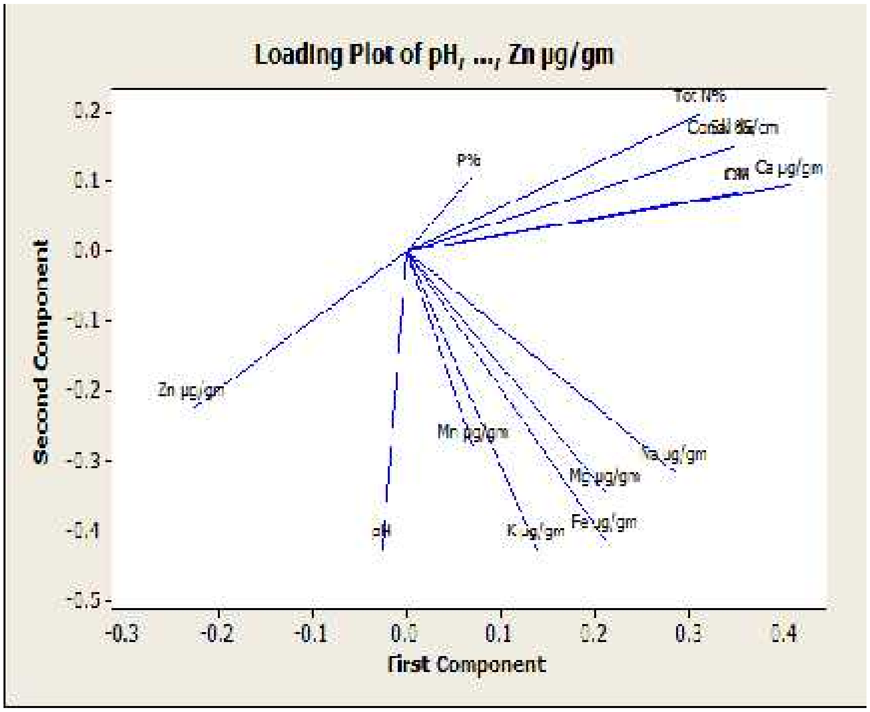
Variable        PC1     PC2     PC3
 pH           -0.127  -0.327  -0.120
 Cond  mS/cm   0.375  -0.063   0.068
 Sal           0.375  -0.063   0.068
 OC%           0.242  -0.279  -0.315
 OM%           0.242  -0.279  -0.315
 P%           -0.234  -0.225  -0.298
 Avl N %      -0.223   0.159   0.393
 Tot N%       -0.329   0.133   0.241
 Na µg/gm      0.087  -0.374   0.341
 K µg/gm      -0.142  -0.416   0.280
 Ca µg/gm      0.244   0.322  -0.058
 Mg µg/gm      0.354   0.036   0.183
 Mn µg/gm      0.271  -0.012   0.339
 Fe µg/gm     -0.051  -0.457   0.284
 Zn µg/gm     -0.290  -0.101  -0.225
```

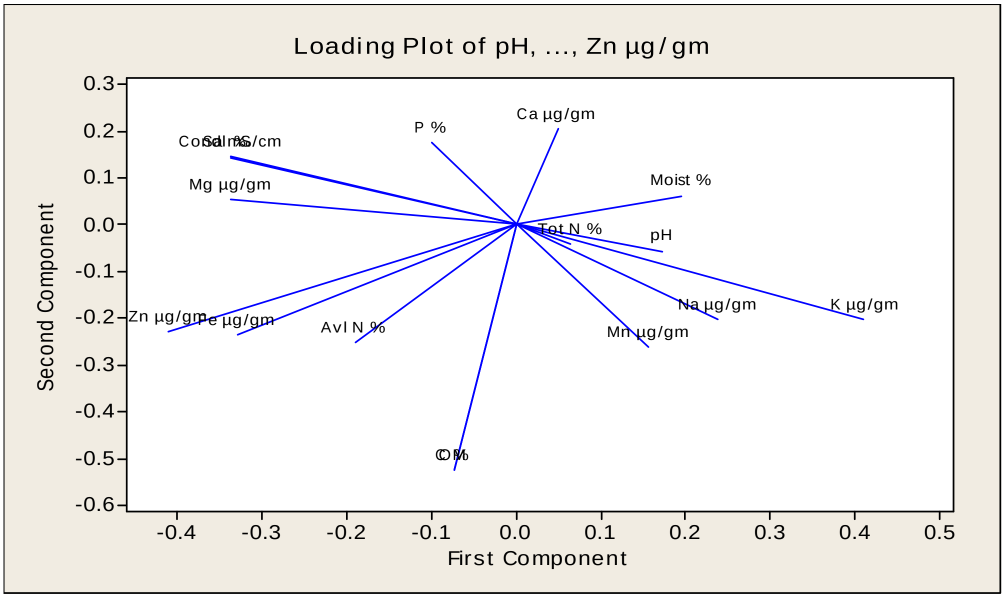
Fig 3.3.18: Principal component analysis of different variables of soils of the three chars (May 2009)

salinity and another one among Na, Mg, Fe and K. PC-1 of the different variables of soils of 2016 showed that it has negative loading with conductivity, salinity, OM (OC), available N, P, Mg, Fe and Zn, and positive loading with the other variables (Fig 3.3.20). Here no distinct cluster was formed like other two years. PC-1 of the different variables of soils of 2017 showed that it has negative loading with pH, Mg, Mn, Fe and Zn, and positive loading with the other variables (Fig 3.3.21).



```
Variable        PC1     PC2     PC3
   pH         -0.026  -0.426   0.071
 Cond. mS/cm   0.347   0.150  -0.329
 Sal ‰         0.347   0.150  -0.329
 OC%           0.351   0.082   0.336
 OM            0.351   0.082   0.336
 P%            0.068   0.104   0.417
 Tot N%        0.312   0.196   0.307
 Na µg/gm      0.284  -0.315  -0.223
 K µg/gm       0.138  -0.427  -0.133
 Ca µg/gm      0.407   0.093   0.016
 Mg µg/gm      0.212  -0.347  -0.039
 Mn µg/gm      0.072  -0.284   0.337
 Fe µg/gm      0.210  -0.412   0.011
 Zn µg/gm     -0.226  -0.224   0.319
```

Fig 3.3.19: Principal component analysis of different variables of soils of the three chars (December 2010)



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Variable        PC1     PC2     PC3
 pH           0.172  -0.057   0.184
 Cond mS/cm  -0.337   0.146  -0.383
 Sal ‰       -0.338   0.144  -0.383
 OC %        -0.074  -0.525   0.170
OM           -0.074  -0.525   0.170
Moist %       0.195   0.062  -0.029
Avl N %      -0.190  -0.252  -0.111
Tot N %       0.064  -0.041   0.135
P %          -0.099   0.175   0.151
Na µg/gm      0.239  -0.204  -0.360
K µg/gm       0.411  -0.204  -0.240
Ca µg/gm      0.049   0.205   0.447
Mg µg/gm     -0.337   0.053   0.354
Mn µg/gm      0.155  -0.261  -0.020
Fe µg/gm     -0.329  -0.235  -0.183
Zn µg/gm     -0.411  -0.229   0.120
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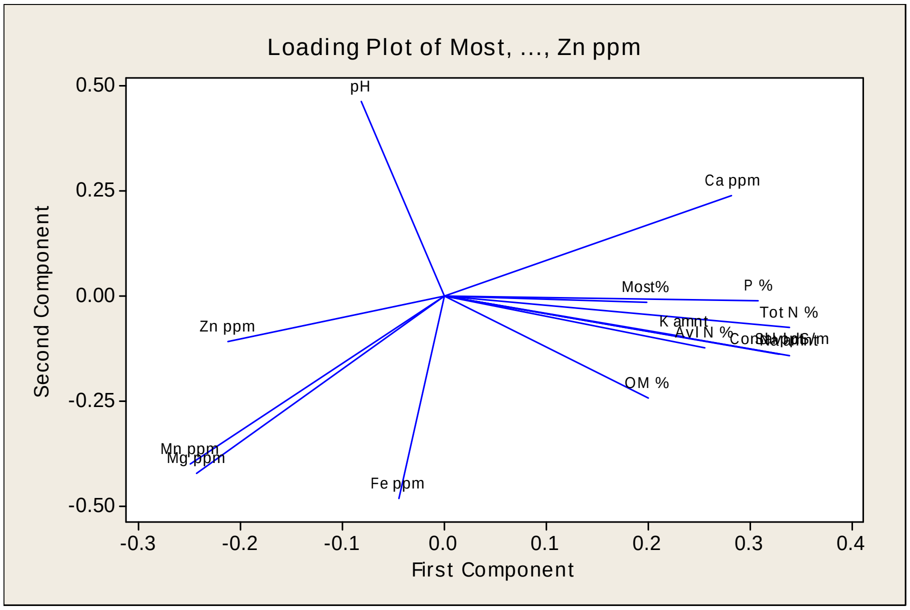
Fig 3.3.20: Principal component analysis of different variables of soils of the three chars (December 2016)



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Variable          PC1     PC2     PC3
Moist%          0.199  -0.016   0.355
pH             -0.081   0.461   0.151
Cond vl dS/m    0.329  -0.139  -0.292
Sal ppt         0.329  -0.139  -0.292
Na amnt         0.339  -0.143  -0.251
K amnt          0.237  -0.097   0.048
OM %            0.201  -0.242   0.365
Avl N %         0.257  -0.123   0.399
Tot N %         0.340  -0.075   0.212
P %             0.309  -0.013   0.256
Ca ppm          0.283   0.237  -0.001
Mg ppm         -0.243  -0.423   0.060
Mn ppm         -0.249  -0.399   0.125
Fe ppm         -0.044  -0.481  -0.203
Zn ppm         -0.212  -0.108   0.389
```

Fig 3.3.21: Principal component analysis of different variables of soils of the three chars (May 2017)

3.4. Mineral Nutrients and Metal Concentrations of Leaves of *S. apetala*

Mangroves are nutrient poor but mangrove trees have been found to be highly productive which may be attributed in part to the evolution of many adaptations for nutrient conservation (Reef *et al*. 2010). The leaves of most mangrove trees are sclerophyllous and evergreen (Komiyama *et al*. 2008) indicated a smaller nutrient investment in new leaves and lower nutrient loss rates due to the long lifespan of the tissue (Aerts 1995). The leaf life span of mangroves have an average of 16 months (1.33 years), that are typical for broadleaved tropical and subtropical evergreens (Reich *et al*. 1992) although this can vary between species and over latitude (Saenger 2002; Suárez and Medina 2005). Results obtained through analysis of the present investigation are presented in the following sections.

3.4.1. Nitrogen Content of Leaves of *S. apetala*

Boto and Willington (1983) suggested that foliar nitrogen and phosphorus may be better indicators of the average nutrient status of mangroves. The values of total nitrogen (N) content in the leaves of *S. apetala* growing in the three chars during the present study are shown in Fig. 3.4.1 and Table 3.4.1 – 3.4.4. The values ranged from 0.42 to 2.38 % with the mean value of 1.11 ± 0.65 % and the coefficient of variation was 58.95 during May 2009. The coefficient of variation (58.95) indicated that there were large variations during this period in leaf N content. Among the three chars, the mean value of N content in leaves of Char Kashem was significantly higher than those of the other two chars. Leaf N content of Char Motherbunia and Char Taposhi varied non-significantly. The amounts of

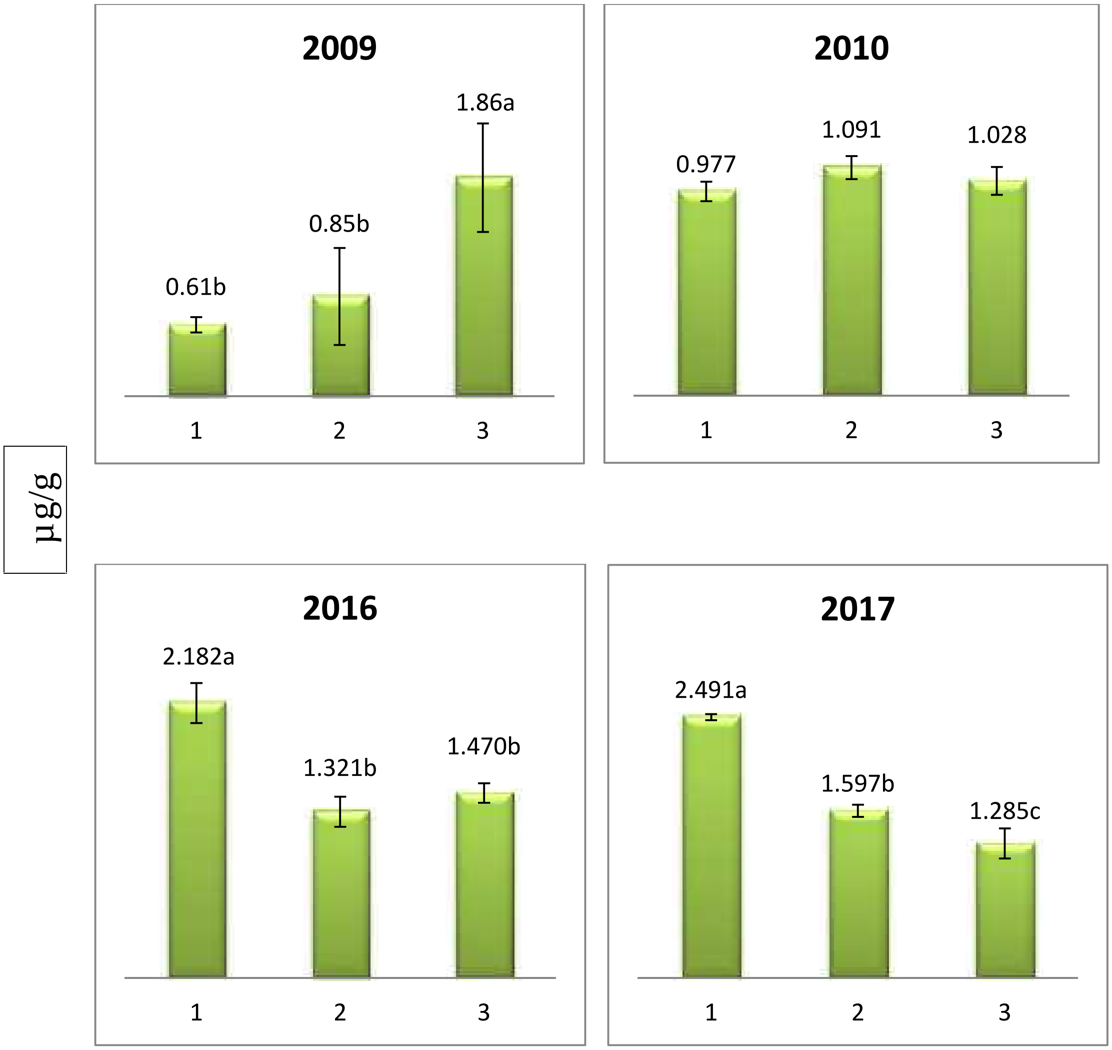


Fig 3.4.1: Spatio-temporal variation of foliar N content (%) of *Sonneratia apetala* growing in different chars. 1 = Char Motherbunia, 2 = Char Taposhi, 3 = Char Kashem

Table 3.4.1: Descriptive statistics of different foliar nutrients of *S. apetala* growing in three chars (May 2009)

Variable	Mean	StDev	CoefVar	Minimum	Median	Maximum
P %	0.102	0.016	16.10	0.076	0.10	0.127
N %	1.108	0.653	58.95	0.420	0.795	2.380
Crude Protein %	6.93	4.08	58.95	2.63	4.97	14.88
Ca µg/g	12021	5633	46.86	2000	11125	22250
Mg µg/g	9150	6659	72.77	2850	7125	26000
Mn µg/g	2638	448	16.98	1750	2750	3300
Fe µg/g	294.3	72.4	24.62	220.0	273.0	473.0
Zn µg/g	38.92	13.44	34.53	20.00	38.00	67.00

Table 3.4.2: Descriptive statistics of different foliar nutrients of *S. apetala* growing in three chars (December 2010)

Variables	Mean	StDev	CoefVar	Minimum	Median	Maximum
P %	0.106	0.019	18.79	0.075	0.113	0.133
N %	1.032	0.077	7.46	0.910	1.010	1.190
Crude Protein %	6.450	0.48	7.46	5.69	6.32	7.44
Ca µg/g	14106	11283	79.99	2332	13777	30289
Mg µg/g	3002	872	29.04	1986	2817	4201
Mn µg/g	477.6	290.0	60.72	213.0	335.0	890.0
Fe µg/g	22539	11728	52.03	6911	27802	33788
Zn µg/g	84.98	31.00	36.48	41.00	102.53	112.22

N in the leaves of *S. apetala* throughout the studies were found almost similar (14.14 mg g^{-1}) to some tropical plants (Tang *et al*. 2018). Amount of N was found to decrease slightly in 2010 and then increase gradually during the study period. It was found that during December 2010, the N content in the leaves of *S. apetala* ranged from 0.91 % to 1.19 % with the mean value of 1.03 ± 0.08 %. The coefficient of variation was 7.46 indicating that there were very small amount of variations during this period in N content of leaves. During December 2016 the values of total N in the leaves of *S. apetala* ranged from 1.16 to 2.41 % with a mean value of 1.66 ± 0.42 % and coefficient of variation was 25.45. An opposite trend was found in the leaf N content during May 2017 compared to 2009. In this sampling occasion highest N content was found in the leaves of Char Motherbunia followed by Char Taposhi and Char Kashem. The values of total N in the leaves of *S. apetala* for overall studied area ranged from 1.16 to 2.51 % with the mean value of 1.79 ± 0.54 % and coefficient of variation was 30.15. Das (2012) has found that the amount of total nitrogen in the leaves of *S. apetala* growing in the Char Tamaruddin, Hatia Upazila, Noakhali district ranged from 0.98 - 1.24 % where the mean value was 1.02 %. In the leaves of *Porterecia coarctata* N values ranged from 1.10 – 1.23 % where the mean value was 1.20 % and in the leaves of *Derris trifoliate* Lour. of that char ranged from 1.02 - 1.20 % where mean value was 1.10 %. N content of the leaves of some mangrove species were almost similar such as 0.80 ± 0.06% in the leaves of *Rhizophora* sp., 1.01 ± 0.13% in the leaves of

Laguncularia sp. and 1.10 ± 0.20% in the leaves of *Avicennia* sp. (Sherman *et al*. 1998).

