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Environmental Assessment in terms of Salinity Distribution in the Tropical Mangrove forest of Sundarban, North East Coast of Bay of Bengal, India

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ABSTRACT

In estuarine areas of the mangrove forest of Sundarbans, surface water salinity variations through tides, seasons and spaces were studied in a comprehensive way for the first time along with dilution efficiencies and extent of salinity exposure. Since Sundarbans is influenced by several numbers of rivers in a criss-crossed way, the entire area has been divided as western sector (under Hooghly, Saptamukhi and Thakuran rivers respectively), the middle sector under Matla and Bidya river (MB estuary) and eastern areas influenced by Gosaba, Harinbhanga, Jilla and Raimangal rivers (GHJR estuary). Study revealed that unlike western sectors, the tidal variations of salinity in other areas were less with negligible salinity difference (1.4 to 2.0 psu) between high and low tides. In contrast, pronounced seasonal variations of salinity were encountered (9.34 to 30.83 psu) in the region. The most parts of the Sundarban attained almost equal level of salinity in monsoon (12.0 to 14.0 psu) and summer (29.0-30.0 psu) indicating less degree of spatial variations. Significant salinity differences between upstream (US) and downstream (DS) was however, recorded in winter and pre-summer relatively higher in GHJR estuary highlighting more fresh water influx in this region. Higher levels of average dilution factors (DF) were encountered in MB (6.5) compared to GHJR estuary (4.5). The seasonal variation of DF forecast that any pollutant would undergo more dilution during summer and less in monsoon season. The whole Sundarban area could be classified into four distinct zones in respect to salinity variation and its exposure period. This may be useful in finding out the presence of similar type of mangroves species diversity and richness, and may also serve as an important tool in future study to explore the factors, other than salinity responsible for mangrove species extinction from this world famous biological kingdom.

Key words: Salinity, tidal, seasonal, spatial, dilution factor, mangrove forest, Sundarbans.

INTRODUCTION

Mangrove forests are among the world's most productive ecosystem that protect coastal population and support coastal fishing and livelihood [1]. Mangroves are halophytic trees and shrubs that normally grow in saline intertidal zone of tropical and subtropical coastline. Salinity, therefore, appears to be one of the key environmental factors influencing the growth and survival of mangrove species. But the tolerance of salinity also varies among the mangroves. The seedlings of *Rhizophora mucronata* do better in salinity of 30 psu but *R. apiculata* do better at 15 psu (Kathiresan and Thangam, 1996). On the other hand, *Sonnaratia alba* grow in waters between 2 and 18 psu and *S. lanceolata* only tolerate salinity up to 2 psu [2]. Experimental evidence also indicates that at too high salinity mangroves spent more energy to maintain water balance and ion concentration rather than primary production and growth (Clough, 1984). This results in reduction in biomass [3], leaf area, increase osmotic pressure in leaf sap and decreases total nitrogen, potassium and phosphorus minerals [4]. Hence, salinity variation and duration of a particular salinity value in a year within a mangrove forest area play a vital role in the species distribution, their productivity and growth [5]. The variations in salinity are normally controlled by climate, hydrology, rainfall, topography and the tidal flooding of an area. All these characteristics are known to undergo spatial as well as temporal variations. Accordingly, the distribution, succession, population and diversity of mangrove species do also vary along with the variation of salinity.

The area of land-ocean boundary is a place where any substances carried by river discharge undergoes repeated oscillation by the influence of tides from sea water, spends considerable time in the estuarine area and consequently, is diluted significantly. Again the degree of dilution depends on large number of factors including space, intensity of tides, seasons etc. Thus, introduction of any chemical pollutants from anthropogenic sources through river discharge into mangroves forest may cause adverse effect if the seawater does not dilute these significantly. Hence the study of dilution factors in land-ocean boundary region is very essential in order to assess the fate of a pollutant.

But all these studies in the entire Sundarban mangroves areas are very rare and lacking. Some studies on aspect of metal contamination in sediments [6, 7, 8] and in biota [9, 10, 11] have been reported from the periphery areas of Sundarbans indicating evidence of entry of pollutants. As a result of intense anthropogenic stress, many species have already been disappeared and many are in the list of endangered species [12]. Most of the studies so far published from this region are solely based on the observation carried out in the accessible areas [13, 14, 15, 16]. But salinity variation can cause change in biotic composition [5] that ultimately affect the ambient chemistry of air, water and soil [17]. The scarcities of adequate scientific information from the whole part of Sundarban are mainly due to inaccessibility into the core areas where the principal inhabitants are tiger, poisonous snakes on land, crocodile in water and restriction for implementation of a number of protective measures for its conservation [12]. The present study however was conducted in collaboration with the state forest department. The primary focus of this paper is to examine and describe the nature and magnitude of tidal, spatial and seasonal variation of salinity throughout the entire area of the Indian part of Sundarban mangrove forest, ii) to explore the degree of dilution caused by seawater during introduction of any river borne pollutants in the area and finally, iii) to classify the study area on the basis of similarities on salinity variation and its duration.

