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ASSESSMENT OF PHYSICO-CHEMICAL PROPERTIES OF THE PASUR RIVER ESTUARINE WATER

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Abstract

This study aimed to investigate physico-chemical properties of the Pasur River Estuarine (PRE) water connected to the Sundarbans mangrove ecosystem during the dry season for examining the ecosystem health. *In-situ* measurement and water sample collection were performed to assess physico-chemical properties at fifteen sampling stations along the main axis of the estuary in March 2018, April 2018, January 2019 and March 2019. Surface water temperature ranged from 20.7 to 33.7°C, pH from 7.1 to 7.9, and salinity from 8.5 to 16.2 PSU (practical salinity unit). Dissolved Oxygen (DO) concentration varied from 5.9 to 8.4 mg/L. Ammonium-nitrogen (NH_4^+) was the dominant nitrogenous compound among the dissolved inorganic nitrogenous (NH_4^++NO_3^-+NO_2^-) compounds, and ranged from 0.11 to 2.11 mg/L. Higher NH_4^+ concentration in water column was largely attributed to release by tidal wash-out of the interstitial waters of the surficial mangrove sediments. In contrast, phosphate concentration varied from 0.07 to 5.8 mg/L. The Pearson correlation coefficient was calculated to elucidate the correlation among physico-chemical properties during the dry season. Temperature showed a significant positive correlation with salinity and total dissolved solids (TDS), and negative correlation with DO. Similarly, salinity showed a significant positive correlation with TDS and negative correlation with DO. According to the Redfield ratio, the PRE is a a nitrogen-limited estuarine system during the dry season.

Keywords: Mangrove ecosystem, nutrient ratios, redfiled ratio.

Introduction

Estuaries are the transitional zones between the land and the sea which are important for both the economic and ecological perspectives. The inflows of marine and freshwater provide high levels of nutrients both in the water column and in the sediment in the estuary (McLusky and Elliott, 2004; Valle-Levinson, 2010). Estuaries occupy less than 10% of the ocean's surface only but play an important role in the global biogeochemical cycles such as carbon cycle, nitrogen cycle, and nutrient cycles (Lisitsyn, 1995; Gebhardt *et al.*, 2005). Among the world's estuaries, the mangrove estuaries are considered as the most productive ecosystems, occupying the intertidal coastal regions of the tropical mangrove ecosystems (Dittmar and Lara, 2001; Chew *et al.*, 2012). Mangroves play an important role in stabilizing the shoreline and act as nutrient filters through modifications of the physical and biogeochemical properties

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of estuarine waters and sediment (Burford *et al.*, 2008). Mangrove estuarine areas may export large amounts of organic material and nutrients to coastal marine environments which significantly affects the biological productivity of the estuary (Pamplona *et al.*, 2013).

Physico-chemical properties of an estuary is influenced by different natural and man-made processes such as precipitation rate, weathering, soil erosion, urban development, industrial and agricultural activities, and human exploitation of water resources (Pejman *et al.*, 2009; Yang *et al.*, 2012; Barboza *et al.*, 2014).Factors such as the morphological characteristics of the estuary, water residence time, tidal regime, and rainfall also determine the ecological status and nutrient input to the estuary (Pamplona *et al.*, 2013). Dissolved inorganic nutrients such as nitrite, nitrate, ammonium, and phosphate are the major essential nutrients for the phytoplankton growth (Dyer, 1986). In an aquatic ecosystem, dissolved inorganic nitrogenous (DIN=NH_4^+ + NO_3^- + NO_2^-) species are therefore very much dependent on biological uptake and regeneration (Flynn and Butler, 1986). Among the DIN species, the ammonia-nitrogen is preferentially used by plants and produced by bacterial breakdown of organic matter and animal excretion (Rahaman *et al.*, 2014). Lower concentrations of ammonia-nitrogen and nitrite are found in unpolluted marine waters, and high concentrations of DIN in polluted waters which can be toxic to the aquatic organisms (Camargo and Alonso, 2006). Thong *et al.* (1993) demonstrated the increase of inorganic nitrogen after heavy rains or tidal inundation of the forest floor. In contrast, dissolved orthophosphate is another important nutrient source for phytoplankton. Low availability of phosphate in the freshwater environment results in decline in primary productivity, while nitrogen compounds are normally limited in the coastal waters. Thus, nutrient availability is directly related to the productivity of the water body. Therefore, nutrient concentration must be within an acceptable limit for a healthy and good aquatic environment and for better production of aquatic organisms including fish.

Marine, freshwater and estuarine phytoplankton have similar and specific requirements of major nutrients especially nitrogen and phosphorus for proper growth (Tait *et al.*, 1972). The scarcity or least availability of one nutrient leading to the depletion of algal growth is called the limiting nutrient. According to the Liebig's Law of minimum, the algal concentrations stop increasing and the eutrophication process is retarded when the limiting nutrient is depleted (Goldman *et al.*, 1979). The ratio between dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) in an aquatic system is used as an indicator of the nutrient limiting conditions for algal growth. The optimal DIN/DIP ratio of 16:1 (molecular concentrations) for phytoplankton growth is known as the Redfield ratio (Redfield, 1958). Deviations from this Redfield ratio at lower values (<16) indicate the nitrogen limitation and at higher values (>16) indicate the phosphorus limitation of the primary production (Redfield 1958). Generally, nitrogen is the limiting nutrient for the estuaries and coastal water whereas the freshwater lakes are most often limited by phosphorus (Ji, 2008). Estuaries and coastal systems receive nutrients inputs from upstream terrestrial ecosystems, atmosphere, and also from the neighboring oceanic water masses. The ocean-water inputs of nutrients tend to have a ratio below the Redfield ratio due to denitrification on the continental shelves (Nixon *et al.*, 1996).

