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RESEARCH ARTICLE

WATER CHEMISTRY IN AND AROUND THE *SUNDARBANS* MANGROVE FOREST, SOUTHWEST BANGLADESH

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Abstract: The study presents the spatial and temporal patterns of river water chemistry at 25 sites in and around the *Sundarbans*. Conductivity, TDS, major cations, major anions, alkalinity, pH and hardness were determined during September 2008 to July 2009 in four seasons at *Sarankhola*, *Chandpai*, *Nalian* and *Burigualiny* from *Bhola*, *Passur*, *Sipsa* and *Khulpatua* rivers respectively. There is wide temporal variation in conductivity (from 201 µS/cm to 43.7 mS/cm) and TDS (0.13 to 31.2 g/L) from the eastern to western *Sundarbans* suggests low flow of fresh water into the western *Sundarbans*. Variation in major cations Na^+ (9225 to 25 mg/L), K^+ (4 to 510 mg/L), Ca^{+2} (26 to 273 mg/l) and Mg^{+2} (5 to 869) and major anions Cl^- (13 to 13471 mg/L), HCO_3^- (102 to 180 mg/L) and SO_4^{-2} (9 to 1414 mg/L) were also observed. Alkalinity, pH and hardness were 90 to 224 mg $CaCO_3$/L, 6.5 to 8.3 and 85 to 4235 mg $CaCO_3$/L respectively. Data on DO, BOD, COD, nutrients and heavy metals during 2001-2009 were collected from secondary sources. Dissolved oxygen (4.9 to 6.9 mg/L) is within the Environmental Quality Standard (EQS) of Bangladesh. BOD and COD are higher in coast than the inner part of the Sundarbans. Ammonium (0.04 to 6.74 mg/L), nitrate (0.1 to 1.4mg/L) and phosphate (0.026 to 0.252 mg/L) are present in sufficient quantity for aquatic life to survive. Heavy metal concentrations are exceeded in some areas. The study reveals that water chemistry of the *Sundarbans* Mangrove Forest are approaching critical value for the survival of organism.

Key words: *Sundarbans* mangrove forests, water chemistry, salinity and nutrients

Introduction

River water chemistry is determined by the interactions between soils and underlying geology, rainfall and atmospheric inputs, anthropogenic sources (e.g. agricultural runoff and effluent discharges) and catchment hydrology (Billett *et al*., 1996; Robson and Neal, 1997; Smart *et al.*, 1998; Cooper *et al.*, 2000; Jarvie *et al.*, 2002; Daly *et al.*, 2002; Buck *et al.*, 2004). Catchment size, estuarine geomorphology, tidal range and rainfall patterns interact to control salinity patterns in mangrove waterways (Wolanski, 1989). Human alteration of the landscape has an extensive influence on watershed hydrology (Claessens *et al*., 2006; Chang, 2007) and heat budget, which subsequently increases water temperature (Nelson and Palmer, 2007) and modifies in stream biogeochemical processes that drive oxygen, nutrients, and sediment cycling (Baker, 2003). On the other hand, rivers play a major role in assimilation or transporting municipal and industrial wastewater and runoff from agricultural land. Municipal and industrial wastewater discharge constitutes a constant polluting source, whereas surface runoff is a seasonal phenomenon, largely affected by climate within the basin (Singh *et al*., 2004). Seasonal variations in precipitation, surface runoff, interflow, groundwater flow and pumped in and outflows have a strong effect on river discharge and, subsequently, on the concentration of pollutants in river water (Vega *et al*., 1998). Therefore, the effective, long-term management of rivers requires a fundamental

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understanding of hydro-morphological, chemical and biological characteristics. However, due to spatial and temporal variations in water quality (which are often difficult to interpret), a monitoring program, providing a representative and reliable estimations of the quality of surface waters, is necessary (Dixon and Chiswell, 1996).