MATERIALS AND METHODS

Study area

The Indian Sundarbans at the apex of Bay of Bengal (between 21^0 $32^/$ to 22^0 $40^/$ N latitude and 88^0 $05^/$ to 89^0 $00^/$ E longitude) are located on the southern fringe of the state of West Bengal, covering the major positions of the North and South 24 Parganas districts. The region is bordered by Bangladesh in the east, the Hooghly river (the Ganges) in the west, "Dampier and Hodges" Line in the north and the Bay of Bengal in the south. Sundarbans being a natural mangrove forest which is a part of estuary with the river Ganges covering a tidal area of 9063 km^2 of which 4264 km^2 comprising of inter-tidal habitat. It is the largest delta in the world and is a unique bio-climatic zone for its diversity of mangrove flora and fauna, both on lands and in water. The area is covered with thick mangroves, which are subdivided into forest and aquatic sub-ecosystem (1781 km^2). This deltaic complex sustains 102 islands, only 48 of which are inhabitant. In 1985, these are included in UNESCO's list of world heritage sites, and in 1989, India designated 9360 km^2 of Sundarban as Biosphere Reserve. In 1985, the area of Sundarban forest was about 20000 km^2. But now it is reduced significantly to the present value.

The land ocean boundary is highly irregular criss-crossed by numerous rivers and waterways with Hooghly River (Ganges) as the main artery in the west and the Raimongal a tributary of Padma in Bangladesh in the east. This forest along the sea-face extends from west to east over 100 km. The depth of this forest varies from almost zero in the west increasing eastward to about 70 Km along the Bangladesh border. The origin and the history of other five rivers in between these two rivers have been highlighted [16] and the upstream connections of these rivers with the Ganges have presently lost due to heavy siltation and solid waste disposal from the adjacent cities and towns [18]. The rapid human settlements, intensive boating and tourist activities, deforestation and ongoing agricultural and aqua cultural practices surrounding the Bay of Bengal make the coastal environment vulnerable to a range of anthropogenic stress factors [19]. There are large numbers of shrimp culture units, industries and hotels located in the upstream areas which in most cases release their wastes without any treatment [20].

Sampling and analytical procedure

In order to assess the pattern of salinity distribution of surface water, the sampling locations have been formulated on the basis of the distribution of forest islands along the important rivers in the entire mangrove area. In the western part of the forest, a single location at each of Namkhana, Lothian and Dhanchi Island has been selected to have an idea about the effect of the river Hooghly, Saptamukhi and Thakuran respectively. Both the river of Matla and Bidya are confluenced at the downstream areas where large number of mangrove iaslands exists along the stretch; more sampling sites are arranged the rivers atre represented as Matla-Bidya (MB) estuary jointly. Similarly, the rivers like Gosaba, Harinbhanga and Jhila are known to fed by the mighty river the Raimangal and also caters significant number of forest islands in the eastern side of the mangrove forest, these together are designated as GHJR estuary [Table 1].

Table 1. Location of sampling sites in the Sundarban mangrove forest (The designation of up, mid and downstream are on the basis of location in the estuarine area)

Serial No.	Sampling Sites	Longitude	Latitude	Influencing Rivers
1.	Namkhana (DS)	88° 15' 24" E	21 ° 45' 24" N	Hooghly
2.	Lothian (DS)	88 ° 18' 41" E	21 ° 42' 22" N	Saptamukhi
3.	Dhanchi (DS)	88 ° 25 '55" E	21 ° 42' 07" N	Thakuran
4.	Chulkati (Extreme DS)	88 ° 31' 42" E	21 ° 42' 52" N	Matla and Bidya (MB estuary)
5.	Dulibasani (DS)	88 ° 34' 17" E	21 ° 43' 55" N	
6.	Kamli (DS)	88° 34' 09" E	21 ° 46' 11" N	
7.	Sundarkati (MS)	88 ° 37' 23" E	21 ° 49' 48" N	
8.	Benephuli (MS)	88 ° 35' 46" E	21 ° 51' 06" N	
9.	Herobhanga (MS)	88 ° 41' 10" E	21 ° 57' 05" N	
10.	Jharkhali (MS)	88 ° 42' 39" E	22 ° 00' 33 "N	
11.	Dobanki (MS)	88 ° 45' 15" E	22 ° 59' 22" N	
12.	Sudhnyakhali (US)	88 ° 48' 04" E	22 ° 06' 09" N	
13.	Sajnekhali (Extreme US)	88 ° 49' 52" E	22 ° 07' 29 "N	
14.	Haldibari (Extreme DS)	88 ° 46' 57" E	21 ° 43' 33 "N	Gosaba, Harinbhanga, Jhila, Raimangal (GHJR estuary) All are dominated by Raimangal River
15.	Choramayadwip (DS)	88 ° 47' 20" E	21 ° 45' 12" N	
16.	Keorasuti (DS)	88 ° 47' 55" E	21 ° 47' 34" N	
17.	Netidhopani (MD)	88 ° 44 '46" E	21 ° 55' 13" N	
18.	Chandraduanibharani (Mid Stream)	88 ° 51' 55" E	21 ° 51' 48" N	
19.	Champta (MS)	88 ° 54'50" E	21 ° 51' 40 "N	
20.	Harinbhangajilla (MS)	88 ° 55' 28" E	21 ° 57' 40" N	
21.	Katwajuri (US)	88 ° 59' 22" E	22 ° 03' 19" N	
22.	Burirdabri (Extreme US)	89 ° 01' 43" E	22 ° 04' 39" N	
23.	Kalukhali (US)	88 ° 59' 12" E	22 ° 03' 45" N	
24.	Sunderkhali (US)	88 ° 49' 55" E	22 ° 02' 25" N	