3.4.2. Phosphorus Content of Leaves of *S. apetala*

The values of total Phosphorus (P) content in the leaves of *S. apetala* growing in the three chars during the present study are shown in Fig. 3.4.2 and Table 3.4.1 – 3.4.4. The amounts of P were found almost similar ((1.11 mg g^{-1}) in the leaves of *S. apetala* throughout the study in comparison to some tropical plants (Tang *et al*. 2018). During May 2009 the of total P content in the leaves of *S. apetala* growing in the three chars ranged from 0.076 to 0.127 % with the mean value of 0.102 ± 0.016 %. The coefficient of variation of 16.10 indicated that there were very small variations during this period in P content of leaves. During first two sampling occasions similar trend was found in P content i.e. highest amount was found in the leaves of Char Kashem followed by Char Taposhi and Char Motherbunia. Almost similar amount of P was found during December 2010 where the minimum value was 0.075 % and maximum was 0.133 % with the mean value of 0.106 ± 0.019 %. The coefficient of variation was 18.79, indicating that there were some variations during this period in P content of leaves. P content in the leaves of *S. apetala* during May 2016 also did not vary with the previous sampling occasions and ranged from 0.090 to 0.129 % with the mean value of 0.111 ± 0.011 %. The coefficient of variation was 10.63. The minimum amount of P in the leaves of *S. apetala* growing in the three chars during May 2017 was 0.065 % and maximum was 0.164 % with the mean value of 0.108 ± 0.025 %. The coefficient of variation was 23.30 indicating that there were some variations during this period in P content of leaves. Das (2012) found that the amount of total P content in the leaves of *S. apetala* ranged from 0.62 to 0.90 % where mean value was 0.812, in the leaves of *P. coarctata* P content ranged from 0.612 tp 0.91% with the mean value of 0.756 % and in the leaves of *Derris trifoliate* P content ranged from 2.42 to 3.67 % where mean value was 3.45%. In the other mangrove species such as *Rhizophora, Laguncularia,* and *Avicennia,* mean concentrations of P were found to be 0.06 ± 0.003 %, 0.12 ± 0.011% and 0.12 ± 0.01 %, respectively (Sherman *et al.* 1998). These values were comparatively very low than those of the values obtained in present studies. Some reports suggested that mangroves are highly efficient in nutrient cycling and nutrient retention mechanisms (Ball 1988) and high rates of leaf resorption (Alongi 2018). Phosphorus has also been found to be tightly immobilized to inorganic phases such as soil aluminum, iron, calcium, and sulfides (Alongi *et al*. 1992; Sherman *et al*. 1998).

In the present study the N : P in plant leaves varied from 10.86 in 2009 to 9.74, 14.94 and 16.58 in 2010, 2016 and 2017, respectively, with the average value of 12.94. Several workers (Sterner and Elser 2002; Ågren 2008) suggested the N : P in plant leaves are very useful in predicting nutrient limitations to primary productivity. This offers a powerful tool for ecological and physiological investigations by providing a straightforward means of characterizing the relative availability of N vs P at a given site (Cernusak *et al*. 2010). The leaf N:P over 16 (on a mass basis) indicated P limitation to biomass production whereas the ratio

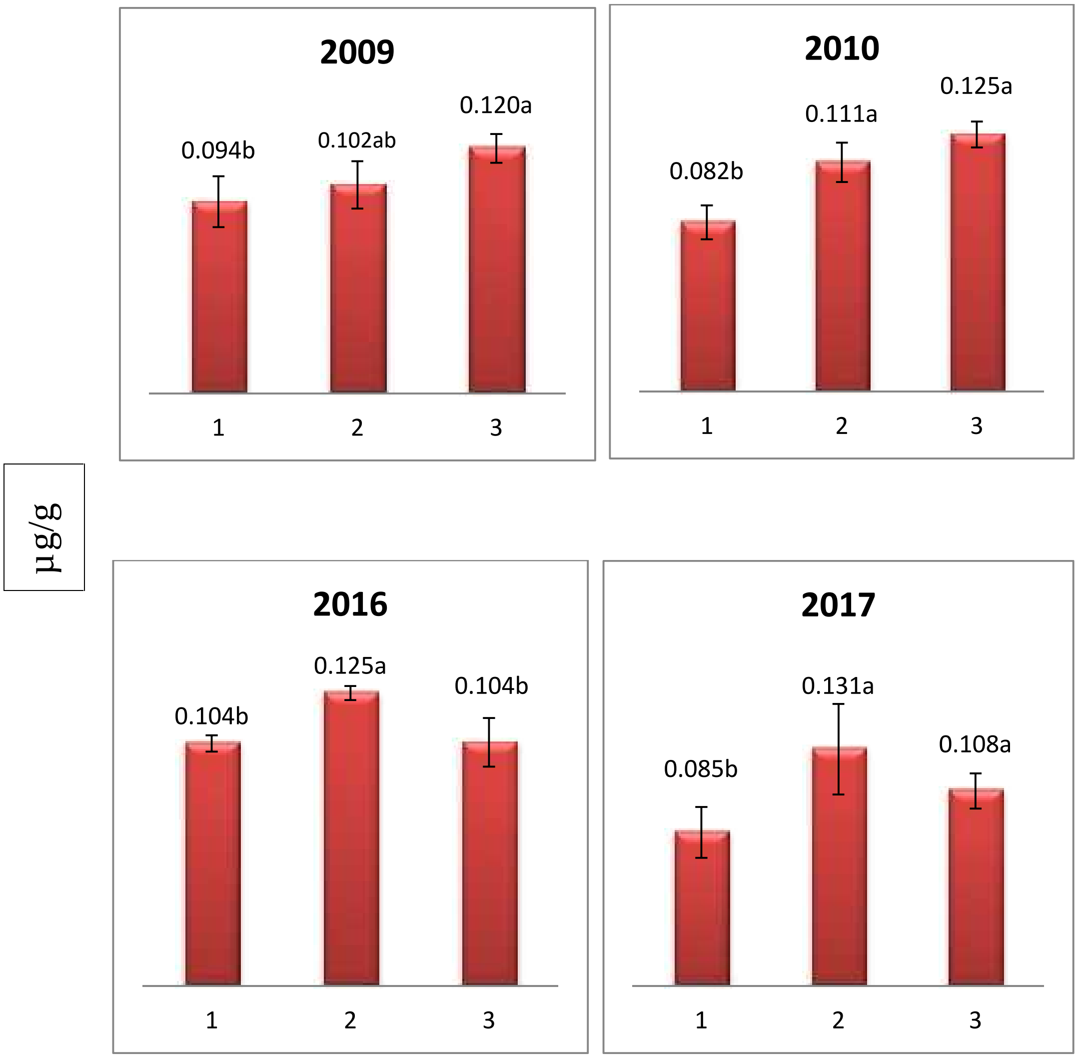


Fig 3.4.2: Spatio-temporal variation of foliar P content (%) of *Sonneratia apetala* growing in different chars. 1 = Char Motherbunia, 2 = Char Taposhi, 3 = Char Kashem

Table 3.4.3: Descriptive statistics of different foliar nutrients of *S. apetala* growing in three chars (December 2016)

Variables	Mean	StDev	CoefVar	Minimum	Median	Maximum
P %	0.111	0.011	10.63	0.090	0.1095	0.129
N %	1.658	0.422	25.45	1.156	1.545	2.412
Crude Protein %	10.36	2.64	25.45	7.23	9.65	15.08
Ca µg/g	10533	8561	81.27	2300	8050	33600
Mg µg/g	4992	1352	27.09	3000	5300	7100
Mn µg/g	1138	2169	190.71	80.0	230	7700
Fe µg/g	238.2	40.0	16.79	161.0	240.5	289.0
Zn µg/g	25.67	5.76	22.43	15.00	25.50	34.00

Table 3.4.4: Descriptive statistics of different foliar nutrients of *S. apetala* growing in three chars (2017)

Variables	Mean	StDev	CoefVar	Minimum	Median	Maximum
P %	0.108	0.025	23.30	0.065	0.103	0.164
N %	1.791	0.540	30.15	1.159	1.605	2.511
Crude Protein %	11.194	3.373	30.13	7.24	10.03	15.69
Ca µg/g	7450	2273	30.51	3900	7600	10600
Mg µg/g	7700	2580	33.51	3600	8050	11800
Mn µg/g	3083	2197	71.26	320	3250	7000
Fe µg/g	337.5	118.7	35.17	176.0	335.0	550.0
Zn µg/g	35.17	6.63	18.86	19.00	36.50	44.00

below 14 (on a mass basis) indicated N limitation (Koerselman and Meuleman 1996; Aerts and Chapin 2000; Tessier and Raynal 2003; Güsewell 2004). It seems that the study area showed a change from N limited to P limited status over a period of 8 years time. Some terrestrial ecosystems also appear not to conform to this expectation (Craine *et al*. 2008) suggesting that the interpretation of terrestrial plant N : P ratios may be more complex (Cernusak *et al*. 2010). On the other hand, *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa* may present high growth rates in soils without nutritional limitations (Reef *et al*. 2010).

3.4.3. Calcium Content of Leaves of *S. apetala*

The values of total calcium (Ca) content in the leaves of *S. apetala* growing in the three chars during the present study are shown in Fig. 3.4.3 and Table 3.4.1 – 3.4.4. During May 2009, the total Ca content in the leaves of *S. apetala* growing in the three chars ranged from 2000 µg/g to 22250 µg/g with the mean value of 12021 ± 5633 µg/g. The coefficient of variation was 46.86 indicating that there were considerable variations during this period in total Ca content of leaves. The minimum amount of total Ca in the leaves of *S. apetala* growing in the three chars during December 2010 was 2332 µg/g and maximum was 30289 µg/g with the mean value of 14106 ± 11283 µg/g. The coefficient of variation was 79.99 indicating that there was very large variations during this period in total Ca

Fig 3.4.3: Spatio-temporal variation of foliar Ca content (µg/g) of *Sonneratia apetala* growing in different chars. 1 = Char Motherbunia, 2 = Char Taposhi, 3 = Char Kashem

content of leaves. During May 2016 the of total Ca content in the leaves of *S. apetala* growing in three chars ranged from 2300 µg/g to 33600 µg/g with the mean value of 10533 ± 8561 µg/g. The coefficient of variation was 81.27 indicating that there were very large variations during this period in total Ca content of leaves. The minimum amount of total Ca in the leaves of *S. apetala* growing in the three chars during May 2017 was 3900 µg/g and maximum was 10600 µg/g with a mean value of 7450 ± 2273 µg/g. The coefficient of variation was 30.51 indicating that there were some variations during this period in total Ca content of leaves. Das (2012) found that the amount of total Ca ranged from 1202 - 2332 µg/g where mean value was 1582 µg/g in the leaves of *S. apetala*, in the leaves of *P. coarctata* it ranged from 42.5 – 45.63 µg/g where mean value was 44.07 µg/g and in the leaves of *D. trifoliata* ranged from 20031 - 30301 µg/g where mean value was 30289 µg/g. In their study Kotmire and Bhosale (1979) found Ca ranging from 0.14 to 2.80 % in the different mangrove species in the west coast of India (Maharashtra) and Ca content of the some mangrove species in the Bhitarkanika, Orissa, east coast of India were 02 - 08 µg/g in *Rhizophora mucronata*, 13 - 26 µg/g in *Avicennia officinalis,* 10-24 µg/g in *Xylocarpus granatum*, 11 - 32 µg/g in *Ceriops decandra*, 31 - 72 µg/g in *B. cylindrica* (Sarangi *et al.* 2002).

3.4.4. Magnesium Content of Leaves of *S. apetala*

The values of total magnesium (Mg) content in the leaves of *S. apetala* growing in three chars during the present study are shown in Fig. 3.4.4 and Table 3.4.1 – 3.4.4. The minimum amount of Mg in the leaves of *S. apetala* during May 2009 was 2850 µg/g and maximum was 26000 µg/g with the mean value of 9150 ± 6659 µg/g. The coefficient of variation was 72.77 indicating that there were very large variations in Mg content of leaves during this period. During December 2010 the Mg content in the leaves of *S. apetala* ranged from 1986 µg/g to 4201 µg/g with the mean value of 3002 ± 872 µg/g. The coefficient of variation was 29.04 indicating that there were some variations during this period in Mg content of leaves. During December 2016, the values of total Mg in the leaves of *S. apetala* ranged from 3000 to 7100 µg/g with the mean value 4992 ± 1352 µg/g and coefficient of variation was 27.09. The values of total Mg in the leaves of *S. apetala* during May 2017 ranged from 3600 to 11800 µg/g with the mean value of 7700 ± 2580 µg/g and coefficient of variation was 33.51.

Das (2012) found that the amount of total Mg in the leaves of *S. apetala* ranged from 1986 - 2507 µg/g where mean value was 2226 µg/g, in the leaves of *P. coarctata* ranged from 1986 – 2296 µg/g with a mean value of 2141 µg/g and in the leaves of *D. trifoliata* ranged from 4102 – 4103 µg/g where mean value was 4102.5 µg/g. Kotmire and Bhosale (1979) found 0.31 - 1.66 % Mg in the

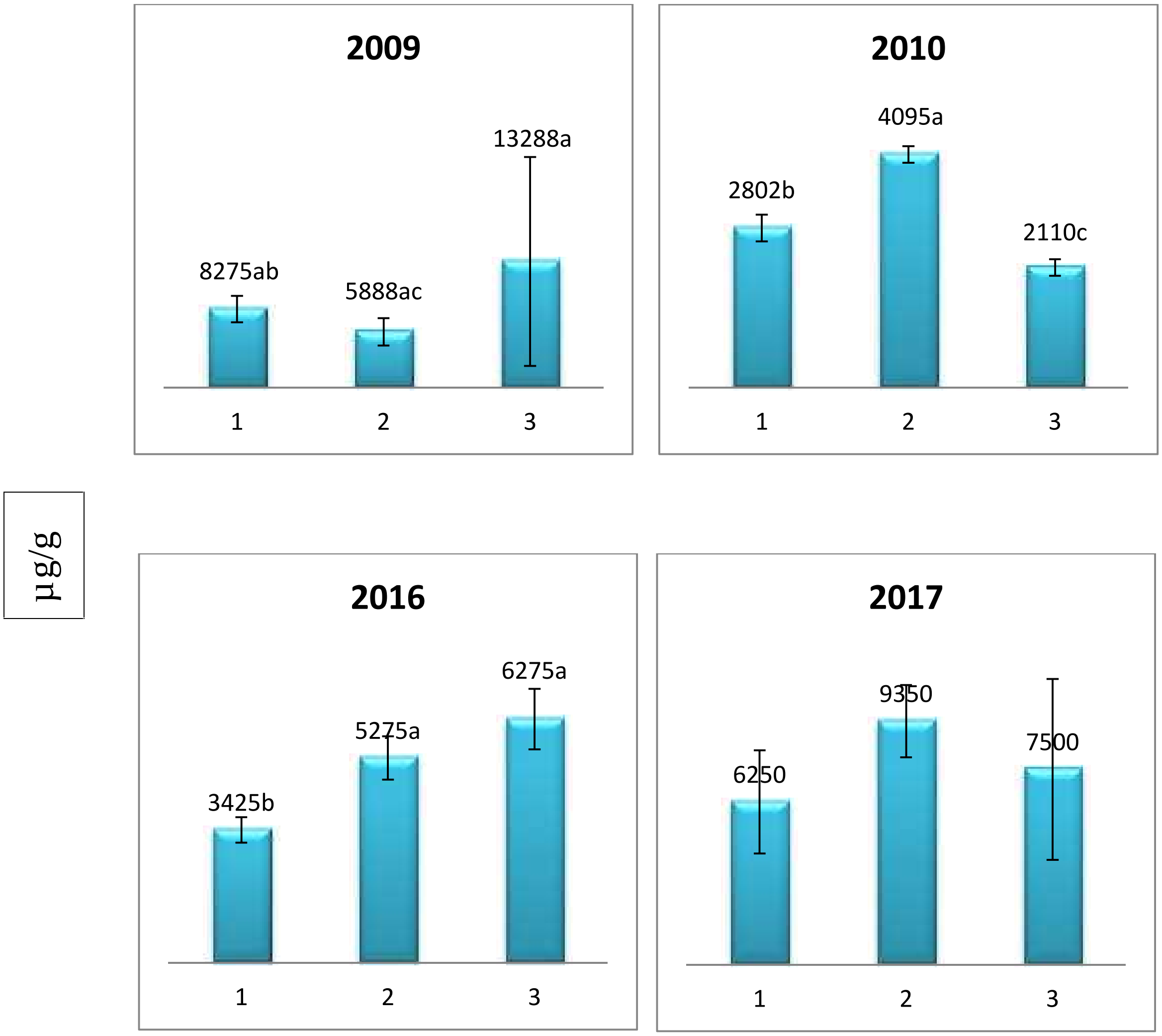


Fig 3.4.4: Spatio-temporal variation of foliar Mg content (µg/g) of *Sonneratia apetala* growing in different chars. 1 = Char Motherbunia, 2 = Char Taposhi, 3 = Char Kashem

mangrove plant of the coast of India (Maharashtra). The adequate amount of Mg in the mangrove is reported as 0.2% (Epstein 1972).