The *Sundarbans* mangrove - dominated Ganges delta-is a complex ecosystem comprising one of the three largest single tract mangrove forests of the world (Blasco, 1975). Shared between two neighboring countries, Bangladesh and India, the larger part (62% of the total mangrove ecosystem) is situated in the southwest corner of Bangladesh between latitudes 21°27′30″–22°30′00″ North and longitude 89°02′00″–90°00′00″ East (Fig. 1). It occupies a land area of 401600 ha, of which 395,500 ha are covered by forests (Chaffey *et al*., 1985). Of the total area, approximately 70% are lands and 30% are waters. The distance between the northern and southern boundaries averages about 80 km. Major rivers include the *Passur*, *Sipsa*, *Shela*, *Arpangasia* and *Jamuna*. The western boundary of the *Sundarbans* in Bangladesh follows the *Harinbhanga–Raimangal–Kalindi* river system and abuts with the *Sundarbans* on the Indian side. To the south the forest meets the Bay of Bengal; to the east it is bordered by the *Baleshwar* river and to the north there is a sharp interface with intensively cultivated land. The natural drainage in the upstream areas, other than the main river channels, is impeded by extensive embankments and polders. Rivers in the *Sundarbans* are meeting places of salt water and freshwater. Thus, it is a region of transition between the freshwater of the rivers originating from the Ganges and the saline water of the Bay of Bengal.

In order to understand the causes of declining ecological status of the forest, a number of studies have been undertaken in the past (Grepin, 1995). These studies emphasize that whilst the physical boundary of the *Sundarbans* has hardly changed since it was first demarcated in 1875 the *Sundarbans* today is wholly surrounded and pressured to the landward side as an island by human communities and their agricultural and commercial activities. Coastal polders have been commissioned since 1968 in the immediate upstream catchments to enhance agricultural productive potential of land by protecting it from saline intrusion. However, the operation and maintenance cost of the polders are very high and most of them are in very bad condition impeding natural drainage of freshwater into western *Sundarbans* (PDO-ICZMP, 2005). Commercial shrimp farming inside the polder areas has emerged as a major economic activity of the ever increasing population during the last two decades. It is ranked as the second largest export item of Bangladesh. Major barrages have been built in the upstream to divert freshwater. Industrial activity near the upstream river system as well as nearby second largest seaport has expanded. Islam and Wahab (2005), Agrawala *et al.* (2003) and Amin (2003) notes that the *Sundarbans* mangrove has been under intensive pressure of exploitation for the last few decades which, in addition to direct clearance and conversion, have placed the mangrove ecosystem under extreme threat. It is believed that the energy flux of the ecosystem has changed due to changes in the tidal behavior, the intensity of the annual floods and the sediments they bring with them, and differing levels of salinity and industrial and maritime pollution (Syed *et al.*, 2001). The salinity conditions in the *Sundarbans* are highly dependent on the volume of freshwater coming from the upstream and the nature of tide. Salinity near the coast and inside the forest varies over a number of different timescales. Daily peak salinity at the coast generally coincides with the arrival of high water, whereas the daily range of salinity level varies with season (Wahid *et al.*, 2006). The degree of horizontal and vertical mixing of water in mangrove waterways also influences other major aspects of mangrove water columns, in particular dissolved oxygen and inorganic nutrient concentrations. The water quality in the ecosystem can largely affected by water pollution from industries situated in the upstream areas and possible oil pollution from nearby ports of Khulna and Mongla. There are 165 industries in the immediate upstream at Khulna district. The wastes from these industries fall into the *Bhairab-Rupsha* river system, which ultimately find their way to the Bay of Bengal through the *Sundarbans*. Loading of municipal wastes (raw sewage and solid domestic wastes) from Khulna and Mongla port entering the *Passur* river is estimated to be 2.2 tons of BOD/day (Wahid *et al.*, 2006). Also there is widespread speculation of oil spill (during transfer of refined petroleum products from tankers to receiving stations and oil depots at Mongla port and Khulna), fuel oil spillage, and discharge of oily ballast and bilge water, residual heavy oil sludge, lubricants and engine in Khulna and Mongla port (Majumder, 1999; JOECLA, 2002).