****MD indicates midstream; *DS indicates downstream; *UP indicates upstream***

Surface water samples were taken by water samplers operated from the deck of research vessel in each location within the mangrove forest area. For diurnal salinity variation study, water samples were collected every two hours throughout one complete tidal cycle in upstream and downstream locations. The study was continued for two years from September 2004 to May 2006. The four observations in a year were conventionally categorized as the monsoon (for the observation at August-September); winter (in December); pre-summer (March) and summer (May- June). The surface salinity value was recorded by means of automatic water analyzer kit (WTW, multi 340 i) in the field after its standardization in a proper way and was cross- checked in the laboratory by using Mohr-Knudsen titration method for chlorinity estimation. Standard seawater of known chlorinity of 19.374 was procured from the National Institute of Oceanography, Goa for standardization. The estimated chlorinity value was then converted to salinity following the relationship of $S = 1.80655 \times Cl$ where S is the salinity and Cl is the chlorinity according to the methods as out lined in the standard literature [22, 23]. A relative error of accuracy of salinity estimation was ± 2.0 % in every case. Salinity values were represented as practical salinity units (psu).

The amount of freshwater contained in any brackish water samples can be calculated from the analysis of salinity levels by using a simple formula as $F = (1 – S_1/S_2)$, where F is the fraction of freshwater, S_1 and S_2 are the salinity of the samples and the source water [24]. In this calculation for the salinity of the source water, surface water samples collected once in every three months from offshore areas about 20 km away from the mouth of the river, was used. The percentage of seawater (PSW) was then deduced as $\{(1 - F) \times 100\}$ and the dilution factor (DF) was calculated as $DF = (1 / F)$.

Statistical analysis

The normality of the salinity distribution levels was tested by employing Kolmogonor-Simirnov test [25]. Along with this, the homogeneity of the variables was verified by Leven's test [26] and where necessary, transformation of the data was done to get homogenous as well as normal distribution. Pearson correlation coefficient was used to compare the means and samples were considered significantly different at $P < 0.05$. All these statistical analysis were carried out by SPSS-11 statistical package for windows.

RESULTS AND DISCUSSION

Salinity could be recognized as the most important parameters in the mangrove system that arises due to introduction of seawater into the river where mixing of water masses takes place. During the study period, salinity ranged from minimum of 9.4 to maximum of 30.8 psu in the whole study region. Minimum values were generally encountered in the period of monsoon due to influx of river borne freshwater and maximum values were during summer for less degree of freshwater contribution from the upstream areas. Salinity distribution in the estuary depends on the strength and amplitude of tide, influx of fresh water runoff throughout the seasons and location of sites. Thus there are spatial variation, tidal or diurnal variation and seasonal variation of the salinity in the estuarine environments.

Spatial variation

As the source of salinity is the seawater, its values in the river areas normally decreased along the distance from the source. In the present study, spatial salinity variations in MB and GHJR estuarine areas were only considered, as there was single location in each of Hooghly, Saptamukhi and Thakuran river complex. As usual, salinity showed decrease in value gradually along the distance from down stream (DS) towards upstream (US) areas (Table 2). But the rate of decrease was found season specific, with lower in monsoon and summer and comparatively higher in winter and pre-summer in both these estuaries. Salinity differences between DS and US areas (Table 3) in MB estuary varied between 0.6 and 4.9 psu and higher differences with statistically significant at $p \leq 0.05$ were recorded in winter and pre summer (4.9 psu and 4.0 psu respectively).

Table 2. Spatial and seasonal variation of Salinity (psu) during the study period