The Sundarbans mangrove ecosystem act as a buffer that protects its inhabitants from different types of natural calamities such as cyclones, natural disasters, sea-level rise, and other hazardous weather events. It is the transition zone between freshwater flow from the Ganges and saline water from the Bay of Bengal (FAO, 2007; Gopal and Chauhan, 2006). The entire mangrove ecosystem has been intersected by an elaborate network of rivers, channels, and creeks which occupies 30% of the total Sundarbans mangrove biome. These river systems carry a huge freshwater flow from upstream and fall into the Bay of Bengal through the Pasur River (Hussain and Acharya, 1994; Hossain *et al.*, 2015).

The Pasur River estuary (PRE) is the largest and most important estuary that experiences upstream saltwater intrusion during the dry season (Shaha and Cho, 2016) as well as supports the world's largest mangrove forest biodiversity by carrying freshwater from upstream. Therefore, any change in the physical, chemical or even biological interest could lead to serious impact on this biological hot spot. Few studies have provided information on seasonal variation in water quality and nutrient distributions in the major river systems in the Sundarbans mangrove ecosystem (Rahman *et al.* 2013a,b). However, those studies avoided the dynamics and spatial distribution of physico-chemical properties in the PRE. For an ecological study, an interdisciplinary approach linking the physical properties with chemical and biological properties is essential. In this context, the present study was conducted to assess the physico-chemical characteristics of the Pasur river estuarine water during the dry season and the inter-linkage among these parameters.

Materials and Methods

Study Area

This study was conducted in the PRE, supporting the Sundarbans mangrove ecosystem (Fig. 1). The PRE splits into two branches, the Shibsa River estuary and the PRE, at Akram Point after entering from the Bay of Bengal. There is no direct link between the Shibsa River estuary (SRE) upstream and the Ganges River. Therefore, relatively higher salinization occurs in the SRE to the PRE in the dry season owing to a lack of freshwater discharge and precipitation (Shaha and Cho, 2016). On the other hand, the PRE is directly connected to the main freshwater source of the Ganges through the Gorai-Madhumati-Nabaganga-Rupsha-Pasur River System. The Chunkhuri Channel connects the PRE to the SRE at Chalna, approximately 68 km upstream from Akram Point. The river receives freshwater from the Padma River through the Rupsha-Modhumoti-Gorai River System and falls into the Bay of Bengal through the Sundarbans mangrove ecosystem.

In situ measurement of water quality parameters

A 42 kilometer transacts of the PRE from Batiaghata to Joymoni was selected for this work. There were 15 sampling stations. The nominal distance between every two stations was approximately 3 kilometers. During data collection, the Global Positioning System (GPS) was used to get the precise location of the sampling stations. Vertical salinity and temperature were taken using a conductivity-temperature-depth (CTD) probe (Model: *In-situ* Aqua TROLL 200, *In-situ* Inc., Fort Collins, Colorado, USA) along the main axis of the PRE from Batiaghata to Joymoni.