Within a Geographical Information System (GIS) framework, spatial datasets, such as land use and geology, can be used to explore the controls on river water quality in a variety of environments and across a range of scales. Understanding the relationships between catchment characteristics and river water chemistry provides a base for determining how future changes in land use and climate will impact on river water quality and functioning. Therefore, it is important to determine the processes that regulate stream water chemistry in landscapes under increasing pressure from human population, whether from urbanization or more intensive food production. In Bangladesh there is no regular monitoring work regarding the collection of water quality datasets particularly *Sundrabans* aquatic ecosystem. There is paucity of information on the variability in river water chemistry in relation to catchment characteristics for the *Sundarbans* river system. This paper presents the water chemistry of the *Sundarbans* with relation to its catchment characteristics.

Materials and methods

Bangladesh *Sundarbans*, is divided into four ranges namely *Sarankhola*, *Chandpai*, *Nalianala* and *Burigoalini* for its management. Water samples were collected near *Sarankhola*, *Chandpai*, *Nalian* and *Burigualiny* stations situated in upstream of four major river-sytems *Bhola-Bolesware*, *Passur*, *Sibsa*, and *Khulpatua-Arpangasia* during 2008-2009 in four seasons (dry: December to February; pre-monsoon: March to May; monsoon: June to August; and post-monsoon: September to November). *In situ* measurements for EC/TDS and pH were carried out by applying a portable EC meter with temperature sensor (Lutron CD 4301), a portable pH meter with accuracy ± 0.1 pH units (Hanna HI 98106). Quadruplicate surface water samples were collected from each of the rivers in upstream covering main rivers and creeks (Fig. 1). Water samples for dissolved metal concentrations, calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}) were acidified to pH<2 with HNO_3 (65% conc.). Sodium and potassium were determined by flame photometer (Jenoy, England). Alkalinity, hardness, calcium, magnesium, chloride, bicarbonate and sulphate were determined in laboratory following standard methods (APHA, 1992) as mentioned in Table 1. All sites were sampled during day time covering high and low tide.

Table 1. Analytical methods used for water chemistry analysis

Parameters	Unit	Methods	References
Alkalinity	mg $CaCO_3$/L	Titration method	APHA, 1992 (2-26)
Hardness	mg $CaCO_3$/L	EDTA titrimetric Method	APHA, 1992 (2-36)
Calcium	mg/L	EDTA titrimetric Method	APHA, 1992 (3-57)
Magnesium	mg/L	Calculation Method	APHA, 1992 (3-74)
Chloride	mg/L	Argentometric Method	APHA, 1992 (4-49)
Bi-carbonate	mg/L	Titrimetric Method	Romesh, 1998
Sulphate	mg/L	Turbimetric Method	APHA, 1992 (4-133)

Water chemistry data from 25 locations between 2001 and 2009 were collected from different sources such as FMRTD (2001), JOECLA (2002), IWM (2003), Rahaman *et. al*. (2003), Rahaman (2006) and Ara *et. al.*,(2009). The parameters are conductivity, TDS, pH, alkalinity, hardness, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), major cations (Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+}), major anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}), nutrients (NH_4^{+}, NO_3^{-} and PO_4^{3-}), and heavy metals (Cr, Mn, Fe, Co, Ni, Cu, Zn, Pb). Tidal context was excluded in this analysis.