Name of Stations	Monsoon	Winter	Pre-summer	Summer	Monsoon	Winter	Pre-summer	Summer
Namkhana	10.41	12.01	17.10	23.62	13.1	14.1	20.0	25.6
Lothian	13.30	16.90	21.80	28.60	15.75	16.39	22.62	26.03
Dhanchi	15.50	18.90	26.21	29.68	16.62	18.26	24..60	30.12
Chulkati (DS)	14.30	18.20	26.62	29.53	15.80	18.37	26.90	30.83
Dulibasani	14.70	17.60	26.43	29.43	14.91	17.22	26.23	30.49
Kalmi	13.50	17.30	26.20	29.17	14.62	16.46	25.84	30.28
Sundarkati	13.50	16.40	26.03	29.13	14.26	16.44	25.48	30.53
	12.40	16.0	25.90	28.71	13.45	16.04	25.39	30.12
Benefuli	12.20	15.60	25.72	28.80	12.62	15.71	24.77	29.95
Herobhanga	12.80	15.30	25.41	29.11	13.41	18.24	24.93	29.50
Jharkhali	12.80	14.90	25.10	28.03	13.31	15.45	23.90	29.60
Dobanki	13.20	15.10	25.50	29.40	14.63	16.83	25.51	30.03
Sudhanyakhali	12.70	14.0	4.64	29.11	13.22	14.71	24.44	29.45
Sajnekhali(US)	12.40	13.70	24.41	28.90	13.10	15.02	24.43	29.53
Haldibari (DS)	13.03	16.60	26.30	30.13	14.84	17.30	26.92	30.09
Choramayadwip	12.04	17.20	26.23	30.02	13.30	16.63	26.30	30.98
Keorasuti	12.30	15.60	25.84	30.10	12.50	16.40	25.60	29.73
Netidhopani	12.43	14.0	25.22	29.63	13.72	15.70	26.18	29.41
Chandraduanibharani	11.40	15.10	25.11	29.85	12.87	15.71	25.63	29.60
Champta	11.05	13.40	23.62	29.34	12.06	14.71	24.12	28.71
Harinbhangajilla	11.30	12.30	22.03	28.04	12.07	12.84	21.95	28.52
Katwajuri	11.40	9.80	20.95	27.39	13.04	10.63	20.93	27.53
BurirdabrI(US)	10.21	8.52	19.41	26.33	11.01	9.44	19.92	26.68
Kalukhali	9.34	9.83	20.33	26.94	10.83	10.62	20.90	27.25
Sudhnyakhali	12.41	13.31	24.25	28.92	12.80	13.81	23.87	29.20

DS-Downstream, US- Upstream.

Table 3. Salinity (in psu) variations of the estuarine system

Area	Locations	Monsoon	Winter	Pre-summer	Summer	Monsoon	Winter	Pre-summer	Summer
MB	**DS (Chulkati)**	**14.3**	**18.2**	**26.0**	**29.5**	**15.8**	**18.3**	**26.9**	**30.8**
	US (Sajnekhali)	**12.4**	**13.3**	**24.4**	**28.9**	**13.1**	**14.3**	**24.4**	**29.5**
	Difference (DS-US)	**1.9**	**4.9**	**1.6**	**0.6**	**2.7**	**4.0**	**2.5**	**1.3**
GHJR	**DS (Haldibari)**	**13.0**	**16.6**	**26.3**	**30.1**	**14.8**	**17.3**	**26.9**	**30.0**
	US (Burirdabri)	**10.4**	**9.8**	**19.4**	**26.3**	**11.4**	**9.4**	**19.9**	**26.6**
	Difference (DS-US)	**2.6**	**6.8**	**6.9**	**3.8**	**3.4**	**7.9**	**7.0**	**3.4**
Hooghly	**Namkhana**	**10.4**	**12.0**	**17.1**	**23.6**	**13.1**	**14.1**	**20.0**	**25.6**
Saptomukhi	**Lothian**	**13.3**	**16.9**	**21.8**	**28.6**	**15.7**	**16.3**	**22.6**	**26.0**
Thakuran	**Dhanchi**	**15.5**	**18.9**	**26.2**	**30.2**	**18.6**	**18.2**	**27.0**	**30.0**

In other seasons the average difference was within 2 psu and was insignificant ($p \geq 0.05$), while in GHJR estuary salinity differences were significant and always higher than the MB estuary with minimum value 2.6 psu in summer and maximum value 7.9 psu in winter. This signified that GHJR estuary is more influenced by fresh water influx than MB estuary. In monsoon, pre-summer and summer, the MB estuary experienced minimum salinity differences (< 2 psu) between US and DS areas and the whole estuarine area could be considered as homo-haline condition during most part of the year. This type of characteristics was not observed in case of GHJR estuarine system where only DS locations showed similar to that of entire MB estuarine system in these seasons but the US areas always registered lower degree of salinity with significant differences ($p \leq 0.05$) between upstream and downstream. The descriptive statistics of box plot (Fig. 1) also revealed that in an average, the salinity value at DS of MB and DS of GHJR estuary were similar whereas the same was true in cases of US areas of GHJR and Namkhana.

