Journal of Spatial Hydrology
Vol.11, No.1 Spring 2011

Spatial and Tidal Variations of Physico-Chemical Parameters in the Lower Gangetic Delta Region, West Bengal, India

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Abstract

The lower stretch of Gangetic delta in the Indian sub-continent is noted for its rich mangrove biodiversity, natural calamities, and livelihood-supporting matrix of millions of people and is the only mangrove base of Royal Bengal tiger (*Panthera tigris tigris*) in the planet Earth. The present trend of industrialization, urbanization and construction of barrage in the upstream zone has changed the landscape of the deltaic complex and the characteristics of the aquatic sub-system have also changed accordingly. This ecosystem offers an ideal site to study a number of physico-chemical parameters in relation to changing scenario of the region. The presence of heavily populated cities of Kolkata, Howrah and the Haldia industrial belt on the bank of the Hooghly estuary has made the mighty River Ganga highly vulnerable to anthropogenic stress. Spatial and tidal variations of important physico-chemical parameters in the Hooghly estuarine stretch of Gangetic delta complex were studied during the summer month April, 2008. The water quality reflects the impact of Bay of Bengal (sea) water almost on all the variables as revealed from the significant difference of parameter values in high and low tides (except surface water temperature and potassium). The 12 selected stations from the upstream to downstream regions exhibited uniformity with respect to surface water temperature. Significant spatial variations (at 5% level of significance) were observed with respect to parameters like surface water salinity, pH, alkalinity, DO, BOD, COD, NO_3, PO_4, SiO_3, extinction coefficient, SO_4, Na, K, Cl and total nitrogen. Along with tidal influences, the anthropogenic factors contributed by the adjacent cities and towns exert a regulatory influence on parameters like BOD, COD, NO_3, PO_4, extinction coefficient, SO_4 and total nitrogen.

***Keywords*:** Duncan analysis, physico-chemical parameter, spatial variation, tidal condition, Hooghly estuary

1. Introduction

Estuaries are important segment of biogeochemical cycle as they regulate the amount of river-borne major and minor elements entering the coastal environment and ultimately the deep ocean. Estuarine ecosystems are complex and dynamic due to strong gradients in chemical composition of water, variable suspended matter concentration and complex hydrodynamic processes. When river water mixes with seawater, different types of physical and chemical processes take place that may affect the partitioning of trace metals between particulate and dissolved phases and hence the composition of the deposited sediments (Forstner, 1983). Recently the importance of estuarine processes in modifying the chemistry of the materials accumulating and passing through this interface has been realized. Several geochemical processes, such as precipitation and flocculation of the dissolved and colloidal substances (Coonley, et al., 1971; Sholkovitz, 1976; Gobeil, et al., 1981), desorption-adsorption phenomenon, chemical diagenesis, and exchange with the bottom sediments (Yeats and Bewers, 1982) have been studied within the mixing zone. The present study area is one of the biggest estuaries of Indian sub-continent formed by the intersection of the River Ganga and the Bay of Bengal.

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The deltaic complex of the mighty River Ganga starts from the extreme upstream region of Farakka in the maritime state of West Bengal. The River Ganga divides into two arms about 40 km southeast below Farakka at Khejurtala village in Murshidabad district. The right arm of the river (which was the original course of Ganga) continues to flow south in West Bengal in the name of the Bhagirathi (called Hooghly in its downstream stretch), which crosses 500 km to the sea (Bay of Bengal). The left arm flows into Bangladesh after flowing by the border of Murshidabad for 60 km in the name of Padma and joined by the Brahmaputra and the Meghna, these rivers form the huge deltaic lobe (known as Sundarbans) before meeting the Bay of Bengal. The Hooghly estuary is the western most estuaries in the Gangetic delta and serves as the lifeline for millions of people inhabiting the mangrove dominated Sundarbans and highly urbanized city of Kolkata, Howrah and the newly emerging Haldia port–and–industrial complex (Figure 1). This coastal plain estuary lies approximately between 21°31' – 23°20'N and 87°45' - 88°45'E (Figure 1). Multifarious industries are situated on the banks of the Hooghly estuary, namely paper, textiles, chemicals, pharmaceuticals, plastics, shellac, food, leather, jute, pesticides etc (UNEP, 1982). A considerable quantity of toxic and hazardous substance is released into this important aquatic system through these industrial effluents along with huge organic load emanating from agricultural and shrimp culture activities and several non-point sources (such as discharges from fishing vessels and trawlers and run-off from adjacent landmasses). We conducted a rapid EIA study during 20th to 25th April, 2008. The month of April (premonsoon) in the present geographical locale is characterized by high salinity and minimum dilution factor which often pose threat to existing flora and fauna (Chaudhuri and Choudhury, 1994; Mitra and Banerjee, 2005). Because of the well-mixed nature and tidal variations of the estuary, physico-chemical parameters of surface waters were monitored in 12 selected stations during two tidal phases. The present study is important because of the fact that the estuary under study is tidal in nature and the changes in speciation of toxic elements are greatly influenced by tidal condition.