3.4.5. Manganese Content in Leaves of *S. apetala*

The values of total manganese (Mn) content in the leaves of *S. apetala* growing in three chars during the present study are shown in Fig. 3.4.5 and Table 3.4.1 – 3.4.4. The minimum concentration of Mn in the leaves of *S. apetala* during May 2009 was 1750 µg/g and maximum was 3300 µg/g with the mean value of 2638 ± 448 µg/g. The coefficient of variation was 16.98 indicating that there were very small variations in Mn concentration in the leaves during this period. It was found that the values of Mn content in the leaves of *S. apetala* growing in three chars were also similar and no significant difference was observed. In the month of December 2010 the Mn concentration in the leaves of *S. apetala* varied significantly in three chars where highest mean value was found in Char Taposhi followed by Char Kashem and Char Motherbunia. The overall values in the study area during May 2010 ranged from 213.0 µg/g to 890.0 µg/g with the mean value of 477.6 ± 290.0 µg/g. The coefficient of variation was 60.72 indicating that there were large amount of variations during this period in Mn concentration of leaves. In December 2016 the values of total Mn in the leaves of *S. apetala* ranged from 80.0 to 7700 µg/g with a mean value 1138 ± 2169 µg/g and the coefficient of variantion was 190.71. The highest mean value was observed in Char Kashem and the values of other two chars were almost similar. The values of total Mn in the leaves of *S. apetala* in May 2017 ranged between 320.0 and 7000 µg/g with the mean value of 3083 ± 2197 µg/g and coefficient of variation was 72.16. Among the three chars, the Mn concentration of leaves of Char Kashem was highest followed by Char Taposhi although they did not vary significantly. Manganese concentration of leaves of Char Motherbunia differed significantly from the values of the other two chars and has the lowest value. Das (2012) found that the total Mn concentration ranged from 213 - 356.0 µg/g where the mean value was 337 µg/g, in the leaves of *P. coarctata* ranged from 318 - 359 µg/g where the mean value was 343.7 µg/g and in the leaves of *D. trifoliata* ranged from 356 - 857 µg/g with a mean value was 756.85 µg/g. Kotmire and Bhosale (1979) found 4 to 80 mg per 100 gm Mn in the mangrove plant of the coast of India (Maharashtra). Manganese concentration in some mangrove species in the Bhitarkanika, Orissa, east coast of India were 6.9 - 7.2 mg/kg in the leaves of *R. mucronata*, 6.2 - 6.8 mg/kg in the leaves of *A. officinalis*, 6.4 - 6.6 mg/kg in the leaves of *X. granatum*, 6.1 - 6.8 mg/kg in the leaves of *C. decandra*, 5.7 - 6.1 mg/kg in the leaves of *B. cylindrica* (Sarangi *et al.* 2002). These values were higher than the values obtained in the present study.

Manganese was found several hundred times higher as in other two mangroves of Brazil than the highest reference concentrations of soil fertility standards (SBCS 2004) (Madi *et al*. 2015). Such high values did not seem to represent a negative factor for the plants, since these were minimized by a series of biotic and abiotic factors (Lacerda *et al*. 1993; Machado *et al*. 2005; Jiang *et al*. 2009). In anoxic environments, Mn tends to undergo reduction, thus become more available

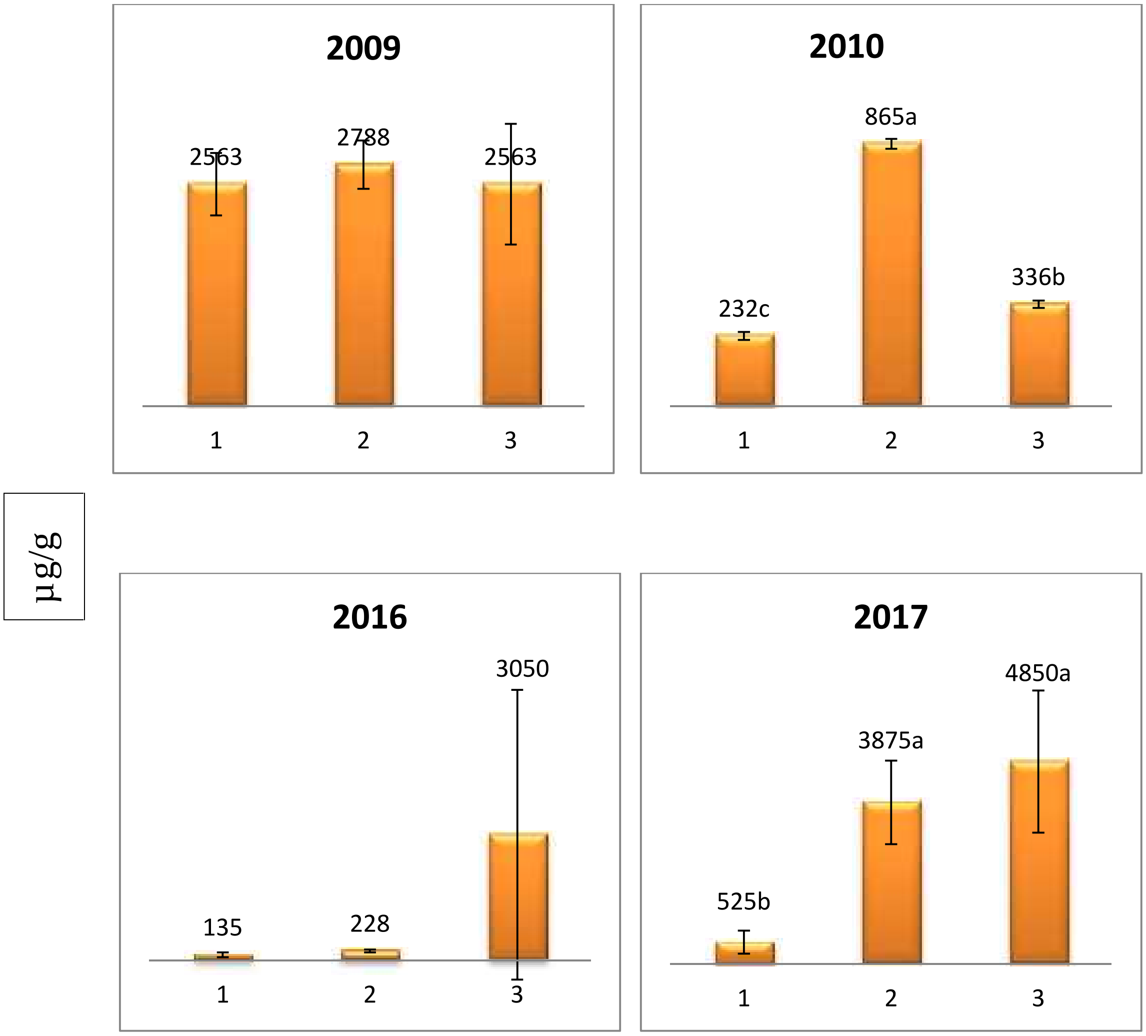


Fig 3.4.5: Spatio-temporal variation of foliar Mn content (µg/g) of *Sonneratia apetala* growing in different chars. 1 = Char Motherbunia, 2 = Char Taposhi, 3 = Char Kashem

(Barber 1984). It was also found that Mn tends to accumulate more in the aerial parts of the plant than in the roots (Cicad 2004).

3.4.6. Iron Content in the of Leaves of *S. apetala*

The values of total iron (Fe) concentration in the leaves of *S. apetala* growing in the three chars during the present study are presented in Fig. 3.4.6 and Table 3.4.1 – 3.4.4. In May 2009 the total Fe concentration in the leaves of *S. apetala* growing in the three chars ranged from 220.0 µg/g to 473.0 µg/g with a mean value of 294.3 ± 72.4 µg/g. The coefficient of variation was 24.62 indicating that there were some variations during this period in total Fe concentration of leaves. Iron content in the leaves of S. apetala growing in three chars did not vary significantly (Fig. 3.4.6) and maximum value was found in Char Motherbunia followed Char Kashem and Char Taposhi. In the following three sampling, maximum values were found in the leaves of Char Kashem followed by Char Taposhi and Char Motherbunia. The minimum concentration of total Fe in the leaves of *S. apetala* growing in three chars during December 2010 was 6911 µg/g and maximum was 33788 µg/g with the mean value of 22539 ± 11728 µg/g. The coefficient of variation was 52.03 indicating that there were very large amount of variations during this period in total Fe concentration of leaves. In May 2016 the Fe concentration in the leaves of *S. apetala* growing in the three chars ranged from 161.0 µg/g to 289.0 µg/g with a mean value of 238.2 ± 40.0 µg/g. The coefficient of variation was 16.79 indicating that there were very small variations during this

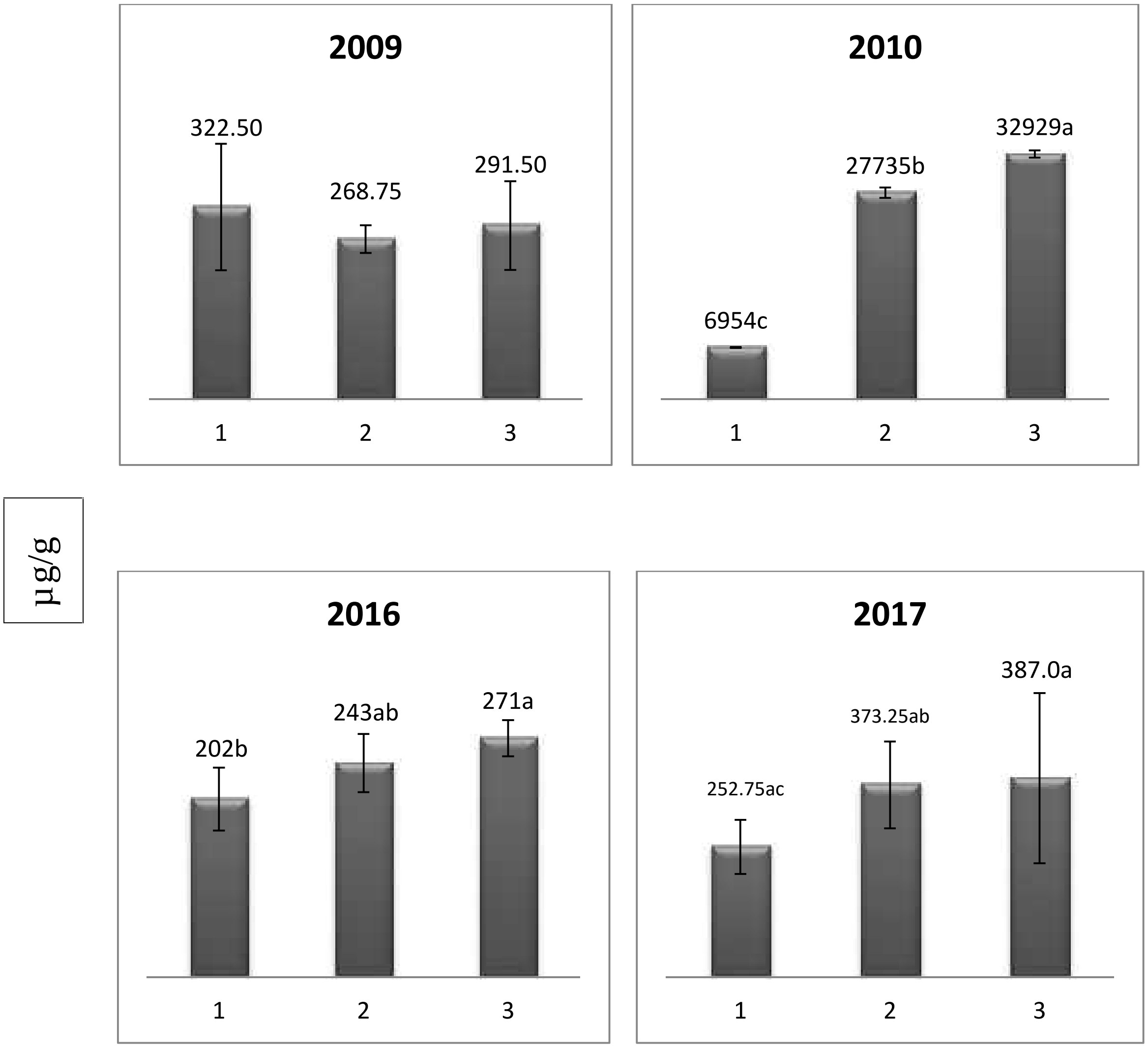


Fig 3.4.6: Spatio-temporal variation of foliar Fe content (µg/g) of *Sonneratia apetala* growing in different chars. 1 = Char Motherbunia, 2 = Char Taposhi, 3 = Char Kashem

period in total Fe concentration of leaves. The minimum amount of total Fe in the leaves of *S. apetala* growing in the three chars during May 2017 was 176.0 µg/g and maximum was 550.0 µg/g with a mean value of 337.5 ± 118.7 µg/g. The coefficient of variation was 35.17 indicating that there were some variations during this period in the concentration of Fe in leaves. Das (2012) found that the amount of total Fe ranged from 6917 - 32078 µg/g where mean value was 13934 µg/g in the leaves of S. *apetala*, in the leaves of *P. coarctata* ranged from 32078 - 33788 µg/g with a mean value 32933 µg/g and in the leaves of *D. trifoliata* ranged from 27891 – 27897 µg/g where mean value was 27894 µg/g. Kotmire and Bhosale (1979) found 0.012 - 2.80 % Fe in the mangrove plants of the coast of India (Maharashtra). The requirement of Fe in the normal plants is 11 mg per 100 g of dry tissue (Epstein 1972). Iron content found in the leaves of other mangrove species in the Bhitarkanika, Orissa, east coast of India were 19 - 32 µg/g in *R. mucronata*, 33 - 61 µg/g in *A. officinalis*, 07 - 36 µg/g in *X. granatum*, 19 - 22 µg/g in *C. decandra*, 17 - 41 µg/g in *B. cylindrica* (Sarangi *et al.* 2002).