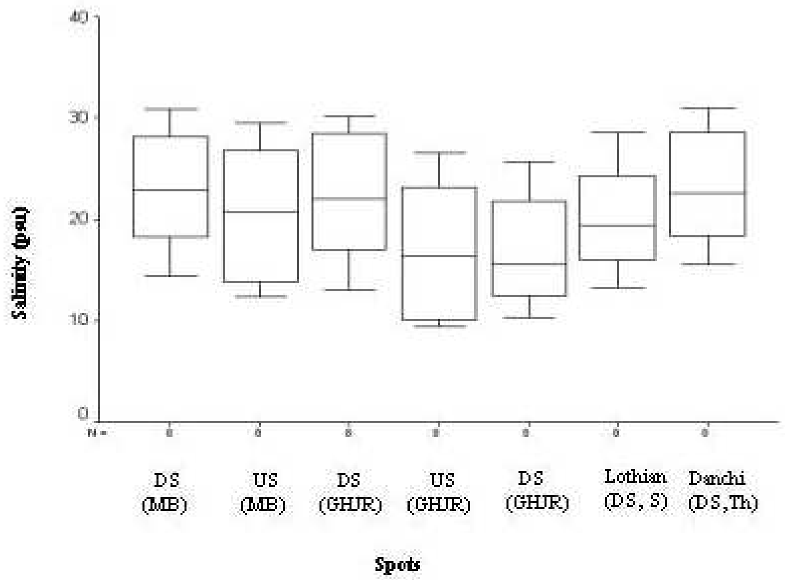

Figure 1 Descriptive statistics (Box plot) of salinity in various estuarine areas.
DS= Downstream, UP= Upstream, MB Matla-bidya estuary, H=Hoogly estuary, Th= Thakuran and Ds= Saptamukhi estuary.

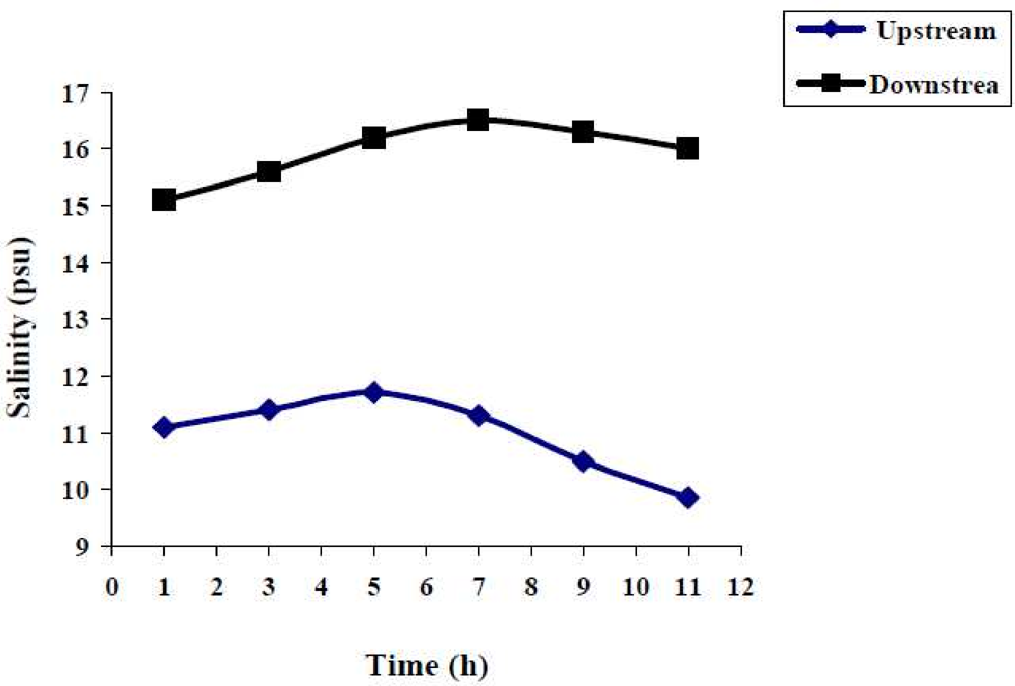

Figure 1 Tidal variations of salinity in GHJR estuary. The figure shows a continuous monitoring for 12 hrs in both the stretches of upstream and downstream area as described in material and methods