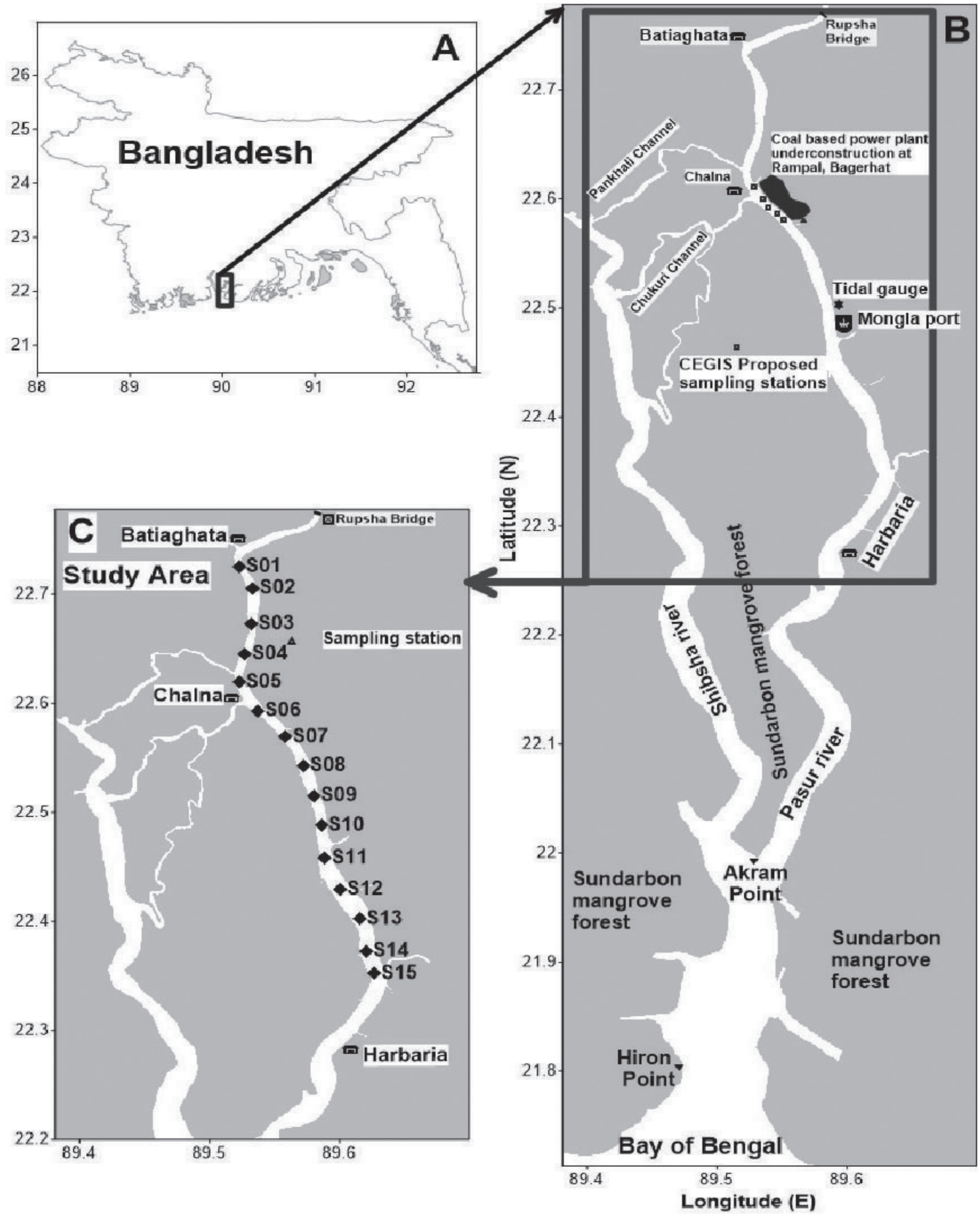

Fig. 1. Map of the study area in the Pasur River estuary. The solid diamond represents CTD sampling stations. Batiaghata are located upward and Harbaria are located seaward from the Mongla port.The map was generated using Golden Software Surfer 9.0.

Salinity is measured in gravimetrically as parts per thousand of solids in liquid or ppt. Another salinity unit is the practical salinity unit or PSU measurement, which is based on water temperature and conductivity measurements made by sondes and the ocean is also generally around 35 PSU (Antonov, 2006). Using ppt or PSU gives similar results for the ocean's seawater salt content (Antonov, 2006). The CTD was deployed at every sampling station from a mechanized boat during the dry months. Four samplings were taken in March 2018, April 2018, January 2019 and March 2019. Longitudinal transects were taken at high water levels. Dissolved oxygen (DO) concentration and pH were immediately measured on the boat using portable dissolved oxygen meter (HQ30d, HACH, USA) and pH meter (Sension+ PH3, HACH, USA) respectively. Sampling stations and tidal conditions were marked on the bottle using a permanent marker for clear identification of samples.

Sample collection and laboratory analysis

Surface water samples were taken using a water sampler (Wildco 1520-C20 Kemmerer Bottle Sampler, 1.5 L Silicone Kit) from each station. Samples were immediately filtered using Whatman GF/Filter papers into acid-washed polypropylene bottles and preserved in the ice box to prevent quality deterioration of water. The samples were carried to the laboratory and preserved in a refrigerator until chemical analysis. Nutrient parameters were analyzed in Water Quality and Pond Dynamics Laboratory, Bangladesh Agricultural University, Mymensingh and post graduate laboratory of the Department of Fisheries Management, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur.

Nitrate (NO_3^-) concentration was measured by Cadmium Reduction Method (Strickland and Parsons, 1972) where the water samples were treated with NitraVer®6 and NitriVer®3 Powder Pillow. Nitrite (NO_2^-) was determined by the USEPA Diazotization Method (Strickland and Parsons, 1972) where NitriVer®3 Reagent Powder Pillow (10 mL) was used. We used the Nessler Reagent Method for determining ammonia-nitrogen. Absorbance was measured by spectrophotometer DR 6000 (HACH, 2017) for chlorophyll determination. Phosphorus concentration (PO_4^{3-}, reactive Orthophosphate) was measured by the Ascorbic Acid Method (Strickland and Parsons, 1972).

Data analysis

The Kruskal–Wallis *H* test was used to determine the significant differences of the physico-chemical parameters between sampling stations and months. The Pearson correlation coefficient was calculated using SPSS software to determine the linear relationship among the physico-chemical parameters. Two-way ANOVA was carried out to examine the differences in water quality variables among the sampling stations and the sampling months. All statistical data were treated using SPSS version 25.

Results and Discussion

Water quality parameters

The surface water temperature varied between 20.7 and 33.7 °C with the highest temperature of 33.7 °C recorded in April 2018 and the lowest temperature of 20.7 °C in January 2019.

The lowest water temperature in January was due to the lowest atmospheric temperature and the higher temperature in April could be attributed due to higher solar radiation. Saifullah *et al.* (2016) observed a significant positive correlation between temperatures of water and the atmosphere. Similar range of temperature between 19°C and 31.1°C has been reported by Rahman *et al.* (2013) during the dry season in the Sundarbans mangrove river system in Bangladesh. According to Wahid (1995), the surface water temperature profile in the Sundarbans mangrove ecosystem is consistent with a typical sub-tropical aquatic system. Mean surface water temperature in the PRE showed spatial uniformity with marginally increasing trends to the seaward stations might be due to changes in sampling time (Fig. 2). The Kruskal-Wallis *H* test showed that the surface water temperature was spatially non-significant among the sampling stations ($p > 0.05$) but statistically significant variations were found among the sampling months ($p < 0.05$). Billah *et al.,* (2016) also reported the spatial uniformity in surface water temperature in the Miri estuary, east Malaysia with significant monthly variations.