3.4.7. Zinc Content in Leaves of *S. apetala*

The values of total zinc (Zn) content in the leaves of *S. apetala* growing in three chars during the present study are shown in Fig. 3.4.7 and Table 3.4.1 – 3.4.4. Zinc concentration in the leaves of *S. apetala* growing in three chars ranged from 20.00 µg/g to 67.00 µg/g with the mean value of 38.92 ± 13.44 µg/g in May of 2009. The coefficient of variation was 34.53 indicating that there were some variations during this period in total Zn content of leaves. During the period of

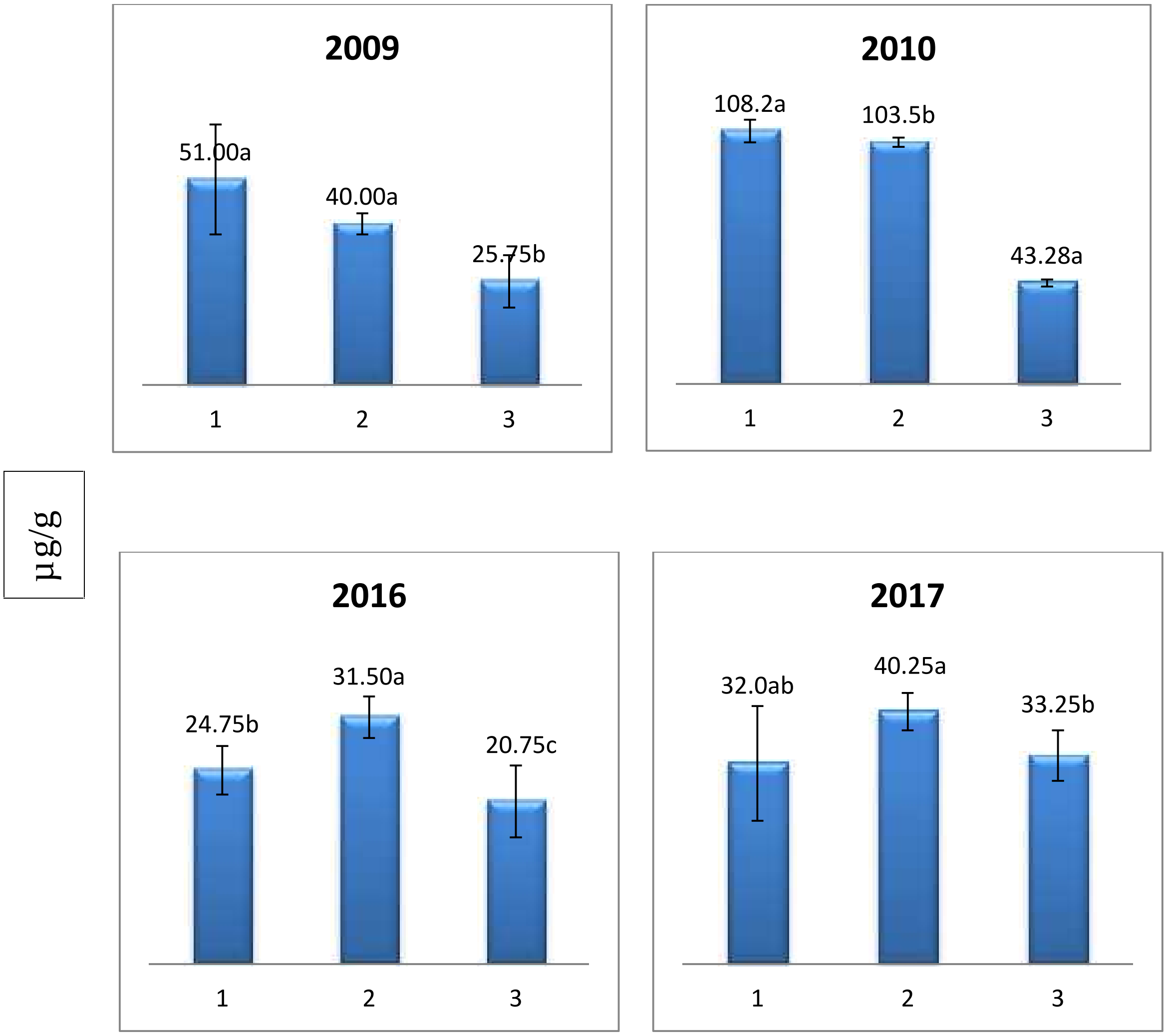


Fig 3.4.7: Spatio-temporal variation of foliar Zn content (µg/g) of *Sonneratia apetala* growing in different chars. 1 = Char Motherbunia, 2 = Char Taposhi, 3 = Char Kashem

May 2009 and December 2010 Zn content in the leaves of *S. apetala* of Char Motherbunia was highest followed by Char Taposhi and Char Kashem. The minimum amount of total Zn in the leaves of *S. apetala* growing in the three chars during December 2010 was 41.00 µg/g and maximum was 112.22 µg/g with the mean value of 84.98 ± 31.00 µg/g. The coefficient of variation was 36.48 indicating that there were some variations during this period in Zn concentration of leaves. During the period of the next two visits Zn concentration was highest in Char Taposhi followed by Char Motherbunia and Char Kashem. In May 2016, Zn concentration in the leaves of *S. apetala* growing in the three chars ranged from 15.00 µg/g to 34.00 µg/g with a mean value of 25.67 ± 5.76 µg/g. The coefficient of variation was 22.43 indicating that there were some variations during this period in Zn concentration of leaves. The minimum amount of total Zn in the leaves of *S. apetala* growing in three chars during May 2017 was 19.00 µg/g and maximum was 44.00 µg/g with a mean value of 35.17 ± 6.63 µg/g. The coefficient of variation was 18.86 indicating that there were some variations during this period in total Zn content of leaves. Das (2012) found that the amount of total Zn in the leaves of *S. apetala* ranged from 92.5 - 105.2 µg/g where mean value was 101.76 µg/g, in the leaves of *P. coarctata* ranged from 42.5 – 45.63 µg/g where mean value was 44.07 µg/g and in the leaves of *D. trifoliata* ranged from 45.63 – 112.2 µg/g with a mean value of 103.86 µg/g. Zinc concentration in the leaves of other mangrove species in the Bhitarkanika, Orissa, east coast of India were 0.7 - 1.1 µg/g in *R. mucronata*, 0.7 - 1.5 µg/g in *A. officinalis*, 0.4 - 0.6 µg/g in *X.*

granatum, 0.3 - 1.0 µg/g in *C. decandra*, 0.8 - 2.0 µg/g in *B. cylindrica* (Sarangi *et al.* 2002). These values were in general lower than those of the values obtained in the present study.

3.4.8. Lead Concentration in Leaves of *S. apetala*

The values of lead (Pb) concentration in the leaves of *S. apetala* growing in three chars during the present study are presented in Fig. 3.4.8 and Table 3.4.1 – 3.4.4. Lead concentrations of the leaves of S. apetala growing in three chars in May 2009 and in December 2016 were below detection level. During December 2010 and May 2017, Pb was found in some leaves of the studied plant species (that is why no standard deviation could be determined and bar showing the values do not have standard deviation bar at the top). During 2010, Pb content of leaves in Char Motherbunia showed highest value (3.427 µg/g) followed by Char Kashem (2.522 µg/g) and Char Taposhi (1.617 µg/g). In 2017, Pb was below detection level in the leaves of *S. apetala* growing in Char Kashem but very high amount was found in the in the leaves of Char Motherbunia (15.750 µg/g) and in Char Taposhi (13.250 µg/g). Isroni *et al*. (2016) found that Pb concentration in the leave of *Rhizophora mucronata* growing in three locations in Mlaten Village, Indonesia varied from 0.28 to 0.62 µg/g. Alzahrani *et al*. (2018) found that the concentrations of Pb in the leaves of *Avicennia marina* (3.79 µg/g) growing in the Red Sea coast of Saudi Arabia was more or less similar to the aerial roots (3.67 µg/g) of the same mangroves. The standard for Pb concentration has been fixed to 5.0 µg/g (FAO 2007). Lead concentration in leaves of *A. marina* growing in different places of

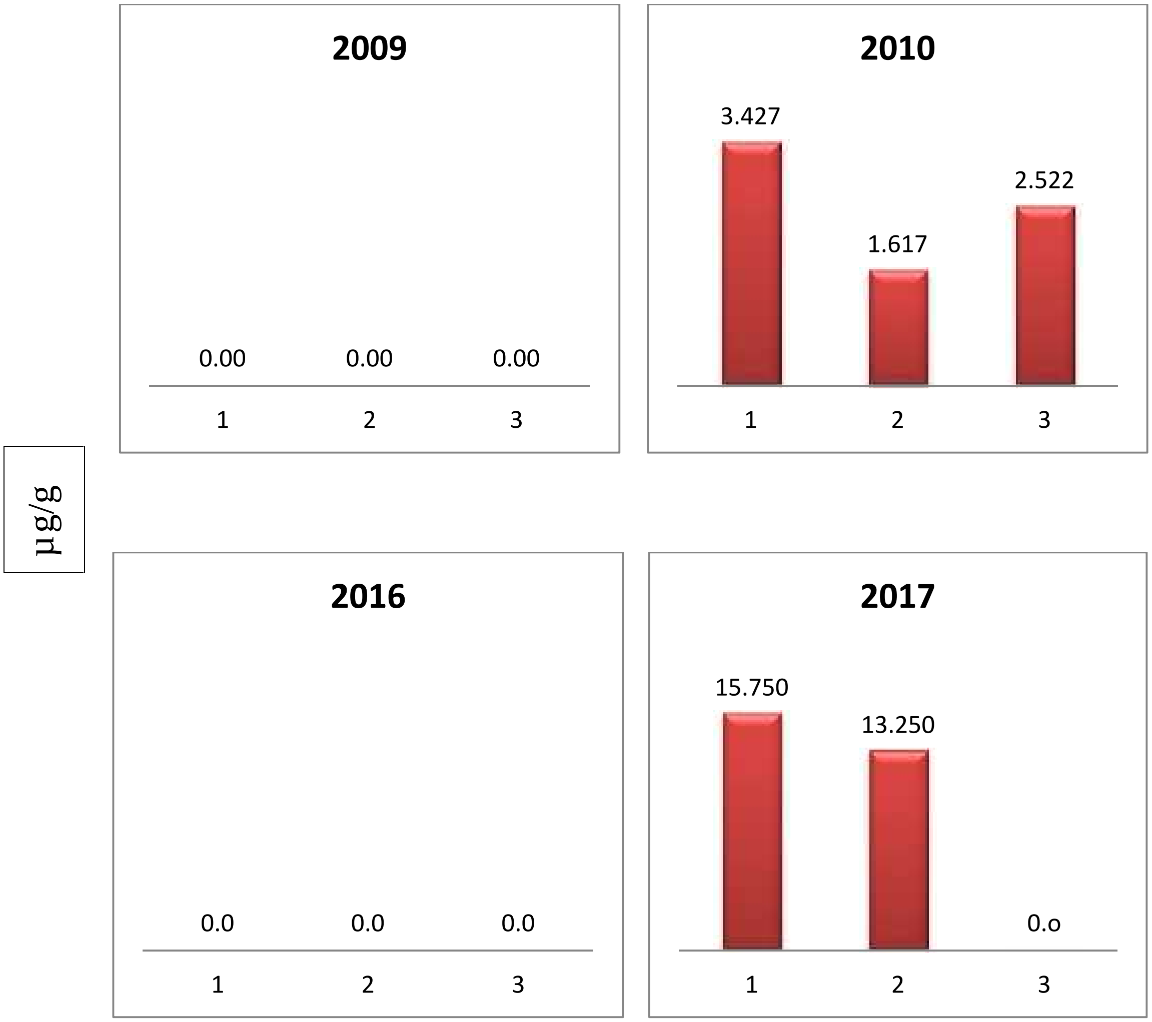


Fig 3.4.8: Spatio-temporal variation of foliar Pb content (µg/g) of *Sonneratia apetala* growing in different chars. 1 = Char Motherbunia, 2 = Char Taposhi, 3 = Char Kashem (0.0 = not present or below detection level)

the world are reported by different authors as 6.20 µg/g in Punta Mala Bay, Panama (Guzmán and Jiménez 1992), 1.7 µg/g in Port Jackson, Australia (MacFarlane and Burchett 2002), 0.57 µg/g in Al-Shouiba, Saudi Arabia (Abohassan 2013), 1.90 µg/g in Shenzhen, China (Li *et al*. 2016). The present study showed very high Pb concentration compared to other mangroves areas and the standard value.

When the values of the present study was compared with some mangroves of Asia (Futian, People's Republic of China (PRC), Tam *et al*. 1995; Fujian, PRC, Lin and Lin 1985; Tansui, Taiwan, Chen 1982) and Paciffic (Queensland, Australia, Spain and Holt 1980), it was found that the mean N content in leaves of *S. apetala* (1.791 %) collected during 2017 was significantly higher than those of *Aegiceras corniculata* (L.) of Futian and Fujian forest of PRC, and Queensland, Australia (Table 3.4.4). But the N content were almost similar to *Kandelia candel* growing in Fujian of PRC (1.88 ± 0.02 %) and Tanushi of Taiwan (1.90 %). P Content in the leaves of *S. apetala* were lower than the *K. candel* (0.87 %) (Fujian, PRC) but the values were almost similar to the plants growing in other forests. Zinc content of the present study was higher than *A. corniculata* of Queensland and within the range of both species of Futian forest (Tam *et al.* 1995). Manganese content in the leaves of *S. apetala* of present studies was higher than the *A. corniculata* of Futian and Queensland (Table 3.4.4). Manganese content in the leaves of *S. apetala* of present studies collected during 2009 was higher than that of *K. candel* (1048 ± 269 µg/g). But the values of present studies collected during rest three sampling

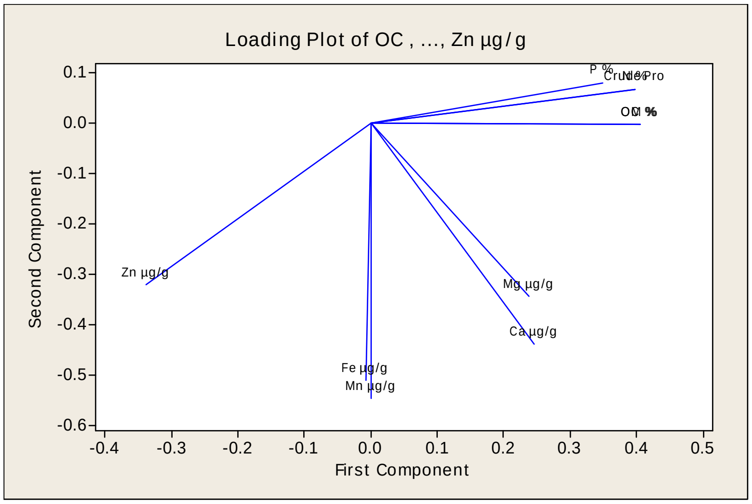
Table 3.4.4: Comparison of concentrations of different elements (%) and some heavy metals (µg/g) in different mangrove species. Standard deviation is shown in parenthesis. ND = Not detected, PRC = Peoples' Republic of China

Mangroves	Species	N	P	Zn	Mn	Source
Rangabali, Patuakhali 2009	*Sonneratia apetala*	1.108 (0.653)	0.102 (0.016)	38.92 (13.44)	2638 (448)	Present study
Rangabali, Patuakhali 2010	*S. apetala*	1.032 (0.077)	0.106 (0.019)	84.98 (31.00)	477.6 (290.0)	Present study
Rangabali, Patuakhali 2016	*S. apetala*	1.658 (0.422)	0.111 (0.011)	25.67 (5.76)	238.2 (40.0)	Present study
Rangabali, Patuakhali 2017	*S. apetala*	1.791 (0.540)	0.108 (0.025)	35.17 (6.63)	337.5 (118.7)	Present study
Hatia,Noakhali, Bangladesh.	*S. apetala*	0.987 (0.02)	0.812 (0.21)	101.86 (5.75)	337 (64)	Das 2012
Hatia,Noakhali, Bangladesh.	*Porteresia coarctata*	1.20 (0.03)	0.756 (0.215)	44.07 (2.21)	343.7 (26.6)	Das 2012
Hatia,Noakhali, Bangladesh.	*Derris trifoliata*	1.095 (0.017)	3.45 (0.343)	103.86 (2.21)	756.85 (26.6)	Das 2012
Futian, PRC	*Aegiceras corniculata*	1.31 (0.01)	0.14 (0.04)	85.2 (28.6)	166 (89)	Tam *et al.* 1995
	Kandelia candel	1.39 (0.01)	0.13 (0.01)	69.7 (25.2)	1048 (269)	
Queenlands, Australia	*A. corniculata*	0.85 (0.06)	0.10 (0.01)	15.5 (3.0)	158 (67)	Spain and Holt 1980
Fujian, PRC	*A.corniculata*	1.22 (0.01)	0.12 (0.00)	ND	ND	Lin and Lin 1985
	K. candel	1.88 (0.20)	0.87 (ND)	ND	ND	
Tanshui, Taiwan	*K. candel*	1.90	0.15	ND	ND	Chen 1982

occasions were significantly lower than this value. However, the concentrations of Zn and Mn of plant materials have been found to be within the standard range of 101.76 and 50 - 1000 g/g, respectively except Mn content of 2009 (Allen *et al*. 1974).