2. Methodology

The entire network of the present programme consists of the analysis of surface water physico-chemical characteristics of Hooghly estuarine water during April, 2008 with respect to selective variables like surface water temperature, salinity, pH, alkalinity, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), nitrate-nitrogen (NO_3-N), phosphate-phosphorus (PO_4-P), silicate-silicon (SiO_3-Si), extinction coefficient, chloride, sodium, potassium and total nitrogen. In order to document tidal variations, water samples were collected both during high tide and low tide periods. For each observational station, triplicate water samples were collected from the surface (depth range = 0 to 25 cm) during two tidal conditions at a distance of 50 meters of each other and analyzed for the selected parameters.

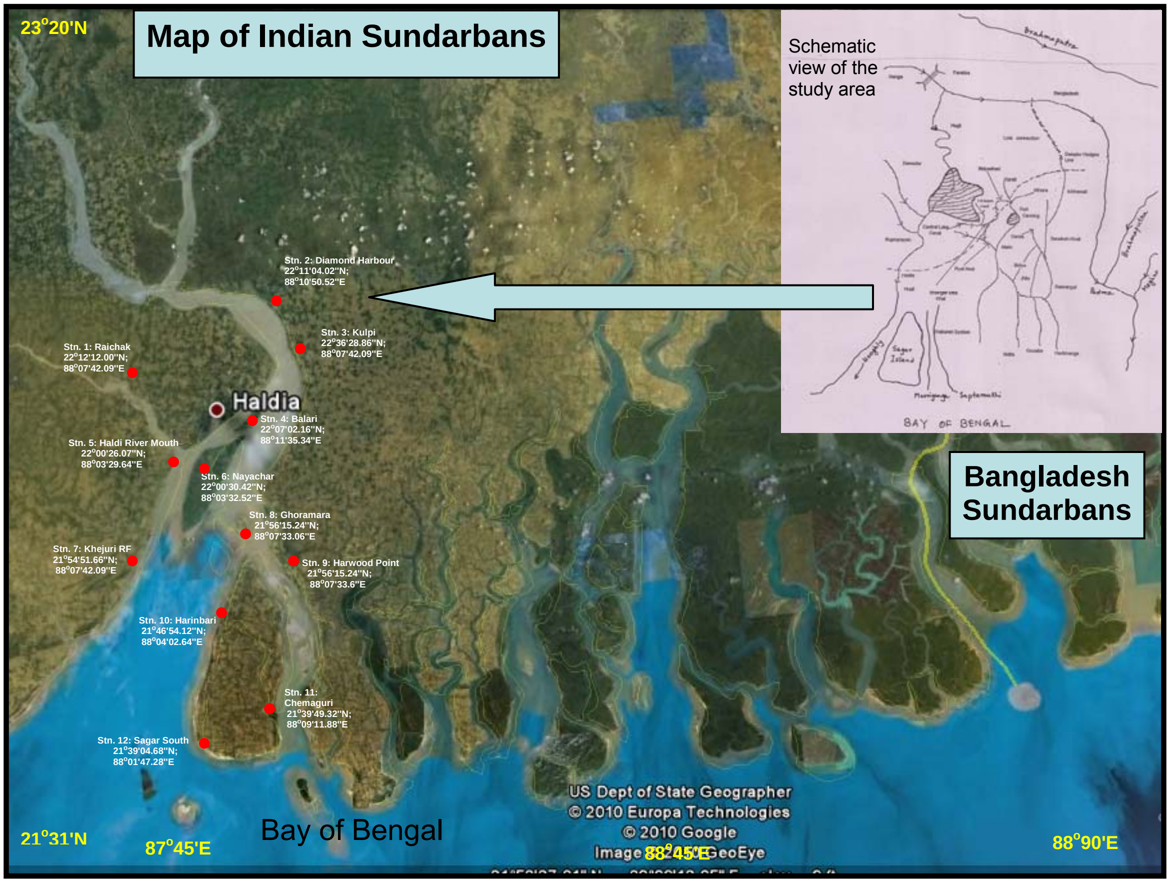


Figure 1. Map showing outline of the river system with zoom-in-map showing the location of sampling stations.

A Celsius thermometer was used to measure the surface water temperature. pH and alkalinity were measured in the field using a portable pH meter (sensitivity = ± 0.02) and micropipette titration method respectively. Surface water salinity was measured by refractometer and crosschecked in the laboratory by argentometric method. The salinity of the standard seawater procured from National Institute of Oceanography (NIO), under Government of India was analyzed by the same method and a deviation of 0.02% was obtained. Transparency was measured in the field by using a Secchi disc of 30 cm in diameter and converted into extinction coefficient using the formula K=1.44/D; where D is the maximum depth of Secchi disc visibility in meters (Raymont, 1980). D.O., BOD, COD, NO_3-N, PO_4-P, SiO_3-Si, chloride, sodium, potassium and total nitrogen were analyzed as per the procedure stated in Strickland & Parsons (1972) and APHA (2001). The precision of analysis is presented in Tables 1 and 2. All reagents for water quality analysis were obtained from Merck (Germany). High purity water obtained from Barnstead Nanopure-II water-purification system (Mumbai, India) was used in the experiment. All glassware was soaked in 10% (v/v) nitric acid for 24 hours and washed with deionized water prior to use. Finally the tidal and spatial variations of the selected physico-chemical variables were evaluated through Duncan's Multiple Range Test in order to determine the spatial and tidal variations of physico-chemical parameters. The alphabetical notations were used to mark the similarity and differences at a significance level of 5% (Gomeez and Gomez, 1984). The mean data points for each station and variable were generated by analyzing triplicate samples collected 50 m apart from the selected station coordinates.

3. Results and Discussion

3.1 Surface Water Temperature

The air temperature in the study area ranged from 37.2ºC to 37.6ºC with a mean value of 37.4ºC. The surface water temperature varied between 35.5±0.05 ºC to 35.6±0.07 ºC during high tide and 35.4±0.05 ºC to 35.5±0.05 ºC during low tide (Tables 1 and 2). The estuarine stretch did not exhibit significant tidal variation of surface water temperature (Figure 2); neither the spatial variation was prominent (Table 3). The uniformity in water temperature values is due to high specific heat of the aquatic phase, which enables water to resist much fluctuation of temperature than the adjacent landmasses. The aquatic sub-system in the present geographical locale therefore acts as a stabilizing factor upon the temperature profile of the Gangetic delta protecting the deltaic biodiversity from drastic thermal shock. The surface water temperature has considerable effect on phytoplankton population density by influencing the process of cyst germination (Ishikawa and Taniguchi, 1994; Blanco, 1995). The present spatial and tidal uniformity in surface water temperature, however, has the least probability to affect the plankton community of the estuary.