In contrast, water temperature showed a significant positive correlation with salinity ($r = 0.85$), TDS ($r = 0.86$), and ammonia-nitrogen ($r = 0.45$) but significant negative correlation with DO concentration ($r = -0.90$). Saifullah *et al.,* (2016) also showed a significant positive correlation of surface water temperature with TDS ($r = 0.71$), salinity ($r = 0.74$) and conductivity ($r = 0.78$) in the mangrove estuary in Sarawak, Malaysia. The spatial uniformity in surface water temperature in PRE has the least probability of affecting the plankton abundance and distribution. The nutrient concentrations of an aquatic system may be influenced when the temperature rises as it affects the photosynthesis rate (Tait, 1972; Plinski and Jozwiak, 1999).

In this study, pH values ranged between 7.11 and 7.86 with the highest value of 7.86 in January 2019 and the lowest value of 7.11 in March 2018. The pH values varied non-significantly among the sampling stations ($p > 0.05$) but varied significantly among the sampling months (Table 1). A recent study in a mangrove estuary (Merbok river estuary, Malaysia) also showed significant variations among the sampling months (Fatema *et al.*, 2015). The mean values of pH concentrations

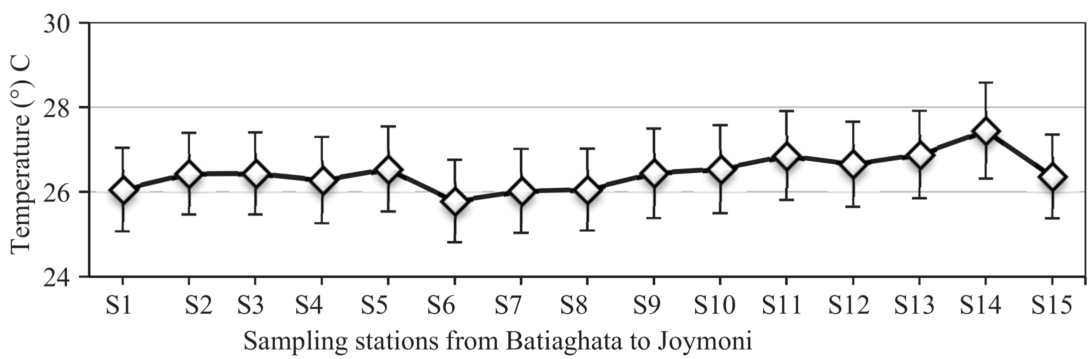

Fig. 2. Spatial variation of average temperature along the Pasur River estuary during the dry season.

Table 1. **Mean, standard deviation, maximum and minimum values of different ecological parameters in the Pasur river estuary during the dry season**

Month	Temp Mean ± SD	pH Mean ± SD	Sal Mean ± SD	DO Mean ± SD	TDS Mean ± SD	NO_2^- Mean ± SD	NO_3^- Mean ± SD	NH_4^+ Mean ± SD	PO_4^{3-} Mean ± SD	Chl a Mean ± SD
2018 March	27.05±0.78	7.48±0.22	11.12±0.46	6.58±0.12	12.07±0.43	0.02±0.01	0.04±0.01	1.30±0.31	0.20±0.16	0.02±0.01
	28.84-26.46	7.75-7.11	11.97-10.32	6.76-6.31	12.86-11.42	0.04-0.01	0.06-0.02	1.75-0.56	0.71-0.09	0.04-0.01
2018 April	30.88±1.10	7.71±0.05	14.98±0.83	6.39±0.27	15.78±0.79	0.01±0.01	0.04±0.01	1.27±0.43	0.59±0.48	0.02±0.01
	33.65-29.68	7.84-7.64	16.15-14.03	6.91-6.05	16.91-14.85	0.04-0.01	0.05-0.02	2.11-0.45	1.75-0.15	0.05-0.00
2019 January	21.05±0.23	7.78±0.05	9.28±0.42	8.04±0.22	10.20±0.33	0.01±0.004	0.04±0.02	0.59±0.33	0.19±0.12	0.18±0.08
	21.37-20.69	7.87-7.69	9.95-8.47	8.43-7.76	10.82-9.77	0.02-0.01	0.08-0.02	1.11-0.11	0.51-0.07	0.37-0.10
2019 March	26.83±0.89	7.68±0.05	12.93±0.37	6.68±0.24	13.47±0.61	0.01±0.005	0.04±0.02	0.52±0.34	1.29±1.97	0.15±0.07
	28.46-25.42	7.76-7.61	13.45-12.31	6.95-5.97	14.15-12.34	0.03-0.01	0.08-0.01	1.19-0.04	5.82-0.12	0.31-0.03

Temp: temperature; Sal: salinity; DO: dissolved oxygen; TDS: total dissolved solids; NO_2^-: nitrite; NO_3^-: nitrate; NH_4^+: ammonium; PO_4^{3-}: phosphate; Chl *a*: chlorophyll *a*

in the PRE showed a high fluctuation among the sampling stations (Fig. 3). This fluctuation in pH values in PRE can be attributed to the removal of CO_2 by photosynthesis through bicarbonate degradation, dilution of seawater by the freshwater influx, reduction of salinity and temperature, and decomposition of organic matter. However, the overall value of pH was within the limit for environmental water quality standards in Bangladesh recommended by the World Health Organization (6.5-9.2; WHO, 2004) and Department of Environment (DoE, 1991).