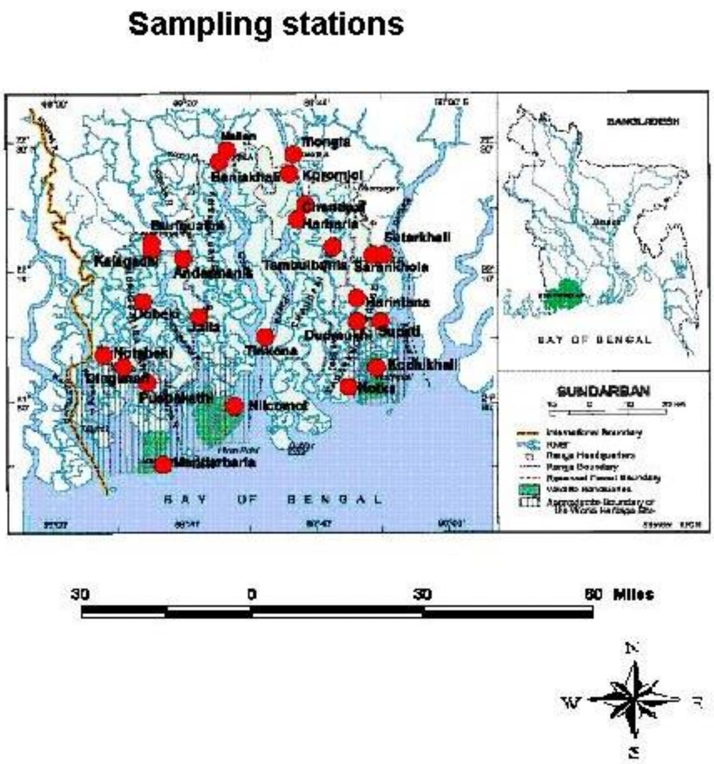

Fig. 1. Map of the *Sundarbans* study area showing the sampling stations

Results

Patterns in average water chemistry: The patterns of average water chemistry in and around the Sundarbans during September 2008 to July 2009 are presented in table 1.

Table 2. Temporal variation of water chemistry parameters in and around the *Sundarbans*, Khulna.

Parameter	Range			
	Post-Monsoon	***Dry season***	***Pre-Monsoon***	***Monsoon***
conductivity in mS/cm	0.201-0.702	2.41- 22.2	8.02 – 43.7	2.11 - 11.8
TDS in gm/L	0.13 -0.48	1.67 – 15.8	5.55 – 31.2	1.46 – 8.38
pH	7.4 -8.0	7.5 – 8.0	7.8 – 8.0	6.5 – 7.3
Alkalinity in mg $CaCO_3$/L	95 - 120	110 - 150	127 - 150	90 - 120
Hardness in mg $CaCO_3$/L	85 - 790	660 - 2470	820 - 4235	145 - 1282
Na^+ in mg/L	25.0-71.10	89.05-3601	1531- 9225	359.8 - 1990
K^+ in mg/L	4.0 - 6.61	5.83 - 182.2	48.3 - 510.0	5.02 - 45
Ca^{2+} in mg/L	26.0 - 110.20	98.2 – 200.4	72 – 273	33.07 - 125.3
Mg^{2+} in mg/L	5.0 - 166.10	100.8 - 567.8	159.4 – 869.0	14.58 - 254.4
Cl^- in mg/L	13.0- 832	152.22 - 6948	2982 - 13471	54 - 2127
HCO_3^- in mg/L	115.9- 146.4	128.1 - 180	154.94 - 180	102.0 - 134.2
SO_4^{2-} in mg/L	9.0 - 276	199.4 - 604.2	359.9 – 1414.0	57 – 492.0

Salinity: Because of high sensitivity and ease of measurement of electrical conductivity (EC), it is most commonly used to determine salinity. EC was found highest (43.7 mS/cm) in *Khulpatua* river near *Burigualiny* station, western part of the *Sundarbans* during pre-monsoon season where as lowest EC (0.201 mS/cm) was observed during post-monsoon (Fig.2). Salinity increases from east to west and northeast to southwest in all seasons. Salinity in the eastern *Sundarbans* is nearly zero where as it in western part does not get totally diluted even during monsoon.

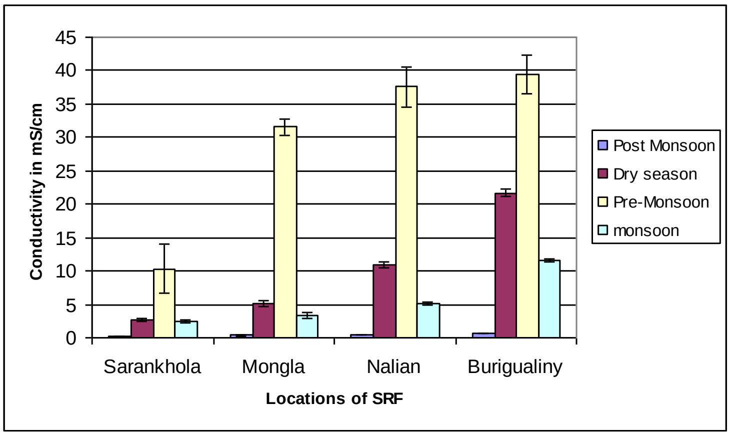

Fig. 2. Spatial and temporal variation of electrical conductivity in coastal boundary of SMF