3.2 Surface Water Salinity

The surface water salinity values ranged from 2.48‰ to 22.08‰ during high tide (Table 1) and 1.39‰ to 20.43‰ during low tide (Table 2). The salinity values (mean of high tide and low tide) decreased from the downstream to the upstream zone (Figure 2) as per the order Stn 12 > Stn 11 > Stn 10 > Stn 9 > Stn 8 > Stn 7 > Stn 6 > Stn 4 > Stn 5 > Stn 3 > Stn 2 > Stn 1, and the significant spatial variation was confirmed by Duncan's Multiple Range Test (Table 3). Station 5 is the opening of Haldi river which is one of the major tributary of Hooghly estuary. The discharge of fresh water by the river is responsible for low salinity at station 5. La Fond (1954) explained that the decline of salinity of the surface waters is mainly due to the riverine contribution, which in the present study area is the effect of freshwater discharge from the rivers like Damodar and Rupnarayan. This is the reason why the upstream stations (stations 1, 2, 3 and 4) experience low salinity even during premonsoon. The discharge from the Farakka barrage has significant influence on salinity profile in the present study area (Mitra, et al., 2009). The barrage was constructed during 1975 to augment water flow in the Hooghly channel for the purpose of navigation, and during our study period the average discharge was (2.975±1.14) $\times 10^3$ m^3s^{-1} of freshwater per day. Five-year surveys (1999 to 2003) on water discharge from Farakka barrage revealed an average discharge of (3.4 ± 1.2) × 10^3 m^3s^{-1}. Higher discharge values were observed during the monsoon with an average of (3.2 ± 1.2) × 10^3 m^3s^{-1}, and the maximum of the order 4200 m^3s^{-1} during freshet (September). Considerably lower discharge values were recorded during pre-monsoon with an average of (1.2 ± 0.09) × 10^3 m^3s^{-1}, and the minimum of the order 860 m^3s^{-1} during May. During post-monsoon discharge values were moderate with an average of (2.1 ± 0.98) × 10^3 m^3s^{-1}. Significant tidal variation of surface water salinity (Table 3) in all the sampling stations along the estuary is being regulated by the discharge of freshwater from the barrage. During high tide water from Bay of Bengal (average salinity ~32 psu) enter the present estuarine zone due to which the salinity rises. However, during low tide the effect of fresh water discharge from the upstream rivers coupled with Farakka discharge lower the salinity of the study area. Such variation of salinity with tide was also documented by several earlier workers (NEERI, 1976; Mitra, 2000; Mukhopadhyay et al., 2006).