The Pearson correlation coefficient matrix (Table 2) showed no significant correlation between pH and salinity but showed a significant positive correlation between pH and DO concentration (r = 0.423). Similarly, a significant negative correlation was found between pH and nitrogenous compounds, NO_2^- (r = -0.39) and NH_4^+ (r = -0.42) in the PRE. The overall fluctuation of pH during the study period showed consistency with the previous study by Rahman *et al.* (2013). Therefore, pH was in suitable range for fish growth, survival and reproduction. An earlier study by Rahman *et al.* (2003) in the Pasur–Shibsa river system showed a pH of water of the Sundarbans Reserve Forest (SRF), Khulna, seasonally varied from 7.0 to 8.4. Hoq *et al.,* (2006) reported that river water of the Sundarbans was characterized by slightly alkaline pH and water pH remains neutral to alkaline (7.4 to 8.1) throughout the year.

Salinity along the main axis of the PRE ranged between 8.5 and 16.2 PSU with the highest salinity of 16.2 PSU in April 2018 and the lowest salinity of 8.3 PSU in January 2019. Salinity distributions during the dry season

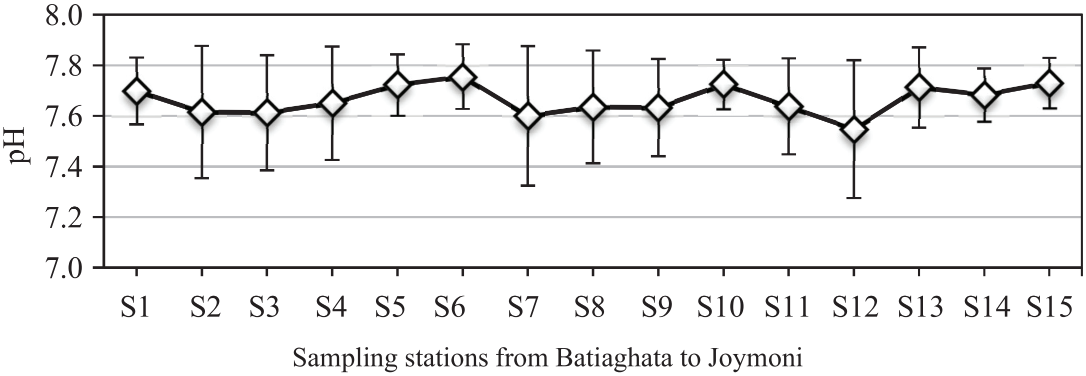

Fig. 3. Spatial variation of average pH along the Pasur River estuary during the dry season.

are shown in Fig. 4. The highest salinity was observed at Chalna and the lowest at Pankhali channel. Salt export to the PRE from the SRE through the Chunkhuri channel contributes significantly to higher salinity at Chalna (Shaha and Cho, 2016). The Kruskal-Wallis *H* test showed that the salinity was non-significant among the sampling stations ($p>0.05$) but significant variations were noticed among the sampling months during the study period ($p< 0.05$). Salinity showed significant positive correlation with temperature ($r = 0.85$), TDS ($r = 0.98$) and ammonium ion ($r = 0.28$) whereas a significant negative correlation was between salinity and DO concentration ($r = -0.73$).

Dissolved Oxygen determines the biological changes brought by aerobic or anaerobic organisms. DO values ranged between 5.97 and 8.43 mg/L throughout the study period with the maximum value of 8.43 mg/ in January 2019 and the minimum value of 5.97 mg/L in April 2018. A relatively lower concentration of DO was recorded in April due to higher atmospheric temperature because the solubility of oxygen in water decreases as the water temperature increases (Fig. 5). Similarly, the concentration of DO was relatively higher in January when the atmospheric temperature decreased. Higher concentration of DO was recorded in the upper region than the lower region with the maximum mean at station S6 and the minimum at station S12 (Fig. 5). The highest DO value at station S6 might be due to photosynthesis, which acts as a major factor, and to the high solubility of oxygen in low surface water. The lowest value of oxygen at station S12 might be due to aquatic pollution, organic wastewater discharge from the nearby industries, construction sites, human settlements, shrimp farms, agricultural lands, which might increased the load of organic matter. The higher values of DO in the upstream stations also might be due to DO-enriched inland freshwater input through the river and lower values in downstream stations may be due to intrusion of highly saline water from the ocean (Rahaman *et al.*, 2014) low oxygen water from the creeks of the Sundarbans mangrove forest.

Spatial variation of DO concentration was found non-significant ($p> 0.05$) but varied

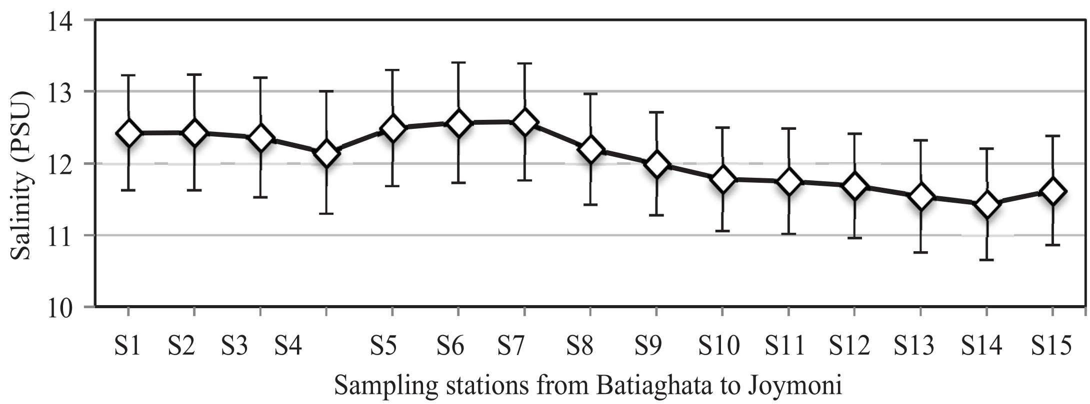

Fig. 4. Spatial variation of salinity distributions along the Pasur River estuary during the dry season.