Major cations and anions: Mean values of concentration of selected major ions in the four river systems of SRF are shown in Table 2. These values are compared with similar the Among the cations sodium showed the highest concentration in western SRF during pre-monsoon. Chloride concentrations were observed higher among the anions in same regions in all seasons. Cations and anions concentrations generally increases from upstream to down stream. Anionic concentration follows the order Cl^{-}>SO_4^{-2}>HCO_3^{-} almost in all samples. Chloride and sulphate were high during pre-monsoon in western Sundarbans.

Alkalinity, pH and hardness: Spatial and temporal variations of pH in and around the Sundarbans are insignificant. Alkalinity and pH values varied 90 to 224 mg $CaCO_3$/L (Fig. 3) and 6.5 to 8.3 (Fig. 4) respectively. Hardness shows highest spatio-temporal variability. In pre-monsoon hardness values were higher in the western *Sundarbans* mostly during pre-monsoon season along the coastal boundary (Fig. 5).

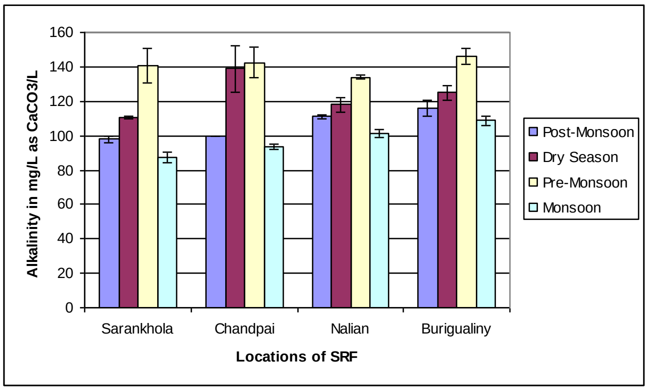

Fig. 3. Spatial and temporal variation of alkalinity in coastal boundaries of SMF