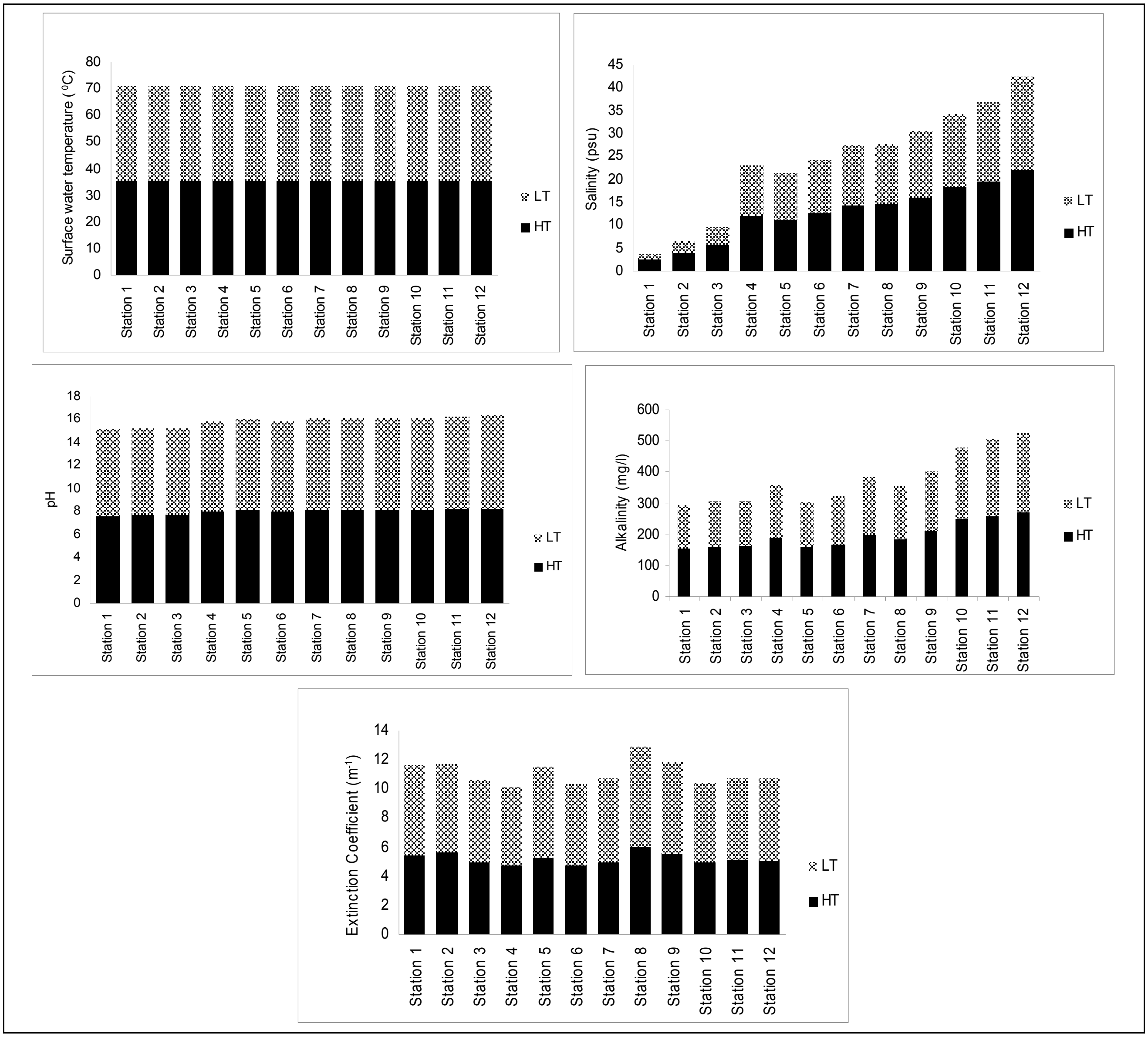


Figure 2. Tidal variation of surface water temperature, salinity, pH, alkalinity and extinction coefficient in the sampling stations.

3.3 Surface Water pH

The pH of the seawater showed variation within a small range. The values ranged from 7.65 to 8.20 during high tide condition (Table 1) and 7.52 to 8.15 during low tide condition (Table 2). The relatively higher values of pH during high tide in all the selected stations are the effect of intrusion of saline water from Bay of Bengal that penetrates almost 250 km upstream (Figure 2). The Hooghly estuary has a funnel shaped mouth towards the sea (Bay of Bengal). This induces maximum penetration of seawater in the upstream zone that caused alkaline effect even in the extreme uppermost zone around station 1. The pH values in the downstream stretch of the estuary (stations 10, 11 and 12) are approximately around 8.15, which is very close to the average pH of the estuarine mouth at lower long sand area (8.28), at the confluence of Bay of Bengal. Significant tidal and spatial variations of surface water pH as revealed through Duncan's analysis (Table 3) may thus be linked strongly to intrusion of seawater from the bay.

3.4 Alkalinity

Alkalinity of seawater is equal to the stoichiometric sum of the bases in solution. In the natural environment carbonate alkalinity tends to make up most of the total alkalinity due to the common occurrence and dissolution of carbonate rocks and presence of carbon dioxide in the atmosphere. Other common natural components that can contribute to alkalinity include borate, hydroxide, phosphate, silicate, nitrate, dissolved ammonia, the