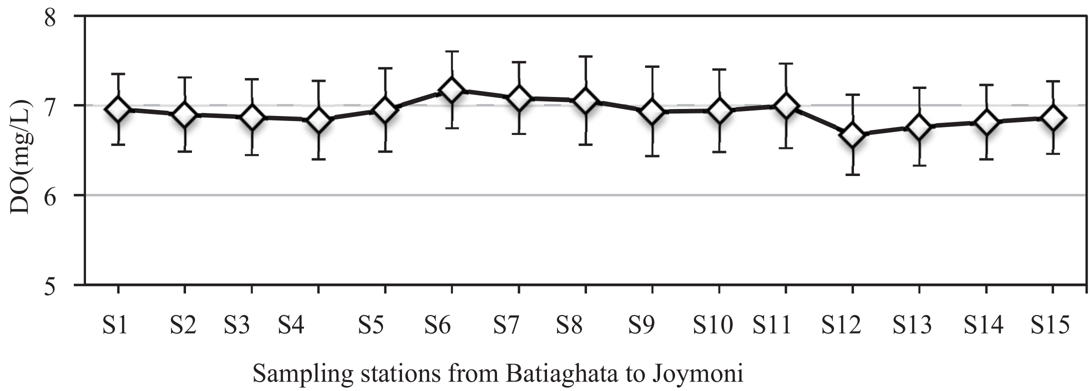

Fig. 5. Spatial variation of dissolved oxygen (DO) concentrations along the Pasur River estuary during the dry season.

significantly among the sampling months (Table 1). DO concentration in the PRE showed a significant negative correlation with surface water temperature (r = -0.90), salinity (r = -0.73) TDS concentration (r = -0.73) and ammonium ion concentration (r = -0.42). At the same time, DO showed a significant positive correlation with pH (r = 0.42). The dissolved oxygen level in the natural water body depends on the physical, chemical and biochemical activities occurring at surface levels. Sadhuram *et al.* (2005) reported that the dissolved oxygen concentration in surface waters ranged between 4.51 and 6.21 mg/L with slight seasonal fluctuation. Wahid *et al.* (2007) reported the average dissolved oxygen level of 5.99 mg/L from the major river systems in the Sundarbans mangrove ecosystem. Rahaman *et al.* (2014) surveyed the water quality of Sundarbans mangrove ecosystem of Bangladesh and recorded dissolved oxygen ranged between 3.9 and 7.4 mg/L throughout the year and the highest was recorded during post-monsoon and lowest in monsoon season.

Nutrients parameters

Nitrate concentrations (NO_3^-) in the PRE were extremely low, varied between 0.01 and 0.08 mg/L with the highest concentration in March 2019 and the lowest in January 2019 (Fig. 6). The maximum concentration of nitrate was found at station S4 (landward) and the minimum was found at station S14 (seaward). A relatively higher amount of nitrate in upper region of estuary might be attributed to agricultural runoff and shrimp farms. Nitrate was found to be non-significant both for the sampling stations ($p > 0.05$) and the sampling months (**$p > 0.05$**). Nitrate concentration in the PRE was found to be negatively correlated with surface water temperature, pH and TDS and positively correlated with dissolved oxygen concentration and nitrite concentration (Table 2). Rahaman *et al.* (2013a) recorded mean nitrate concentration ranging from 0.04 to 0.46 mg/L with an average of 0.15 mg/L in the Kholpetua-Arpangashia River system in the Sundarbans mangrove ecosystem. The maximum desirable range of nitrate concentration in the estuary has been recommended as much as 10 mg/L by Environmental quality standards (EQS). The present study showed very poor condition of dissolved nitrate concentration in the PRE compared to the desired limit (10mg/L, DOE, 1991). It might have resulted from overuse by primary producers because only the nitrate is the nitrogenous compound directly absorbed by phytoplankton and other organisms.

The concentrations of ammonia nitrogen ranged between 0.11 and 2.11 mg/L in the PRE during the dry season with the highest mean value of 1.3 mg/L in March 2018 and the lowest mean of 0.5 mg/L in March 2019 (Fig. 7).

Ammonium concentration varied non-significantly among the sampling stations ($p > 0.05$) but varied significantly among the sampling months (Table 1). The Pearson correlation matrix (Table 2) showed that the concertation of ammonium in PRE had significantly positive correlation with surface water temperature ($r = 0.45$), salinity ($r = 0.28$) and TDS ($r = 0.29$) but showed negative correlation with DO concentration ($r = 0.42$) and pH ($r = 0.42$). Rahaman *et al.* (2013a) recorded NH_3–N concentrations between 0.02 and 0.38 mg/L with an average of 0.14 mg/L