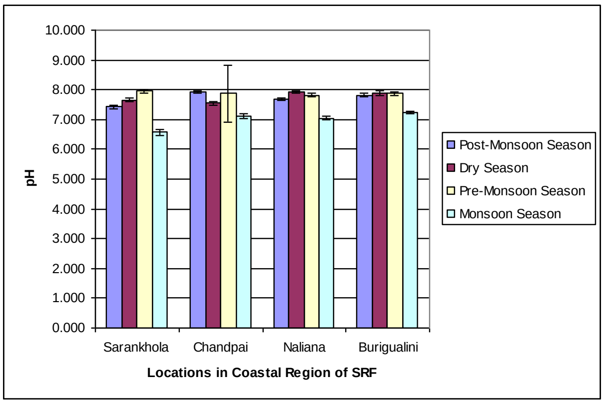

Fig. 4. Spatial and temporal variation of pH in coastal boundaries of SMF5

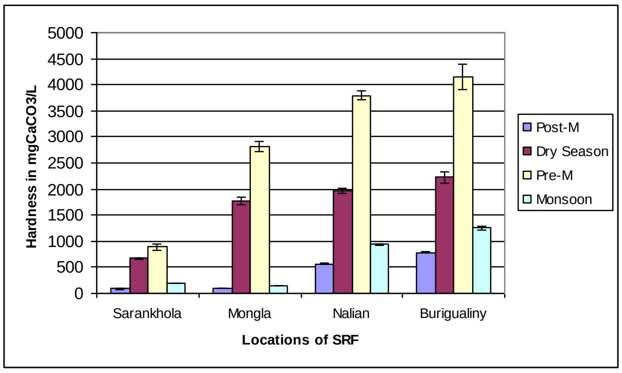

Fig. 5. Spatial and temporal variation of hardness in coastal boundaries of SMF

DO, BOD and COD: Dissolved oxygen (DO) values were recorded *in situ*, during tidal discharge in an interval of half an hour for a full tidal cycle in different time and space during January 2001 to December 2002 (IWM, 2003). Dissolved oxygen (DO) was found to vary between 4.9 to 6.9 mg/L. Low DO values were observed during dry season where as high DO values were observed during rainy season. In general, high DO levels are found in the eastern rivers. The solubility of oxygen is less in salt-containing water than it is in clean water and thus for a given temperature DO decreases from fresh water to estuarine water. Biological oxygen demand (BOD) and chemical oxygen demand (COD) were ranged 3.8 to 22.7 and 8.4 to 81.5 mg/L respectively exceeded DoE Environmental Quality Standard (EQS) in some locations. BOD and COD are higher in coast then interior of the *Sundarbans*.

***Nutrients*:** Data on the nutrient concentration of river water from the *Sundarbans* is also very scanty. Concentration of nutrients (ammonium, nitrate and phosphate) in SRF waters were determined monthly covering the major rivers during January 2002 to December 2002 (IWM, 2003). Elevated NO_3^- concentrations (0.1 to 1.4mg/L) were observed in SRF water and highest concentration was observed during dry season, and lowest was observed during post monsoon. Average phosphate (PO_4^{-3}-P) concentrations in different seasons were in the range of 0.2 to 0.78 mg/L. Ammonium-N ranged 0.04 to 6.74 mg/L. At eleven locations both for nitrate and phosphate were assessed during post-monsoon, dry, pre-monsoon and monsoon seasons. Variation of nutrients in most cases is irregular both in spatial and temporal context.

Heavy Metals: The dissolved heavy metals in rivers (*Passur* river System) from six stations were analyzed. Cd, Co, Cr, Ni, Pb, and Se values are <2, <4.30, <5.90, <3.60, <8.0, and <0.02 in µg respectively. The concentrations of heavy metals in water ranged total- Pb: <8-120.0, Cd: <2-15.0, Zn: 7.6-108.3, Fe: 108.0-1016.0, Cu: 8.98-45.54, Co: <4.30-15.0, Ni: <3.60-10.0, As: 0.21-1.95, Mn: 3.0-62.0, Se: <0.02, Cr: <5.90-41.0 µg/L during sampling period. The maximum concentration of lead and zinc was measured at *Mongla* during rainy season and cadmium during winter. *Koromjol* showed maximum concentration of iron, nickel and arsenic during rainy season; manganese during winter and copper during summer. The height value of cobalt was encountered at *Dangmari* in summer and chromium showed maximum value at *Koromjol* in summer. Selenium is always less than the detection limit.

Spatial similarity and site grouping: Variables such as BOD, COD and ammonia were used in order to cluster the polluted sites. Data source is secondary (IWM, 2003). The cluster 1 (*Harintana*, *Dudmukhi*, *Mrigamiri*, *Harbaria* and *Sarankhola*) corresponds to relatively less polluted (LP) sites. In cluster 1, *Harintana*, *Dudmukhi*, *Mrigamiri*, *Harbaria* and *Sarankhola* are situated at the eastern *Sundarbans*. The inclusion of the most downstream sampling location, *Nanbubashi*, in cluster 1 group suggests the self purification and assimilative capacity of the river. Cluster 2 (*Nalianala*, *Kaikhali*, *Kobadak*, *Hironpoint*, *Arpangasia*, *Bal*, *Malancha*, *Jafa*, and *Mandarbari*) correspond to moderately polluted sites (HP). These stations can receive pollution mostly from non-point sources such as agricultural runoff and shrim farm waste located north-western part of the *Sundarbans*. *Hironpoint* and *Mandarbaria*, however, located downstream of the Sundarbans rivers. Cluster 3 (*Dingimari* and *Kotka*) corresponds to highly polluted locations. Kotka is located to downstream near the sea where the pollution source may be the Bay of Bengal. While analysis was performed from samples taken only during a low-flow period, it can be said that there is a groundwater contribution in pollution-loading into the water bodies of this area.