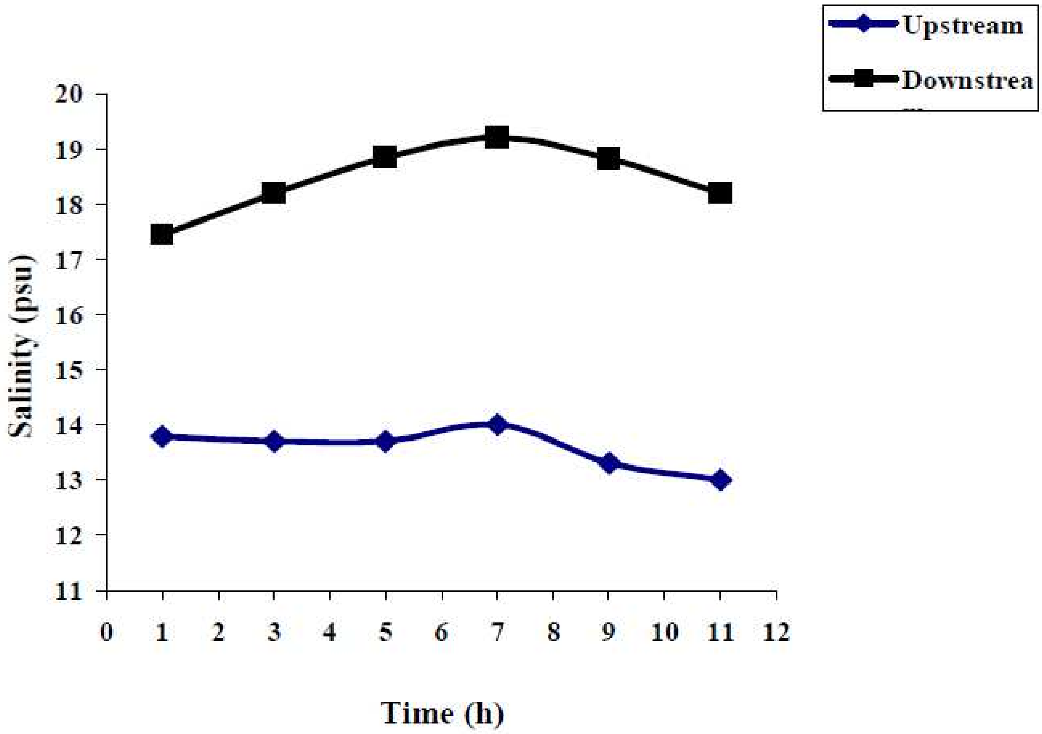

Figure 2 Tidal variation of salinity in MB Eastuary. The figure shows a continuous monitoring for 12 hrs in both the stretches of upstream and downstream area as described in material and methods.

Tidal Variation

The tide in area is predominantly semidiurnal and the vertical tide range at the coastal areas varies from 5.2m during spring to 1.8m at the neap tide [26]. Tidal variation of salinity in two estuarine areas (MB and GHJR) at DS and US locations (Fig. 2 and Fig. 3) were assessed during winter season when significant differences were observed. The study revealed that salinity varied from 15.1 to 16.5 psu and 12.0 to 14.0 psu respectively and there were no considerable differences in variation either between up streams or down streams of these two estuaries. Even the differences in salinity during tides as encountered at US and DS areas were only1.4 psu and 2.0 psu respectively. This means that the amount of seawater or freshwater introduced through tides (high and low respectively) into any of these estuaries was unable to change the salinity level significantly ($p \geq 0.05$) indicating that the tides are mostly dominated by equivalent quality of water with higher residence time in the region.

On the other hand, there were found considerable salinity differences (4.0 to 8.0 psu) between high and low tide at Namkhana influenced by river Hooghly, Lothian (Saptamukhi river) and Dhanchi (Thakuran river) (Mukhopadhaya et al., 2006 and Biswas et al., 2004) following the order of Namkhana > Lothian > Dhanchi. But in any other stations located in MB and GHJR estuary, the tidal salinity differences were observed very minimum. These facts indicated that the most part of mangrove ecosystem extending from Dhanchi towards eastern side which is influenced by the MB and GHJR River is devoid of any statistically significant tidal variation of the salinity due to less river flow of fresh water into the estuarine area.

Seasonal Variation

The entire mangrove area is subjected to undergo intense seasonal variation of the salinity because of surface runoff from the catchment area through the rivers during onset of monsoon. The fresh water discharge of the rivers intermixes with the seawater during high tides and causes a significant dilution of the salt water thereby reducing the salinity values to a large extent. In monsoon, salinity values in DS areas of all locations were reduced within 13 -15 psu and within 10 -12 psu in US areas with very small salinity differences between them (Table 3). It then distinctly indicated that the whole area of Sundarban become almost equally diluted by the fresh water influx during monsoon. After the cessation of precipitation, the river runoff gradually decreased and due to invasion of seawater through tides, salinity values gradually increased initially especially in all the coastal areas that resulted in sharp salinity differences between coastal areas and riverside areas.

At the onset of pre-summer, the river water discharge was reduced considerably especially in MB estuary due to lack of fresh water discharge source and consequently salinity values increased a lot even in riverside areas (US) with minimum salinity difference (1.6 psu) with DS. To the contrary, GHJR estuary due to higher river runoff by the river Raimangal, registered always-low salinity values in US areas in comparison to DS areas showing considerable salinity difference in all seasons (Table 3). In a similar way, the MB estuary in summer almost behaved as completely marine dominated in the entire area, even beyond the US of Sajnekhali. Thus during summer period almost whole area of MB estuary and most part of GHJR estuary become marine dominated with salinity ranging from 29 to 30 psu and in this period MB estuary acted as backwaters only. On considering the salinity distribution in the whole Sundarban area it was prominent that during monsoon (12 to 14 psu) and summer (29 to 30 psu) most part of the mangrove area attained almost similar salinity condition between coastal side areas and riverside areas. Only, the areas comprising of locating Chamta, Katwajhuri, Burirdabri and Sundarkhali under the river Raimangal experienced significant salinity variation ($p < 0.05$).