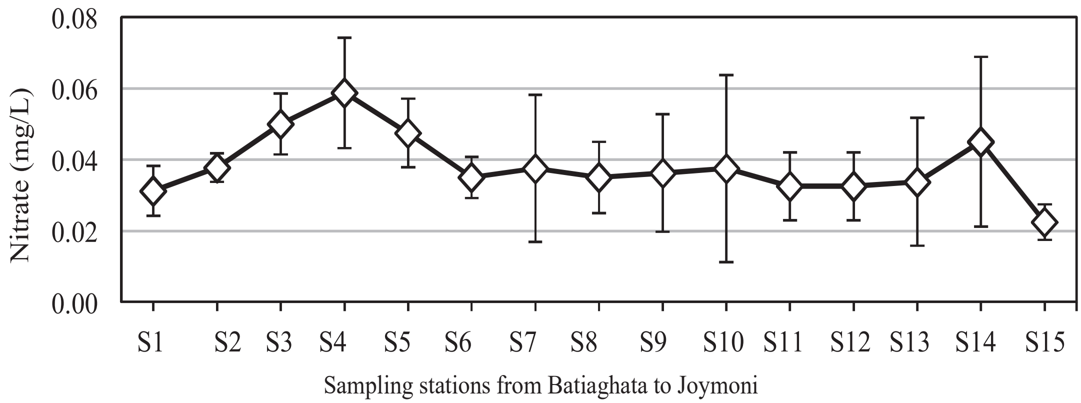

Fig. 6. Spatial variation of nitrate (NO_3^-) concentrations along the Pasur River estuary during the dry season.

Table 2. Pearson correlation coefficient matrix of four-months water quality parameters in the Pasur River estuary

	Temp	pH	Sal	DO	TDS	NO_3^-	NH_4^+	PO_4^{3-}
Temp	1							
pH	-0.234	1						
Sal	.853**	-0.017	1					
DO	-.900**	.423**	-.734**	1				
TDS	.859**	-0.025	.981**	-.732**	1			
NO_3^-	-0.171	-0.002	-0.114	0.169	-0.096	1		
NH_4^+	.452**	-.421**	.279*	-.416**	.288*	-0.092	1	
PO_4^{3-}	0.142	0.059	0.226	-0.103	0.245	-.326*	-0.088	1

Temp: temperature, Sal: salinity, DO: dissolved oxygen, TDS: total dissolved solids, NO_2^-: nitrite, NO_3^- : nitrate; NH_4^+: ammonium; PO_4^{3-}: phosphate). **Correlation is significant at p<0.01; *Correlation is significant at p<0.05

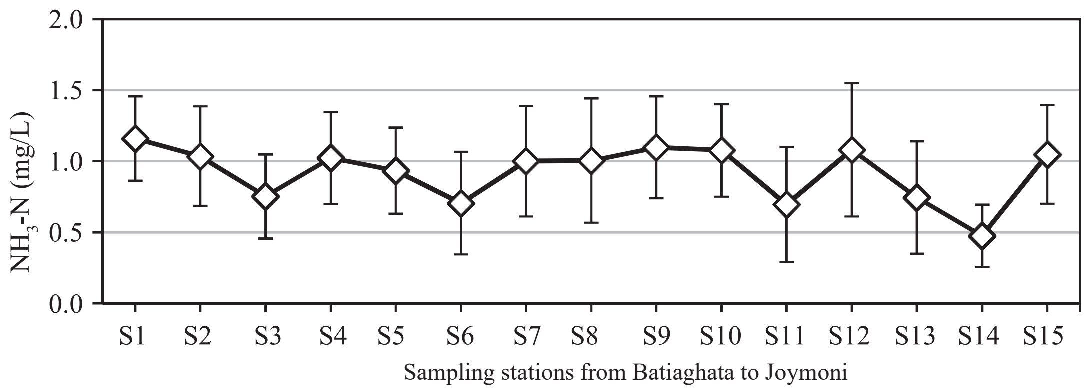

Fig. 7. Spatial variation of ammonia-nitrogen (NH_3-N) concentrations in the Pasur River estuary during the dry season.

with significantly higher concentrations ranging from 0.26 to 0.38 mg/L during the monsoon season and relatively lower amounts ranging from 0.02 to 0.08 mg/L during the post-monsoon and winter periods. Wahid *et al.* (2007) reported an average ammonia concentration of 0.054 mg/L, whereas the earlier studies reported that ammonia concentration ranged from 0.001 to 0.33 mg/L with an average of 0.043 mg/L (IWM, 2003). Dissolved inorganic nitrogen concentration also varied non-significantly among the sampling stations ($p>0.05$) but varied significantly among the sampling months ($p < 0.05$).

The study results showed lower concentration of phosphate at the sampling stations, ranging from 0.07 to 5.82 mg/L during the dry season with the highest mean value of 1.29 mg/L in March 2019 and the lowest mean value of 0.19 mg/L in January 2019 (Fig. 8).

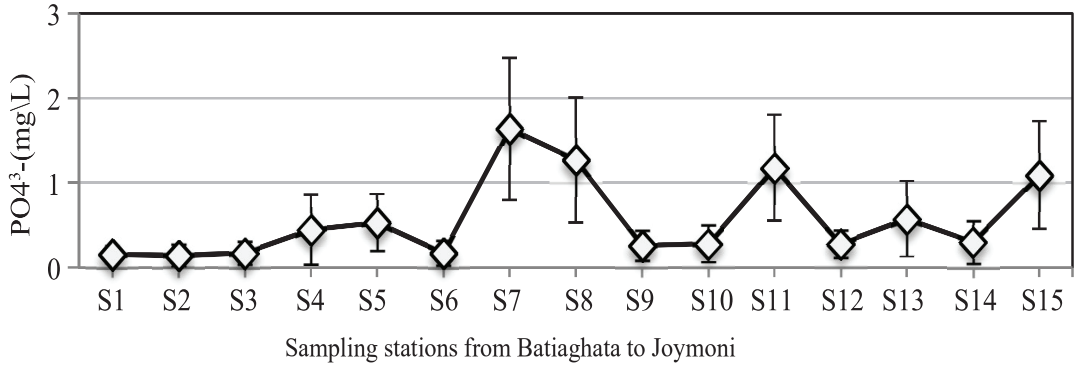

Fig. 8. Spatial variation of phosphate (PO_4^{3-}) concentrations along the Pasur River estuary during the dry season.