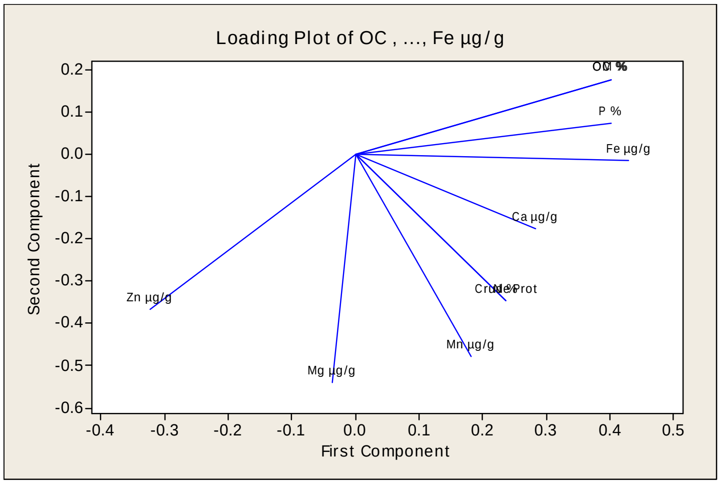
Principal component analysis (PCA) was carried out and the result is presented in Fig. 3.4.9 to 3.4.12. PC-1 of different variables of leaves of *S. apetala* during 2009 showed positive loading with P, N, Crude Protein, Ca, and Mg; and negative loading with Mn, Fe and Zn (Fig. 3.4.9). PC-2 showed positive loading of P, N and Crude Protein and negative loading of the rest variables. PC-3 showed positive loading of P, Ca, Mn and Zn with negative loading of the rest variables. Phosphorus showed positive loading with all three components whereas Fe showed negative loading with all three components. There were several clusters formation between different variables, such as P, N and hence Crude Protein formed a cluster where as Ca and Mg; and Fe and Mn formed two different clusters.

PC -1 of different variables of leaves of *S. apetala* during 2010 showed positive loading with P, N, Crude Protein, Ca, Mn and Fe; and negative loading with Mg and Zn (Fig. 3.4.10). PC-2 showed positive loading with P only and negative loading with all the rest variables. PC-3 showed positive loading with N and hence



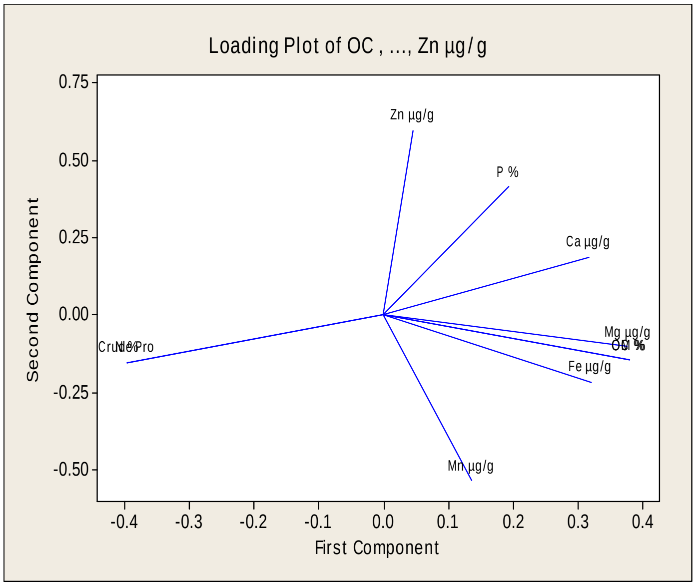
Variables	PC1	PC2	PC3
P %	0.349	0.079	0.100
N %	0.398	0.067	-0.218
Crude Pro%	0.398	0.067	-0.218
Ca µg/g	0.246	-0.442	0.333
Mg µg/g	0.239	-0.346	-0.490
Fe µg/g	-0.008	-0.514	-0.494
Mn µg/g	-0.000	-0.549	0.459
Zn µg/g	-0.339	-0.323	0.004

Fig 3.4.9: Principal component analysis of different nutrients of *S. apetala* growing in three chars (May 2009)



Variables	PC1	PC2	PC3
P %	0.403	0.072	-0.277
N %	0.237	-0.347	0.487
Crude Prot%	0.237	-0.347	0.487
Ca µg/g	0.283	-0.177	-0.567
Mg µg/g	-0.036	-0.541	-0.151
Mn µg/g	0.182	-0.480	-0.221
Zn µg/g	-0.323	-0.369	-0.052
Fe µg/g	0.430	-0.017	-0.121

Fig 3.4.10: Principal component analysis of different nutrients of *S. apetala* growing in three chars (December 2010)



Variables	PC1	PC2	PC3
P %	0.193	0.415	0.705
N %	-0.395	-0.154	-0.044
Crude Pro%	-0.395	-0.154	-0.044
Ca µg/g	0.316	0.189	-0.417
Mg µg/g	0.376	-0.101	-0.293
Mn µg/g	0.135	-0.536	0.452
Fe µg/g	0.319	-0.216	0.171
Zn µg/g	0.046	0.599	0.008

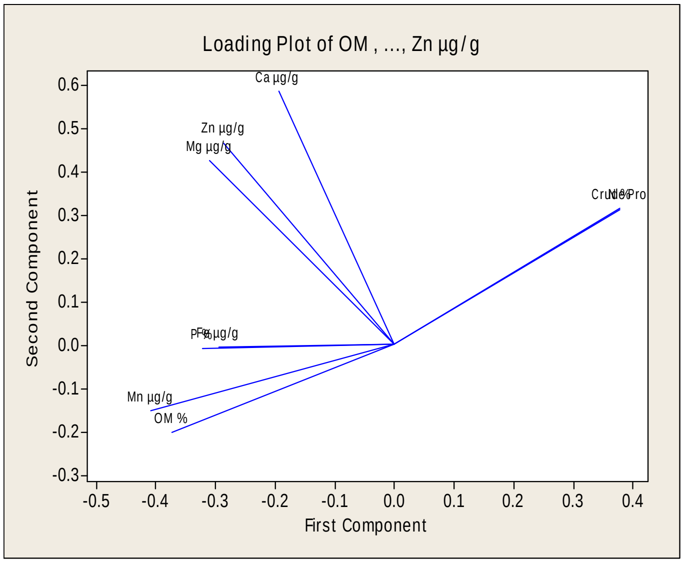
Fig 3.4.11: Principal component analysis of different nutrients of *S. apetala* growing in three chars (May 2016)

Crude Protein only and negative loading with all the rest variables. No cluster formation was found among the variables.

PC-1 of different variables of leaves of *S. apetala* during 2016 showed negative loading with N and Crude Protein, and positive loading with the rest variables (Fig. 3.4.11). PC-2 showed positive loading with P, Ca and Zn and negative loading with the rest variables. PC-3 showed positive loading with P, Mn, Fe and Zn and negative loading with the rest variables. Here P and Zn showed positive loading whereas N and Crude Protein showed negative loading with all the three components. No cluster formation among the variables was found.

PC-1 of different variables of leaves of *S. apetala* during 2017 showed positive loading with N and Crude Protein, and negative loading with the rest variables (Fig. 3.4.12). PC-2 showed negative loading with P, Mn and Fe and positive loading with the rest variables. PC-3 showed positive loading with P, Mg and Zn and negative loading with the rest variables. Here Mn showed negative loading with all the three components. P and Fe showed cluster formation. In the studied areas, the differences in different element concentrations in the soils, both between the plants and chars could be related to temporal (Cuzzuol and Tocha 2012) and spatial variations, which might be linked to the chemical and physical characteristics of the soil (Bernini *et al*. 2006, Bernini and Rezende 2010). Tides variation have also found to interfere on the availability of chemical elements

(Lacerda *et al*. 1986), resulting in a concentration/dilution effect on the nutrients of mangrove ecosystems (Ong Che 1999).



Variables	PC1	PC2	PC3
P %	-0.322	-0.009	0.620
N %	0.378	0.313	-0.080
Crude Pro%	0.378	0.314	-0.080
Ca µg/g	-0.195	0.585	-0.075
Mg µg/g	-0.310	0.424	0.033
Mn µg/g	-0.409	-0.153	-0.225
Fe µg/g	-0.296	-0.005	-0.727
Zn µg/g	-0.286	0.467	0.121

Fig 3.4.12: Principal component analysis of different nutrients of *S. apetala* growing in three chars (May 2017)

3.5. Biochemical and anatomical adaptation to stress and relative growth rate of *S. apetala*

Different natural stresses such as salinity, drought affect the plants growth and development (Uddin *et al*. 2017). The plant showed some adaptation in terms of both anatomical and biochemical properties.

3.5.1. Crude protein content of leaves of *S. apetala*

The amount of Crude Protein content gradually increased in the leaves of *S. apetala* in Char Motherbunia and Char Taposhi whereas it showed fluctuation in Char Kashem (Table 3.4.1 – 3.4.4, previous chapter). The minimum amount of crude protein in the leaves of *S. apetala* during May 2009 was 2.63 % and maximum was 14.88 % with a mean value of 6.93 ± 4.08 %. The coefficient of variation was 58.95 indicating that there were large amount variations during this period in crude protein content of leaves. It has been found that crude protein content in the leaves of *S. apetala* were highest in the Char Kashem which was significantly higher than those of the other two Chars. On the other hand, these two Chars did not vary significantly (Fig 5.1). During December 2010 the crude protein content in the leaves of *S. apetala* ranged from 5.69 % to 7.44 % with the mean value of 6.45 ± 0.48 %. The coefficient of variation was 7.46 indicating that there were very small variations during this period in crude protein content of leaves. The three chars did not vary significantly among themselves in the terms of leaf crude protein contents during this sampling occasion.

Fig 5.1. Spatio-temporal variation of foliar crude protein content (%) of *S. apetala* growing in different Chars (1 = Char Motherbunia, 2 = Char Taposhi, 3 = Char Kashem)

During December 2016 the values of crude protein in the leaves of *S. apetala* ranged from 7.23 to 15.08 % with the mean value 10.36 ± 2.64 % and coefficient of variation was 25.45. Comparatively higher amount of crude protein content was found in the leaves of Char Motherbunia which was significantly higher than the other two chars where the values of these two chars did not vary significantly. An opposite trends was found in May 2017 in comparison to May 2009 sampling occasion where the highest value was found in Char Motherbunia followed by Char Taposhi and Char Kashem. The crude protein content of leaves of these three chars varied significantly among themselves. The values of crude protein in the leaves of *S. apetala* ranged from 7.24 to 15.69 % with a mean value 11.19 ± 3.37 % and coefficient of variation was 30.13 indicating that there were some variations. Highest value (15.69 % in 2017) was found in Char Motherbunia which indicated that stress condition due to flooding caused higher crude protein content. Uddin *et al*. (2017) in an experiment observed the effect of water regimes on the growth of *Portulaca oleracea* L. and found that crude protein content in this plant increased with continuous flooded treatment condition. Crude protein in *Xylocarpus granatum* was 3 to 6 times higher in leaves than those of septum, seed, fruit wall and stem and ranged from 26.41 - 37.45% (Web 1).

3.5.2. Proline content of leaves of *S. apetala*

Proline is a secondary amino acid which, under environmental stress condition such as water and saline stress is accumulated in plant parts especially in leaves than other parts (Web 1, Ozturk and Demir 2002). Proline content in the leaves of *S. apetala* increased to withstand salinity stresses. It was highest (7112 ± 1221 µmol/g) during 2017 in the plants growing in Char Kashem where soil salinity was also higher (3.9 ± 0.94 ‰) than the other two chars. The mean values of proline content in the leaves of *S. apetala* in Char Motherbunia and Char Taposhi were 1385 ± 356 and 5321 ± 4662 µmol/g respectively. Parida *et al*. (2004) has shown that *Aegiceras corniculatum* growing hydroponically treated with NaCl has reduced proline content in the leaves of the plants by 75% at 250 mM concentration of NaCl. Proline was found to accumulate more in leaves than those of other parts of plant body of *X. granatum* (Web 1). Very high level of increase in the proline content, 147.52 % higher when compared to control, was found in *Excoecaria agallocha* L. leaves with increasing concentration up to extreme level of 300 mM NaCl (Sivasankaramoorthy *et al*. 2010). Kamalraj *et al*. (2008) have found that the proline content have increased only marginally, but increased significantly at 120 th day in *Ceriops roxburghiana* Arn. due to salinity. Popp *et al*. (1984) in a study of young and old leaves collected from twenty-three different mangrove species from northern Queensland (Australia) investigated mineral ion and organic solute content. Proline, compatible organic solutes known for halophytes, occurred only in two *Xylocarpus* species. Stewart and Popp (1987) reported proline content of 57 mol m^{-3} tissue water in *X. mekongenesi*. Kathiresan and Visveswaran (1990) have found 0.058 - 0.271g/100g dwt proline in *Acanthus illicifolius* whereas Kotmire and Bhosale (1986) have reported 16-18 mg/100 g dwt in *Thespesia populnea.* Popp *et al.* (1984) concluded low molecular weight carbohydrates storage as organic solutes in mangrove species rather than compounds containing nitrogen which might be attributed due to the relatively low nitrogen content of mangrove habitats (Boto 1982).

3.5.3. Anatomical adaptation of *S. apetala*

The leaves of mangroves are usually uniform in shape and texture with the nature of evergreen that Tomlison (1986) had described as the main responsible factors of dull, uninspiring and unchanging aspects of mangal. The leaves of the mangroves is leathery in nature with the veins are obscure and cuticles are thick and smooth resulted in glossy appearance of the plant (Nascar and Palit 2015). In the present study, the leaves of *S. apetala* have been found to be isobilateral with single layer epidermis (Plate 1 to 5). Cuticular surface is uneven. It is interesting to note that hypodermis was totally absent in *S. apetala* which is a characteristic of mangroves.

In *S. apetala* stomata are found sunken in nature with sub-stomatal chamber. Guard cells have cuticular beak-like outgrowth on either the outer or both outer and inner sides of the stomatal aperture. Messophyll are composed of thin walled chlorenchymatous cells. One, 2 or 4 layers of palisade cells occurred beneath each epidermal layer (Plate 2) and the middle cells are polygonal and colourless that functions as water storage tissues. Mucilage cells occurred just beneath the epidermis. Collenchyma cells are found in lower midrib (Plate 3). Sclerenchyma cells are found followed by collenchymatic cell and were higher in number in Char Kashem. Higher numbers of vessels were found in the vascular bundle in the leaves of this char. Middle vein is composed of double-edged vascular bundle. Vascular bundle is surrounded by more sclerenchyma cells. Large vacuolar space for storage of salts is one of the main mechanisms in salinity tolerance (Munns and Tester 2008).

Tanniniferous cells are present (Plate 4). Tannin protects plants, resistance to hydrolysis, anti-rot and prevents animal hazards effects (Zhong *et al.* 2002). In messophyll, tannin containing cells exist which are helpful for immersion in seawater. Since leaf characteristics are generally considered as a product of environment, specific adaptations are expected to enable plants to survive in saline sediments (Nascar and Palit 2015). The results indicated that leaf structure of *S. apetala* had good drought and corrosion tolerance.