On the other hand, the salinity varied from minimum of 10.4 psu in monsoon to maximum of 25.6 psu during summer in Namkhana under the strong fresh water influx of Hooghly River. The location of Lothian and Dhanchi are on the eastern fringe of Lothian and showed salinity variation between 13.3 and 28.6 psu and between 15.5 and 30.2 psu during monsoon and summer respectively. Similar ranges of salinity variations were recorded by earlier studies [26, 13, 15]. The salinity variation of Namkhana and Lothian were found similar to those of Burirdabri, Katwajhuri and Sundarkhali. While Dhanchi area showed equivalency to those of Chulkati and Haldibari in this respect through the season due to same geographic position in a horizontal line. Thus it is evident that there are different patterns of salinity distribution in the western, middle and eastern parts of the Sundarbans.

Dilution efficiency of the study area

Fraction of fresh water (FF), dilution factor (DF) and their differences between up and down stream locations in both MB and GHJR estuary demonstrated that FF gradually decreases (0.39-0.07) in levels from monsoon to summer season, specially in down stream locations mainly due to greater extent of invasion of seawater in the respective seasons (Table 4, Table 5). Comparatively higher FF values were observed in GHJR estuary, especially in monsoon and winter season while almost the same levels were attained in summer seasons. Similar trend of FF was recorded in upstream areas of GHJR estuary with higher degree all along the seasons highlighting more (10-20%) fresh water influx in the region.

Table 4. Fraction of Fresh Water (FF), Dilution Factor (DF), % of Sea Water (PSW) and their differences within the stretch of Down and Up Stream in MB estuarine system

Sampling Location	Components	Monsoon	Winter	Presummer	Summer	Monsoon	Winter	Presummer	Summer
Down Stream (DS) (Chulkati)	FF	0.29	0.24	0.16	0.10	0.31	0.24	0.13	0.07
	DF	3.44	4.17	6.25	10.0	3.22	4.16	7.69	14.28
	PSW	71	76	84	90	69	76	87	93
Up Stream (US) (Sajnekhali)	FF	0.38	0.41	0.21	0.12	0.44	0.40	0.21	0.11
	DF	2.63	2.44	4.76	8.40	2.27	2.5	4.76	9.09
	PSW	62	59	79	88	56	60	79	89
Differences	FF(US – DS)	0.09	0.17	0.05	0.02	0.13	0.16	0.08	0.04
	DF(DS – US)	0.81	1.73	1.49	1.6	0.94	1.20	1.09	1.04
	PSW(DS – US)	9.0	7.0	5.0	2.0	13	16	8	4

US- Downstream, UP- Upstream

Table 5. Fraction of Fresh Water (FF), Dilution Factor (DF), % of Sea Water (PSW) and their differences within the stretch of Down and Up Stream in GHJR estuarine system

Sampling Location	Components	Monsoon	Winter	Presummer	Summer	Monsoon	Winter	Presummer	Summer
Downstream (DS) (Haldibari)	FF	0.35	0.31	0.15	0.09	0.41	0.28	0.13	0.09
	DF	2.87	3.22	6.66	11.1	2.43	3.57	7.69	11.10
	PSW	65	69	85	91	59	72	87	91
Upstream (US) (Burirdabri)	FF	0.48	0.59	0.37	0.20	0.33	0.61	0.36	0.19
	DF	2.08	1.69	2.70	5.0	3.03	1.64	2.77	5.26
	PSW	52	41	63	80	67	39	64	81
Differences	FF(US – DS)	0.13	0.28	0.22	0.11	0.12	0.33	0.23	0.10
	DF(DS – US)	0.79	1.53	3.96	6.10	0.40	1.93	4.92	5.84
	PSW(DS – US)	13.0	28.0	22.0	11.0	12.0	33.0	23.0	10.0

Since DF value is related to the reciprocal value of FF [24], an opposite trends of variation to those of FF values were recorded varying from minimum of 2.43 in winter to the maximum of 14.28 in summer at down stream and minimum of 1.64 in winter to 9.09 in summer at upstream locations of both the estuary. Relatively higher DF values were observed in MB estuary throughout all seasons. Differences of DF values between US and DS locations were relatively more in GHJR estuary and less in MB estuary. This indicated that any pollutant if introduced through upstream areas will be equally diluted through out the entire stretch of MB estuary and higher dilution will take place at DS areas of GHJR estuary in comparison with US locations. The seasonal variation of DF distinctly highlighted that the pollutant will undergo extensive dilution if it is introduced during summer season in GHJR and pre summer and summer in MB estuary. In an annual average, the DF value at US areas of MB estuary was about 1.67 times higher in comparison to DF value at US areas of GHJR estuary. On the other hand, the grand average DF values of MB and GHJR estuary as calculated were 6.0 and 4.5 respectively (Table 4, Table 5).

Ranges of salinity duration of the locations

Mangrove species distribution is known to depend not only on the range of salinity variation but also duration of a particular salinity level during a year [27, 28]. Existence of an area with a fixed salinity level largely depends on its position in the estuary, strength of freshwater discharge and degree of seawater intrusion in the region [5]. There are significant variations of all these factors throughout the whole Sundarban forest. From the degree of salinity variations throughout the various seasons of a year, the duration of a particular salinity level in the study areas was calculated and presented in Table 6. It is evident that four distinct separate areas with different intensity of salinity exposure could be identified.