Phosphate concentration in the study area non-significantly varied among the sampling stations (*p> 0.05***)** but significant variation was found among the sampling months (*p< 0.05*). Rahaman *et al.* (2013a) also observed lower phosphate concentration ranging from 0.05 to 0.42 mg/L with an average of 0.12 mg/L in the Rupsha-Pasur river system. The average phosphate value of 0.323 mg/L was recorded in this study was higher than that of 0.115 mg/L, as has been reported by Wahid *et al.* (2007). IWM (2003) also recorded an average phosphate concentration of 0.115 mg/L in the Sundarbans mangrove estuarine system which was also relatively lower to the values that has been recorded during the present study. Phosphates compounds in water stimulate the growth of algae and other photosynthetic aquatic life, especially primary producers (Ji, 2008). The addition of phosphorus to the aquatic ecosystem is derived mainly from domestic sewage and the runoff from agricultural areas. A study conducted by Rahaman *et al.* (2013a) indicated a comparatively higher phosphate value of 0.314 to 1.347 mg/L in the post-monsoon season than winter and monsoon period (0.045-0.5 mg/L) in the Rupsha-Pasur river system.

In this study, the DIN:DIP ratios ranged between 2.24 and 9.32 (Fig. 9) with an average value of 5.02 during the dry season which is below the standard Redfield ratio (16:1). The upper estuarine region showed higher values of the ratio may be due to higher concentration of dissolved ammonia-nitrogen and lower phosphate concentrations, indicating P-limitation upstream. The ratios dropped gradually downstream as PO_4^{3-} increased and subsequent decreased in DIN concentrations which indicates N-limitation in the lower region. Klausmeier *et al.* (2004) reported that the optimal N:P ratios vary from 8.2 to 45.0, depending on the ecological conditions. Low N:P supply ratios may result in a significant shift in the phytoplankton assemblage to a community dominated by N-fixing cyanobacteria and a supply of atmospheric N_2 estimated to be up to 60% of total supply (Vrede *et al.*, 2009). Achary *et al.* (2014) reported that the comparison of ambient nutrient ratios with the Redfield ratio (N/P =16:1) showed a clear temporal variation in the factors that regulate the phytoplankton

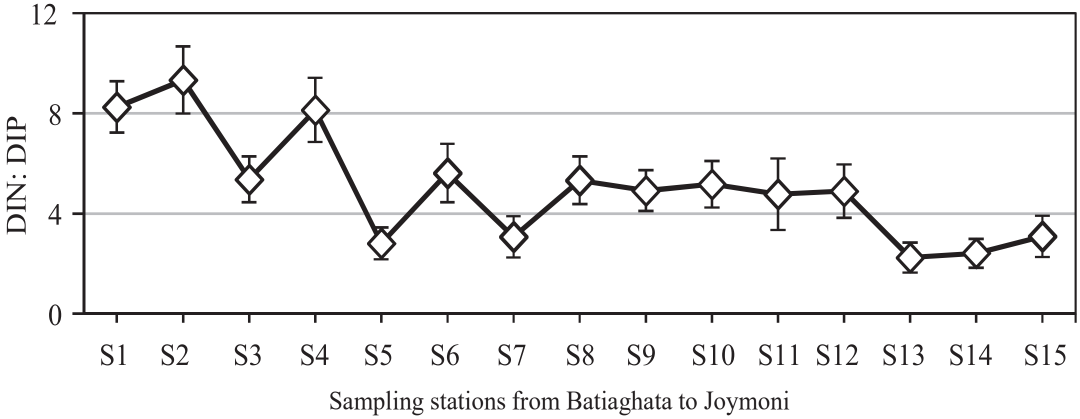

Fig. 9. Spatial variation of average DIN: DIP ratios along the Pasur River estuary during the dry season.

growth. The dry season was evident to have an acute N-limitation for algal growth whereas P-limitation was encountered during the wet season**.** Thangaradjou *et al.* (2014) also reported that the N:P ratio was less than Redfield ratio (16:1) during all seasons, indicating the Bay of Bengal is nitrate limited zone and confirmed that results from the principal component analysis The nitrogen-limitation in the PRE could be attributed to the denitrification process that effectively reduces nitrogen load from the estuarine systems or the competition among the microbial community for inorganic nitrogen requirements.

Conclusions

Comprehensive field study were conducted in the dry season to quantify important parameters of water quality in the Sundarbans intertidal mangrove forest. Dissolved oxygen concentration and pH in the PRE was within the desired range. Surface water temperature showed a significant positive correlation with salinity ($r = 0.853$), TDS ($r = 0.86$) and negatively correlated with DO ($r = -0.90$) at 1% significance level. Similarly, salinity also had a significant positive correlation with TDS ($r = 0.98$) but a negative correlation with DO ($r = -0.73$). Water temperature, pH, dissolved oxygen, salinity, nitrite, nitrate, ammonium ion, and phosphate concentration were found to be spatially non-significant ($p > 0.05$). The ratio between dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphate (DIP) was found lower than the Redfield standard value of 16 indicating that nitrogen was the limiting nutrient in the PRE during the dry season. The results of the present study will be providing information on water chemistry of the PRE in the Sundarbans mangrove ecosystem in order to find factors responsible for biodiversity loss andto maintain sound management of the Sundarbans mangrove ecosystem.

Conflicts of interest

The authors declare no competing financial interest.

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