Discussions

Water circulation in the mangroves controls the chemistry and biology of the swamps and estuary. Water levels in the river network of the *Sundarbans* are highly dependent on the tidal oscillation and to a lesser extent on the freshwater inflow from the upstream. Tides in the Bay of Bengal are semidiurnal, exhibiting two highs and two lows per day. The daily, fortnightly and seasonal variations in water levels and tidal amplitudes experienced at the coast propagate inland during each tidal cycle. In an earlier studies, salinity concentration were recorded in situ, during tidal discharge in an interval of half an for a full tidal cycle. Salinity varied significantly among the various sites, with depth and seasons ranging between 0 and 26.63 ppt. Salinity in the *Sundarbans* is dependent on the volume of fresh water from the upstream and the nature of the tide. Salinity near the coast and inside the forest varies over a number of different time scales. So salinity, dissolved cations and anions, are the most important water quality index which can influence the chemistry of the *Sundarbans*. Carbonate and bicarbonate are major anions which can influence on alkalinity and pH. Alkalinity can be affected by all processes that yield or consume H^+ or OH^- in stoichiometric equation. Alkalinity increases as a result of photosynthetic NO_3^- assimilation; conversely the aerobic bacterial decomposition of biota to NO_3^- is accompanied by a decrease in alkalinity. Such processes occurring in land ecosystems are often not without influence on the pH and alkalinity of the adjoining aquatic ecosystems. Variation of alkalinity and pH of the *Sundarbans* water in spatial and temporal context is low. Values of alkalinity in this study area are low as compared with another study in Mangalavanam – protected shallow water mangrove ecosystem in India (Bava and Seralanthan, 1999). Alkalinity may be greater than or less than the total hardness. If the alkalinity is less than the total hardness, the alkalinity equals the temporary hardness. If the alkalinity is greater than the total hardness than all hardness is temporary. In the *Sundarbans* waters total hardness is extremely high in some locations with timescale which is permanent hardness. Total hardness is an aggregate property and cannot be precisely interpreted

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 Dendrogram using Ward Method

                          Rescaled Distance Cluster Combine

    C A S E        0         5        10        15        20
25
  Label       Num  +---------+---------+---------+---------+--------+

  Nalianala     7   ⇩⬂
  Kaikhali     12   ⇩⇳⇩⬂
  Kobadak      13   ⇩▫ ⬄
  Hironpoint   15   ⇩⬃  ⬄
  Arpangasia    8   ⇩⬂ ▫⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⬂
  Bal           9   ⇩▫ ⬄              ⬄
  Malancha     10   ⇩▫ ⬄
▫⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⬂
  Jafa          5   ⇩⇳⇩⬃              ⬄
⬄
  Mandarbari   16   ⇩⬃                ⬄
⬄
  Dingimari    11   ⇩×⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⬃
⬄
  Katka        14   ⇩⬃
⬄
  Harintana     2   ⇩⬂
⬄
  Dudmukhi      3   ⇩▫
⬄
  Mrigamiri     6   ⇩⇳⇩⬂
⬄
  Harbaria      1   ⇩⬃
▫⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⇩⬃
  Shwarankho    4   ⇩⇩⇩⬃
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Fig. 8. Dendrogram showing clustering of sampling sites according to surface water quality of the *Sundarbans* river system

in relation to aquatic animal health unless the concentrations of substances contributing to total hardness are known. The total hardness of natural waters ranges from less than 5 to over 10,000 mg/L as $CaCO_3$. The geology of the aquifer or watershed determines the total hardness and the relative concentration of calcium and magnesium. Calcium and magnesium are derived primarily from dissolution of alkaline earth carbonates. Also, hardness may be contributed by dissolution of noncarbonate minerals (such as gypsum) that do not contribute to alkalinity. Calcium and magnesium are abundant in seawater and are usually do not limit normal life function of marine animals. Calcium and magnesium, also being divalent cations, decrease the toxicity of heavy metals by competing with metals for binding and uptake sites at the gill epithelium (Pagenkopf 1983). In this study, high concentration of sulphate and chloride were observed which justify the values of hardness in SMF waters.