Table 6. Zonation of Sundarbans mangrove forest on the basis of year round salinity variations and duration

Zones	Locations	Estuarine Areas	Salinity Ranges (psu)	Duration in months
	Chandraduanibharani			
	Chamta	GHJR Estuary	9-18	10 months
	Katwajhuri	Upstream	18-26	2 months
	Burirdabri			
	Sundarkhali			
	Namkhana	Hooghly (DS)	12-18	10 months
			18-25	2 months
1	Lothain	Saptamukhi (DS)	12-18	10 months
			20-28	2 months
	Benephuli	MB Estuary		
	Herobhanga	Midstream	12-18	7 months
	Jharkhali	+		
	Dobanki	Upstream		
	Sudhyanakhali		20-30	5 months
	Sajnekhali			
	Haldibari		12-18	7 months
2	Choramayadip	GHJR Estuary		
	Keorasunti	DS	20-30	5 months
	Netidhopani			
3	Dhanchi	Thakuran (DS)	15-20	6 months
			20-28	6 months
	Chulkati			
	Dulibhasani	MB Estuary	14-20	4 months
4	Kamli	Downstream(DS)		
	Sundarkati		20-30	8 months

In the first case, the location of Namkhana and Lothian island in the western part, influenced by Hooghly estuary and the area comprising of locations Chandraduani-varani, Champta, Katwajuri, Burirdabri and Sundarkhali in the eastern part under GHJR estuary showed salinity duration between 9.0 and 18.0 psu for 10 months and between 18.0 and 26.0 psu for 2 months in a year. In second case, salinity variation in the range from 12.0 to 18.0 psu for 7 months and from 20.0 to 30.0 psu for 5 months were observed in the area consisting of Benefuli, Herobhanga, Jharkhali, Dobanki, Sudhnyakhali and Sajnekhali in upstream of MB estuary and Haldibari, Choramayadwip, Keorasuti, Netidhopani in down stream of GHJR estuary. In third case, the areas at downstream of MB estuary recorded salinity duration of 14.0 and 20.0 psu for 4 months and 20.0 and 30.0 psu for 8 months. On the other hand, in fourth case, the existence of salinity between 15.0 and 20.0 psu and between 20.0 and 30.0 psu for 6 months each was recorded at Dhanchi, downstream location of Thakuran estuary due to partial influence of Hooghly River.

In a nutshell, it can be highlighted that whole Sundarban area could be classified into four distinct zones on the basis of similarity on salinity exposure; 1) between downstream areas of Hooghly estuary and upstream areas of GHJR estuary with salinity range of 9.0 and 18.0 psu in most part of the year, 2) between upstream areas of MB estuary and downstream areas of GHJR estuary with the above salinity range more than 7 months, 3) down stream of Thakuran estuary (20.0 to 30.0 psu 6 months) and 4) downstream areas of MB with more saline exposure (20.0 to 30.0 psu more than 8 months). Consequently, if salinity level and duration could be the main driving reason for mangrove species distribution and the vegetation is more luxuriant in lower salinities as suggested by Kathiresan, 1996, then similar species diversity could be expected in Namkhana-Lothian and Upstream of GHJR estuary followed by upstream of MB estuary and downstream of GHJR estuary. The more salinity tolerant species with less diversity might flourish at downstream of Thakuran and especially in MB estuarine areas.

CONCLUSION

From the salinity variation in the whole areas of Sundarbans, it is evident that the interactions between seawater and river water in western, middle and eastern sectors of this area were to a large extent different. The locations in western sector showed significant salinity variations due to strong influx of freshwater supply by the mighty river the Hooghly and were similar to the area of the eastern parts of Sundarbans upstream of GHJR estuary influenced by the river the Raimangal. However, no significant tidal variation in salinity was observed in any part of eastern sectors. In addition to this, the spatial variations in salinity were only encountered during winter and pre-summer period that were insignificant in other seasons highlighting existence of almost equal level of salinity distribution throughout the entire areas. Appreciable salinity variations between DS and US areas were recorded only during other seasons (winter and pre-summer). Contrasting to this, degree of seasonal variation in salinity was found almost similar to those of western sectors.

On comparative account, slightly more impact of freshwater discharge from US areas on salinity changes was recorded in GHJR estuary during the study period. The consequence of this resulted in relatively more difference in DF values between DS and US locations in GHJR and less in MB estuary. This indicated that any pollutant if introduced in any part of these estuarine areas will be equally diluted in summer and monsoon seasons, but comparatively more dilution will take place in summer.

The whole Sundarban area could be classified into four distinct zones on the basis of close similarities on salinity variation as well as its exposure period. Similar level of salinity variation and its duration may be useful in finding out the presence of similar type of mangroves species diversity and richness in those areas and may also be important for future studies in bringing into light the factors responsible for mangrove species extinction other than salinity from this world famous biological kingdom.

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