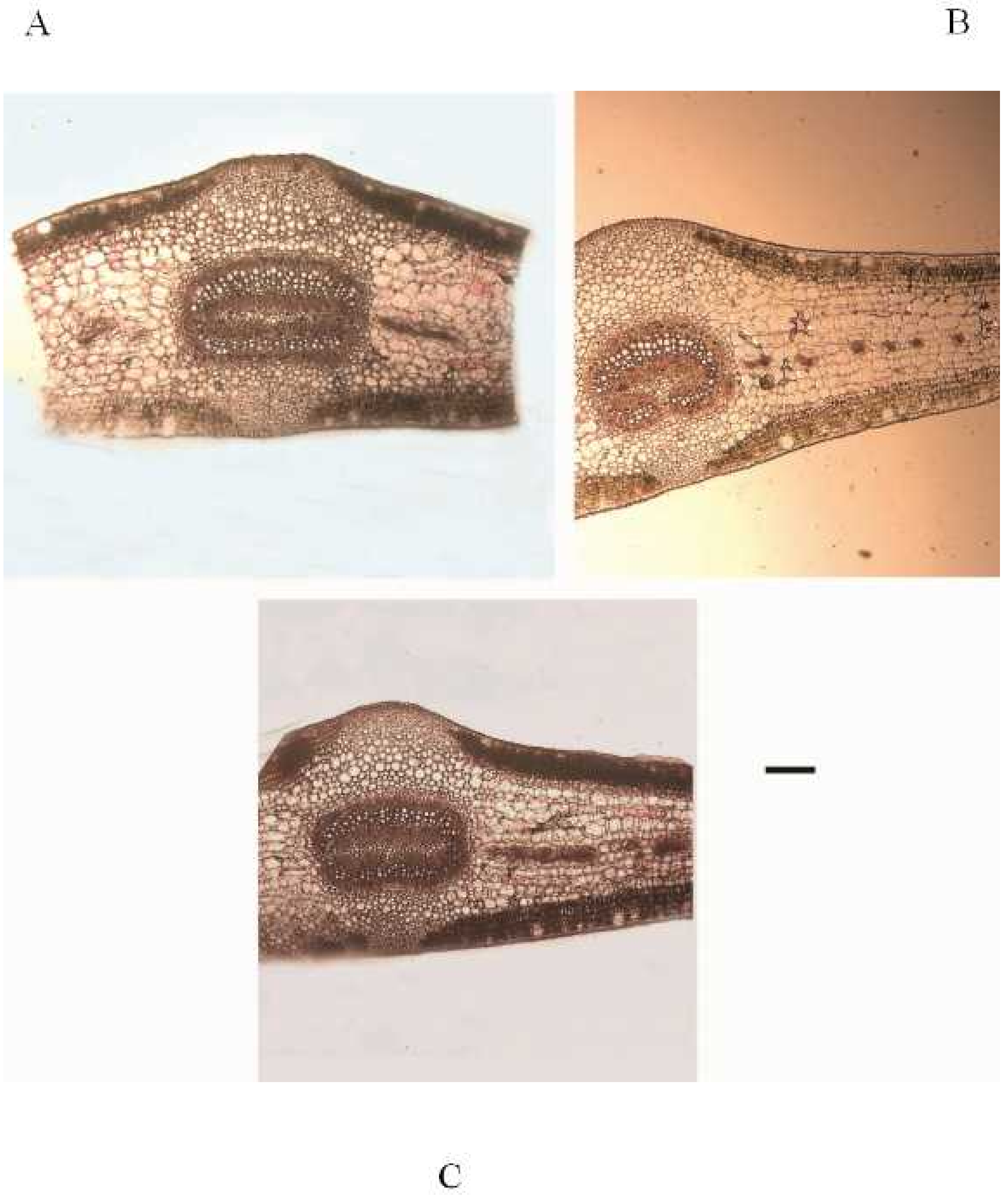


Plate 1: Transverse section of leaf of *S. apetala* showing midrib regions at 100x. A = Char Kashem, B = Char Taposhi, C = Char Motherbunia Bar = 50 µm

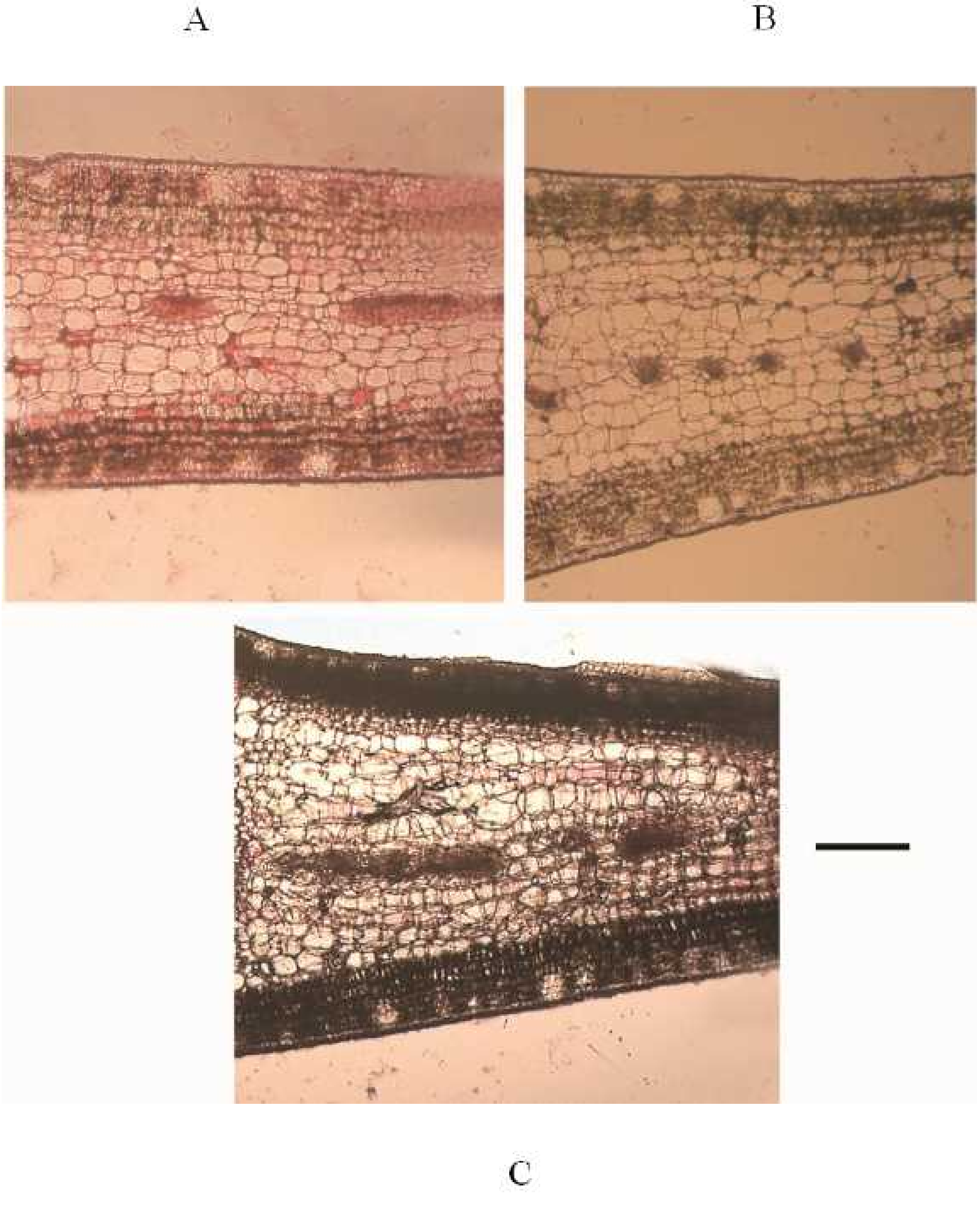


Plate 2: Transverse section of leaf of *S. apetala* showing lamina at 400x.
A = Char Kashem, B = Char Taposhi, C = Char Motherbunia.
Bar = 50 µm

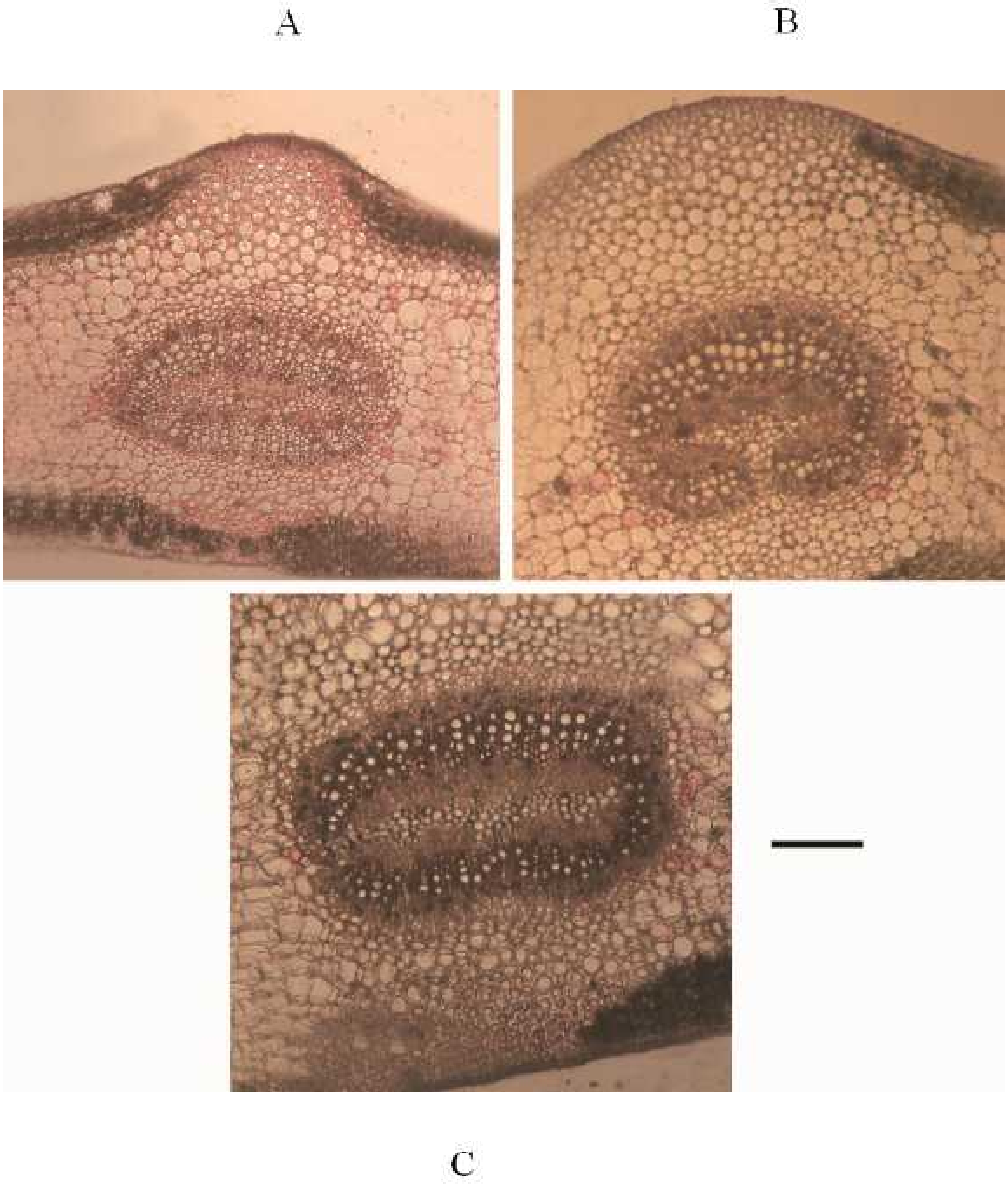


Plate 3: Transverse section of leaf of *S. apetala* showing vascular bundle at 400x. A = Char Kashem, B = Char Taposhi, C = Char Motherbunia Bar = 50 µm

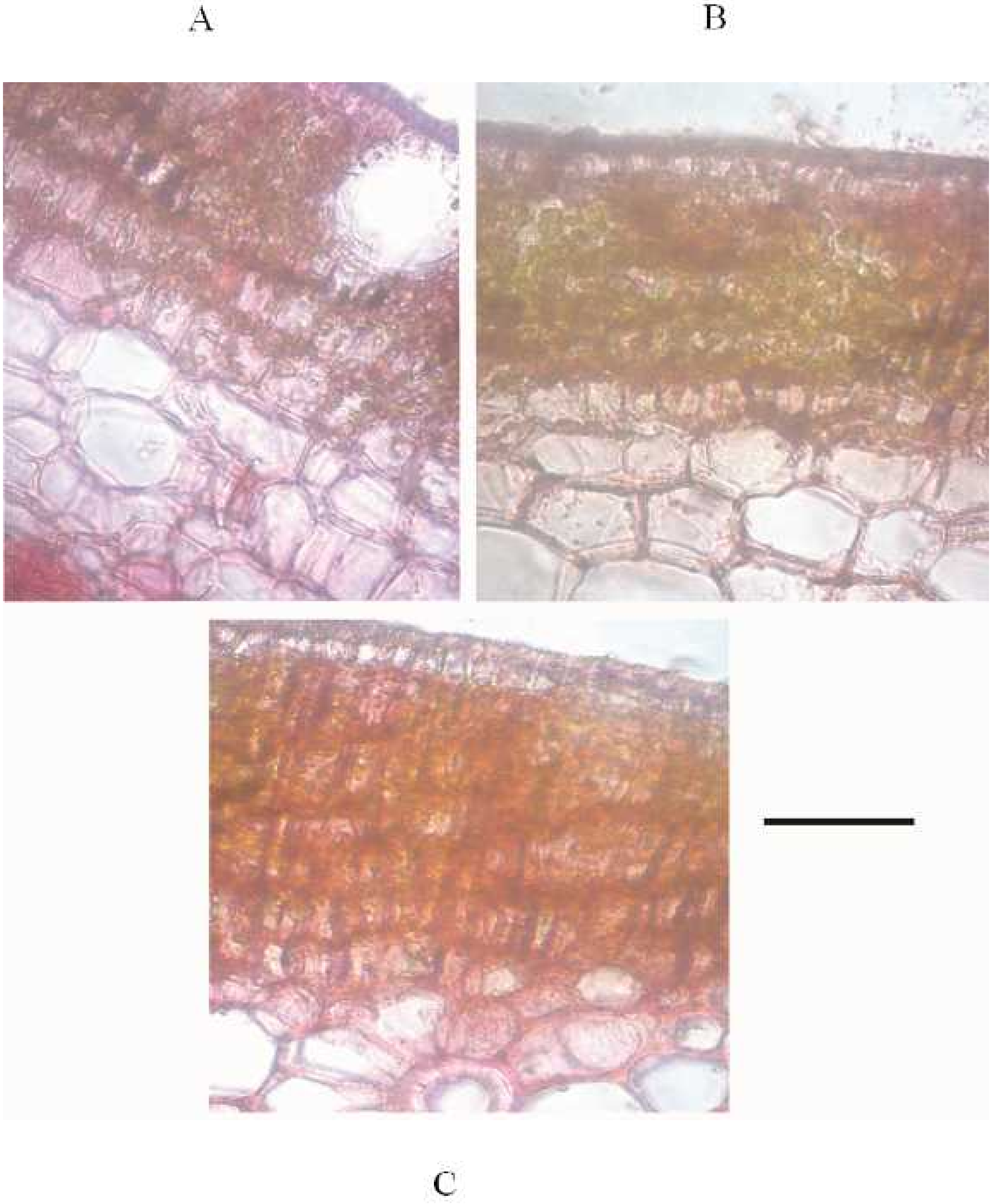


Plate 4: Transverse section of leaf of *S. apetala* showing lamina at 400x. A = Char Kashem, B = Char Taposhi, C = Char Motherbunia. Bar = 50 µm

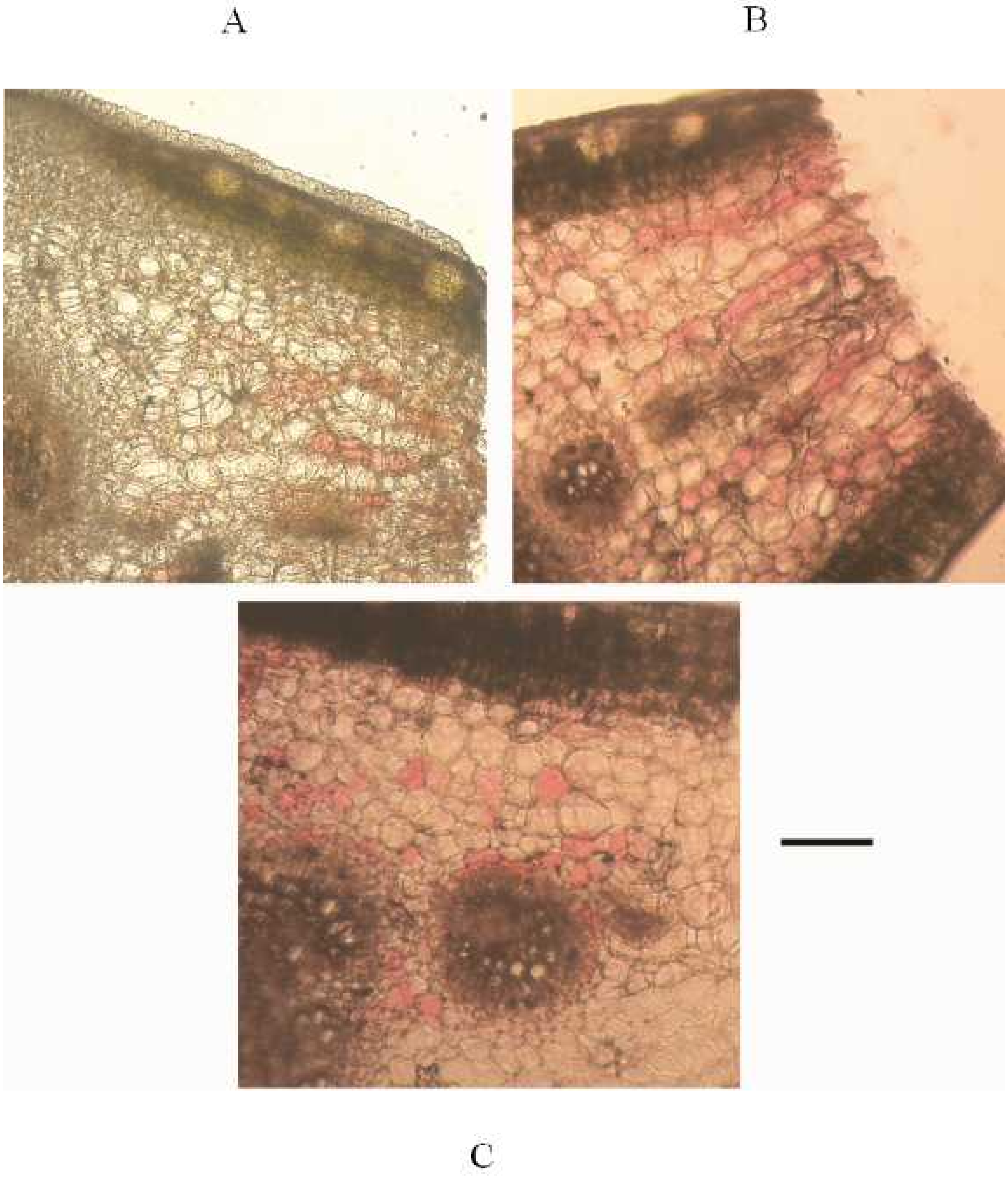


Plate 5: Transverse section of leaf of *S. apetala* showing tanniniferous tissues at 400x. A = Char Kashem, B = Char Taposhi, C = Char Motherbunia Bar = 50 µm

3.5.4. Relative growth rates (RGR) of *S. apetala*

For characterizing plant growth, growth analysis is a widely used analytical tools and relative growth rate (RGR) is the most important among the most used parameters (Hoffmann and Poorter 2002). Usually RGR deals with total dry weight, but other measures of size may be used that give more equitable comparisons than an absolute growth rate (Hunt 1990). Blackman (1919) called it an ‘efficiency index’. In the present study RGR has been estimated in terms of stem height and diameter at breast height (dbh) during a period of 15 years span but data of the years 2003, 2008, 2010 and 2017 were compared for a better understanding. The RGR in terms of height in 2008, 2010 and 2017 were 0.24±0.02, 0.23±0.04 and 0.07±0.01, respectively in comparison to previous sampling year's height of plants. The first data for plant height and dbh was collected during 2003. The relative growth rate in terms of dbh in 2008, 2010 and 2017 were 0.38±0.04, 0.11±0.03 and 0.05±0.01, respectively in comparison to previous sampling year's dbh of plants.