The amount of dissolved oxygen in mangrove waters is generally lower than that of the open sea. This low content may be depressed further in areas of organic pollution, to the point of creating an anoxic zone in the water column. Oxygen in the soil between sediment particles (interstitial oxygen) is used up by the decay and respiration of bacteria. In the present study area comparatively higher values for DO are found in the eastern rivers than the western river. Although dissolved oxygen values are not so much higher in the *Sundarbans* water in spite of tidal nature of the river systems, the average value indicates that rivers are healthy for aquatic ecosystem. Due to more suspended solid in surface waters, re-aeration can be hampered and hence DO is lower compared with sea water. Seasonal variation of BOD as well as COD in the eastern *Sundarbans* is observed with maximum values during dry season. On an average, the western *Sundarbans* assumes higher biodegradable pollution than that in the eastern *Sundarbans*.

Concentrations of dissolved inorganic nitrogen are low in tropical mangrove waters, within µM range, and are dominated by ammonium with usually lower amounts of nitrate and nitrite (Robertson and Alongi, 1992). Variations in concentration among estuaries and mangrove waterways may be ascribed to differences in the extent of freshwater and groundwater input, degree of solar insolation, oxygen availability, and standing stocks and productivity of phytoplankton and bacterioplankton. Dissolved nitrogen concentrations decrease with increasing salinity at the seaward end in mangrove wet tropics due to dilution from monsoonal rains (Nixon *et al*., 1984; Wong, 1984). Lowest concentrations are generally recorded in the pre-monsoon season, coincident with high rates of primary productivity (Sarala Devi *et al*., 1983). In the dry tropics, variations in estuarine nutrient concentrations are greatest over a tidal cycle with highest concentrations occurring at high tide and decreasing during ebb tide (Guerrero *et al*., 1988; Ovalle *et al*., 1990). There was no distinct seasonal variation of nitrate in this study. Concentrations of dissolved inorganic and organic phosphorus in mangrove waters are low, within the µM range. Values of unpolluted mangrove waterways range from <0.1 to 20 µM. As in the case of nitrogen, differences in concentrations among mangrove estuaries can be ascribed to local characteristics, such as the extent of fresh water and groundwater input, and the productivity of biota. Variations in dissolved P concentrations may mirror changes observed for dissolved N (Robertson and Alongi, 1992). In some wet tropical river systems, the extremes of rainfall and runoff shift the importance for biological availability of dissolved orthophosphate to P tied to the suspended load. As for NO_3-N, no distinct seasonal variation of PO_4-P could be observed with the available data. Heavy metal concentrations are exceeded in some areas of the *Sundarbans*. An earlier study observed that the concentration of Cu, Zn, Fe, Pb, Cd, Cr and Ni seasonally varied from 0.025 to 0.136, 0.002 to 0.154, 0.695 to 19.54, 0.205 to 0.598, 0.0045 to 0.013, 0.245, and 0.0085 to 0.1065 mg/L respectively (Haque *et al*., 2004). The concentration of Hg, Cr and Pb were observed within the permissible limits set by EQS in the river water in another study (Wahid *et al*., 2006). Only on four occasions (out of 168 sets of data), the Cr concentrations were found to be higher than the permissible limit of 0.05 mg/L and on occasion the Pb concentration exceeded the permissible limit of 0.2 mg/L (Wahid *et al*., 2006).

Conclusion

It is observed that human activities in the region have no significant imprint on river water chemistry. Detail chemical data especially on redox chemistry of the *Sundarbans* are lacking. There are very few studies on river water chemistry of SMF. It is important to monitor regularly considering the rapid industrial and agricultural development around the forests. The importance of nutrient inputs from non-point sources in coastal belt of the western *Sundarbans* is critical in relation to effective catchment management. River water chemistry (especially N and P concentrations) is highly variable due to a complex set of interacting hydrological and biogeochemical processes. Many parameters of water chemistry of the *Sundarbans* are approaching the critical value for the survival of different aquatic organisms. The addition of flow data and soil physico-chemical data would strengthen the value in terms of linking water quality and change to catchment hydrology and biogeochemistry. Integration of GIS approaches and extensive monitoring data can provide a base for underpinning environmental management at local, regional, national and international scales.

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