In comparison to 2003 the RGR of 2010 in term of height and dbh were 0.19 ± 0.01 and 0.12 ± 0.01, respectively. In comparison to 2008 the RGR of 2017 in term of height and dbh were 0.09 ± 0.01 and 0.05 ± 0.02, respectively and were 0.12 ± 0.01 and 0.14 ± 0.02 respectively in terms height and dbh in relation to 2003. Nazim *et al*. (2013) have estimated the monthly radial growth of main trunk and branches of *A. marina* and reported significant increase with the passage of time where the maximum growth rate (9.54 ± 0.95cm) was in the month of July and minimum was found (0.58 ± 0.058cm) in the month of October. They also reported the average growth rate ranged between 0.98 ± 0.04 to 1.40 ± 0.16 cm /year. Sevanto (2003) observed that cambial growth and changes in the water content and water tension resulted in the changes in tree stem diameter. Growth rate for *Rhizophora mucronata* has been estimated to be < 0.5 - 4.81 mm per year (Verheyden 2004) whereas *Avicennia* species exhibited higher growth rate of 3.8 - 5.7 mm per year than *R. mucronata* (Thampanya 2006). Verheyden (2004) have estimated the age, height and diameter of an oldest sample of *R. mucronata* in Kenyan mangrove forest at Mida which displayed an age of 89 years with a height of 12 m and a diameter of 28.6 cm. In the present study higher height and diameter were recorded in *S. apetala* and the maximum height was recorded to be 19.4 m and diameter of 41.97 cm growing in Char Taposhi with an age of about 35 years.

3.5.5 Bioaccumulation of metals in *S. apetala*

Mangroves have an important role to accumulate metal in the tropical and subtropical marine ecosystems (Alzahrani *et al*. 2018). The mean bioaccumulation or bioconcentration factors (BCFs) of different metals such as Ca, Mg, Mn, Fe and Zn in different years are presented in Table 3.5.1. Higher accumulations of Mn during 2009 and 2017 and of Fe during 2010 were recorded. This could be considered as a clear reflection of the bioavailability of these metals in the soils of Rangabali coastal area of Bangladesh in comparison to other metals (Alzahrani *et* *al*. 2018). Ca has also been found to accumulate in the leaves of *S. apetala*. The lower BCF values of Mg during 2010, 2016 and 2017; of Fe during 2009, 2016 and 2017, and of Zn during all sampling occasions could be attributed to the low bioavailability of these heavy metals in the soils during the sampling seasons. Several workers (Li *et al*. 2016; MacFarlane *et al*. 2003; Nath *et al*. 2014) have tried to explain this as the binding of heavy metals to form immovable compounds as a result of chelation with organic molecules. Bioconcentrations of Pb in the leaves of *A. marina* have been reported by several workers from different mangrove forests of the world and the values obtained were 1.57 in Red Sea coastal areas, Saudi Arabia (Alzahrani *et al*. 2018), 1.07 in Al-Shouiba, Saudi Arabia (Abohassan 2013), 0.06 in Shenzen, China (Peng *et al*. 1997), 0.24 in Ting Kok, Hong Kong (Chen *et al*. 2003) and 0.05 in SE, Australia (MacFarlane *et al*. 2003).

Table 3.5.1: Bioaccumulation of different metals in the overall study areas in different sampling occasions

Metals Year	Ca	Mg	Mn	Fe	Zn
2009	2.83	1.51	15.89	0.21	1.11
2010	2.69	0.52	1.80	14.55	0.23
2016	1.98	0.81	5.86	0.51	0.81
2017	1.91	0.91	10.01	0.07	0.82

It is generally accepted that the ecology of coastal area of Bangladesh is regulated by tidal impact from Bay of Bengal. But the present study revealed that fresh water supply from the Meghna River also plays a vital role on the ecology of this area. Slight acidifications of the studied estuarine waters observed in all the three locations till 2016 that might be attributed to the rise in atmospheric CO_2 content due to climate changes. The level of salinity also indicated that the fresh water supply from upstream reduced the intrusion of the sea water in the study area i.e. till now the effect of sea level rise has not been felt. Manganese, Zn and Pb showed very severe to extremely severe enrichment in Char Motherbunia. In addition, Mn showed extremely severe enrichment in Char Taposhi and Char Kashem and Zn showed extremely severe enrichment in Char Kashem. Contamination index indicated that Char Motherbunia was low contaminated in all sampling years. Char Taposhi was found to be also low contaminated during 2009 and moderately contaminated in 2010. Char Kashem has been found contamination free. Although these are some enrichment of some metals namely Mn, Fe, Zn and Pb, the three chars were found to be still at low ecological risk in all sampling occasions. Measures should be taken to protect the chars for the proper growth of the *S. apetala* plants because the chars along with the mangrove plants save the lives and resources of the coastal areas from natural calamities and are providing various ecosystem and social services. These chars will also act as barriers to safeguard from the sea level rises due to global climate change. The data provided here will also be helpful for the management of the coastal areas and fisheries sectors as these areas are considered as breeding ground of Hilsa fish.

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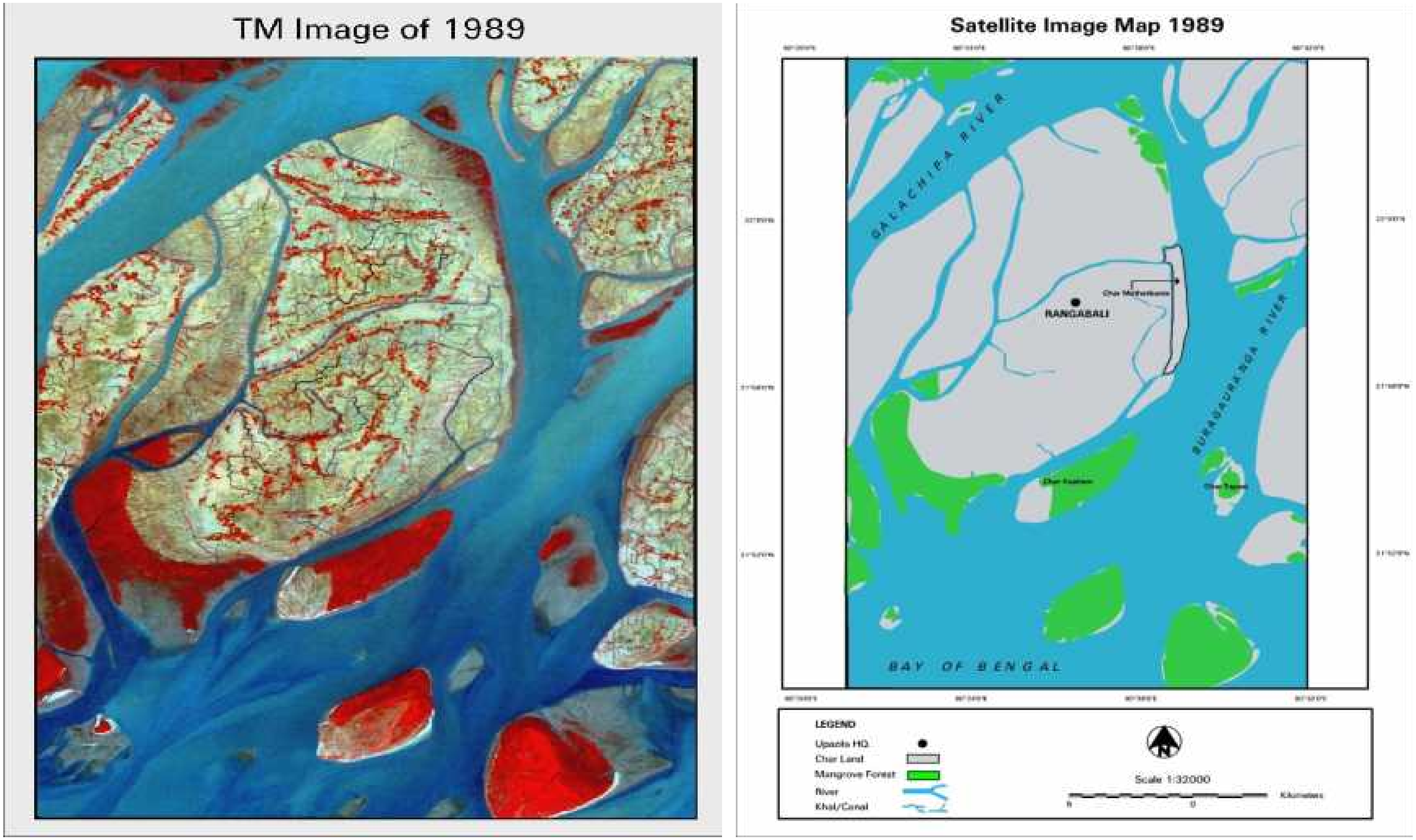


Fig. 3.1.a. Thematic mapper (TM) image and satellite image map of 1989

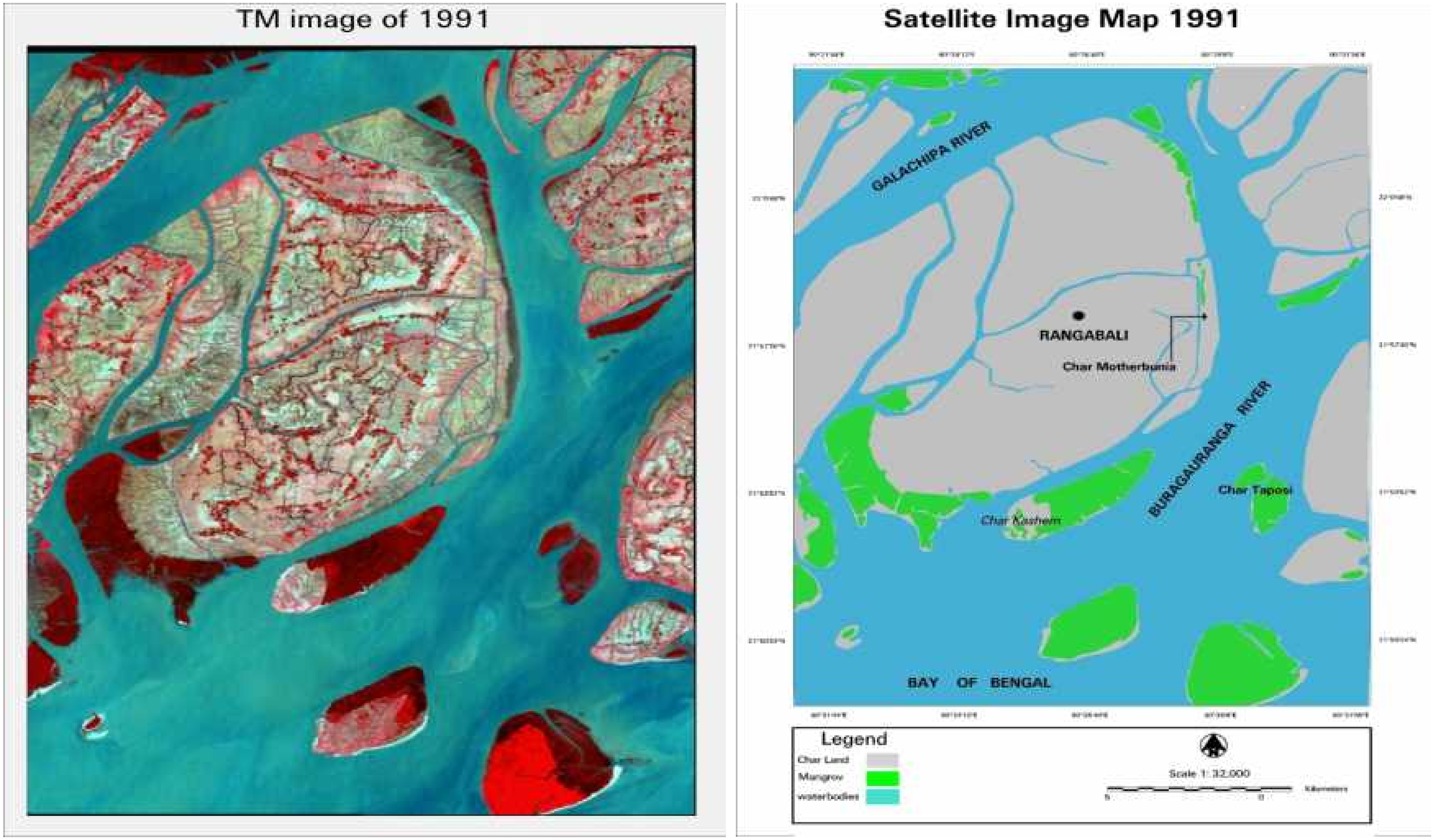


Fig.3.1.b. Thematic mapper (TM) image and satellite image map of 1991

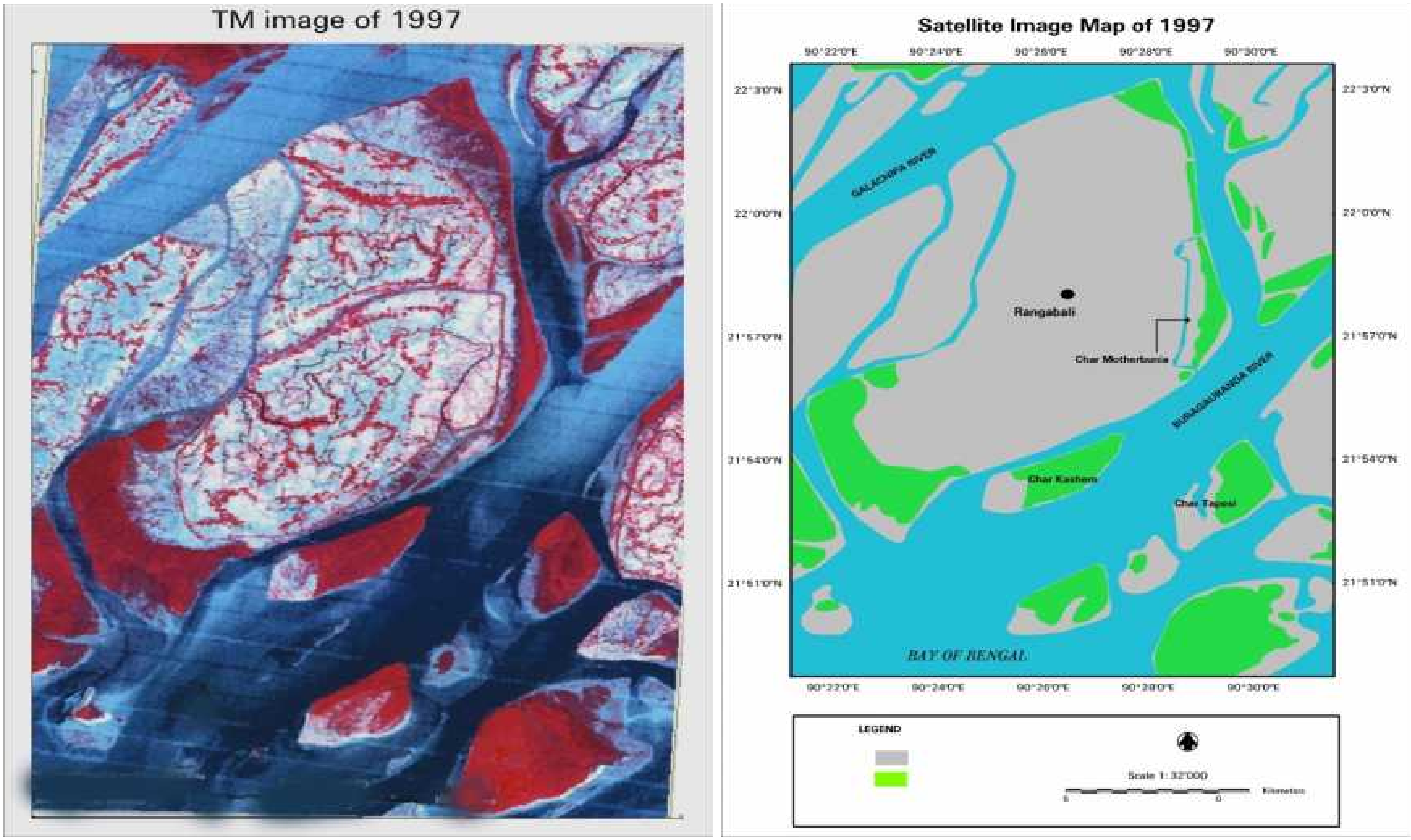
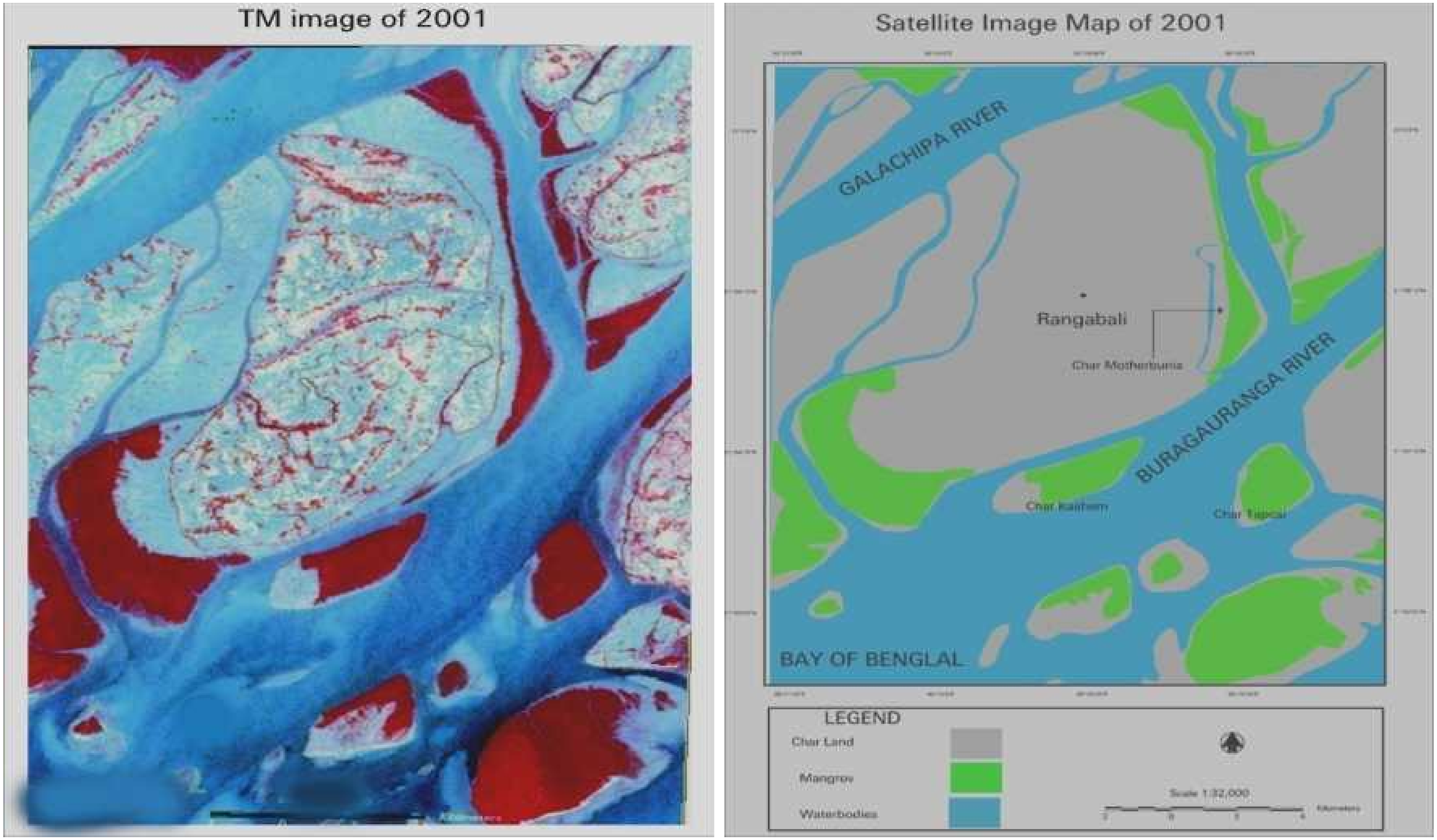


Fig. 3.1.c. Thematic mapper (TM) image and satellite image map of 1997



TM image of 2001

Satellite Image Map of 2001

Fig. 3.1.d. Thematic mapper (TM) image and satellite image map of 2001

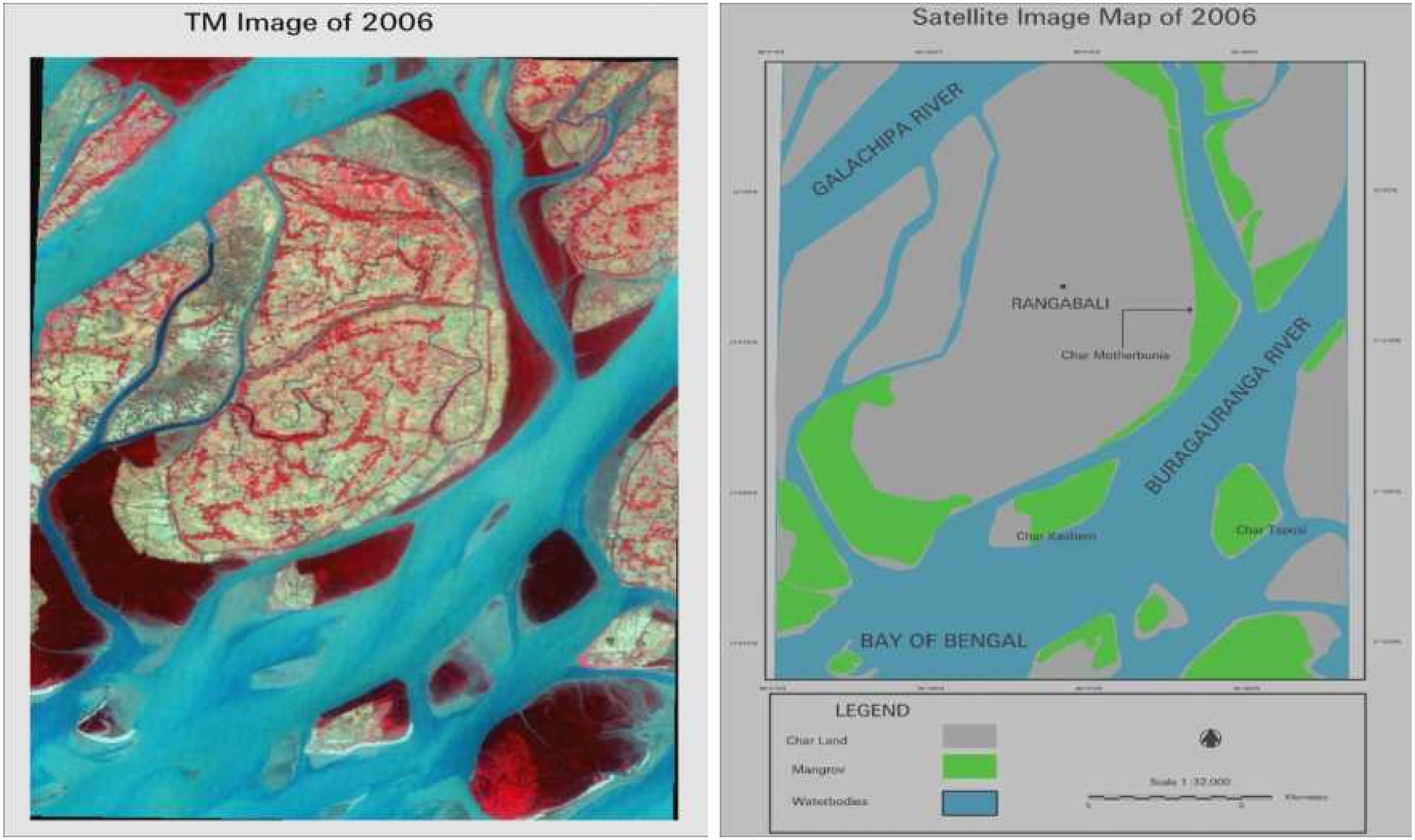


Fig.3.1.e. Thematic mapper (TM) image and satellite image map of 2006

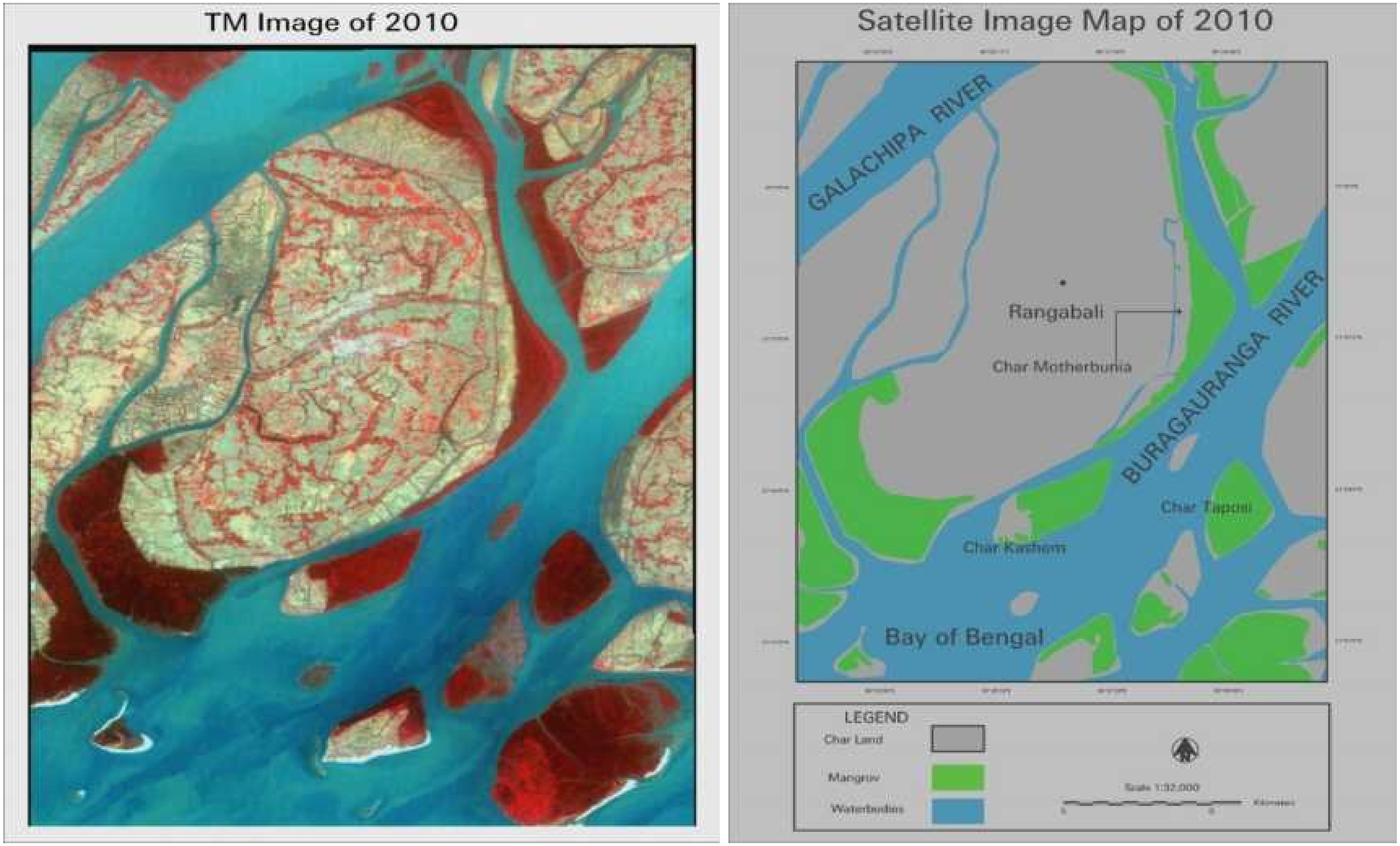


Fig. 3.1.f. Thematic mapper (TM) image and satellite image map of 2010

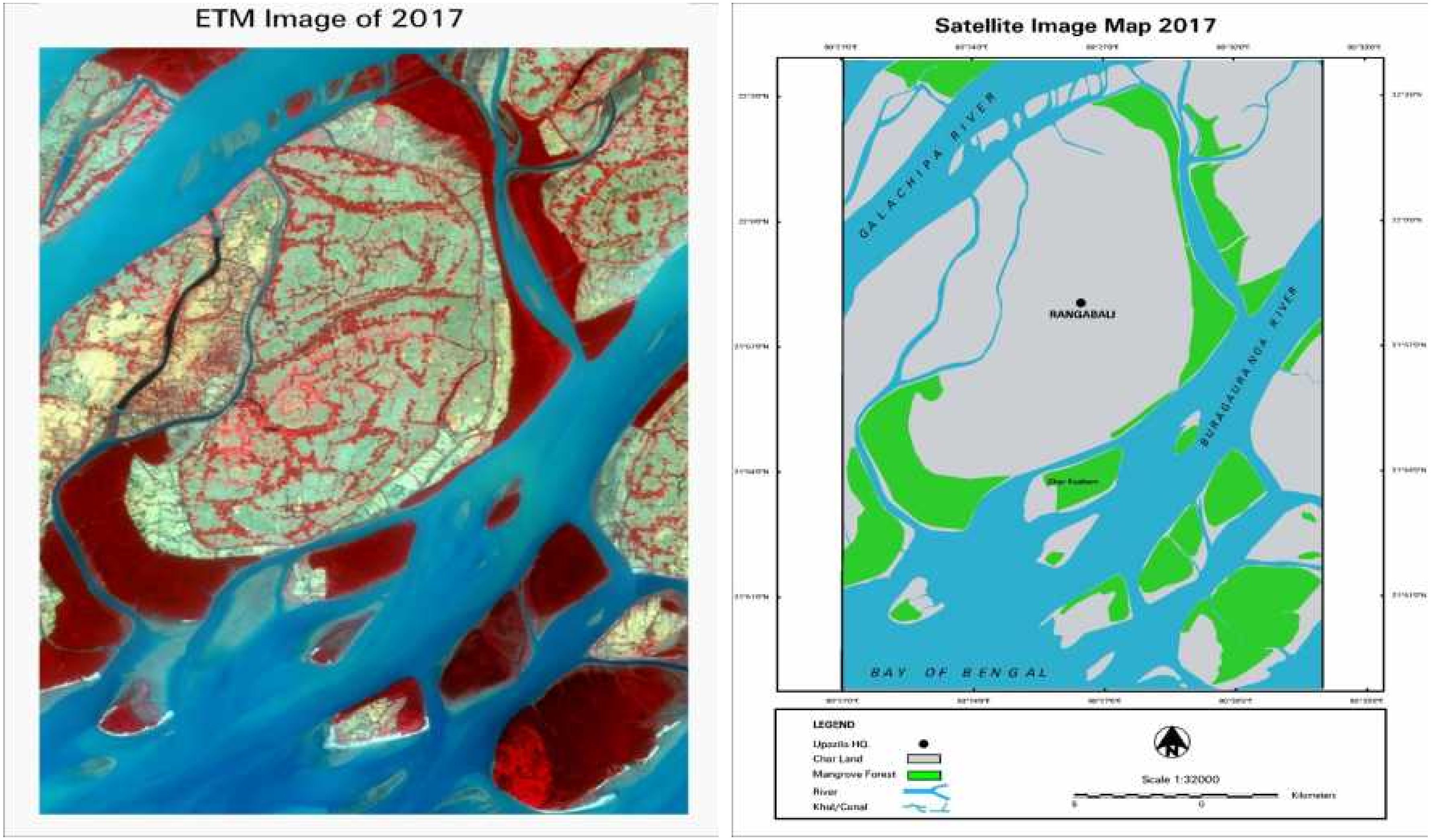


Fig. 3.1.g. Enhanced thematic mapper (ETM) image and satellite image map of 2017