conjugate bases of some organic acids and sulphide. The major components contributing to alkalinity in the present geographical locale are carbonate rocks and other substances like nitrate, phosphate, ammonia etc. that originate from sewage, municipal wastes (from the city of Kolkata, Howrah and Haldia) and large number of shrimp culture units in the Gangetic delta region. The alkalinity values ranged from 155 to 270 mg/l during high tide condition (Table 1) and 137 to 258 mg/l during low tide condition (Table 2). Significant tidal and spatial variations of alkalinity (Table 3) were confirmed in the study stretch. The relatively higher alkalinity values in the downstream stations (stations 9, 10, 11and 12) may be related to the proximity of the stations to Bay of Bengal and presence of luxuriant mangrove vegetation in these zones (Figure 2). The higher pH values in the downstream stations are due to mixing of seawater with estuarine waters and by the mangrove photosynthetic activity, which utilize CO_2, thereby shifting the equilibrium towards high alkalinity (Ruttner, 1953). Mangroves in the present study area are luxuriant in and around stations 9, 10, 11 and 12. Alkalinity is important for fish and aquatic life because it protects or buffers against rapid pH changes. Living organisms, especially aquatic life, function best in a pH range of 6.0 to 9.0. Higher alkalinity levels in surface waters of downstream stations will buffer acid rain and other acid wastes and prevents pH changes that are harmful to aquatic life. The downstream stations of Gangetic delta are therefore relatively less stressful in comparison to upstream zones.

3.5 Extinction Coefficient

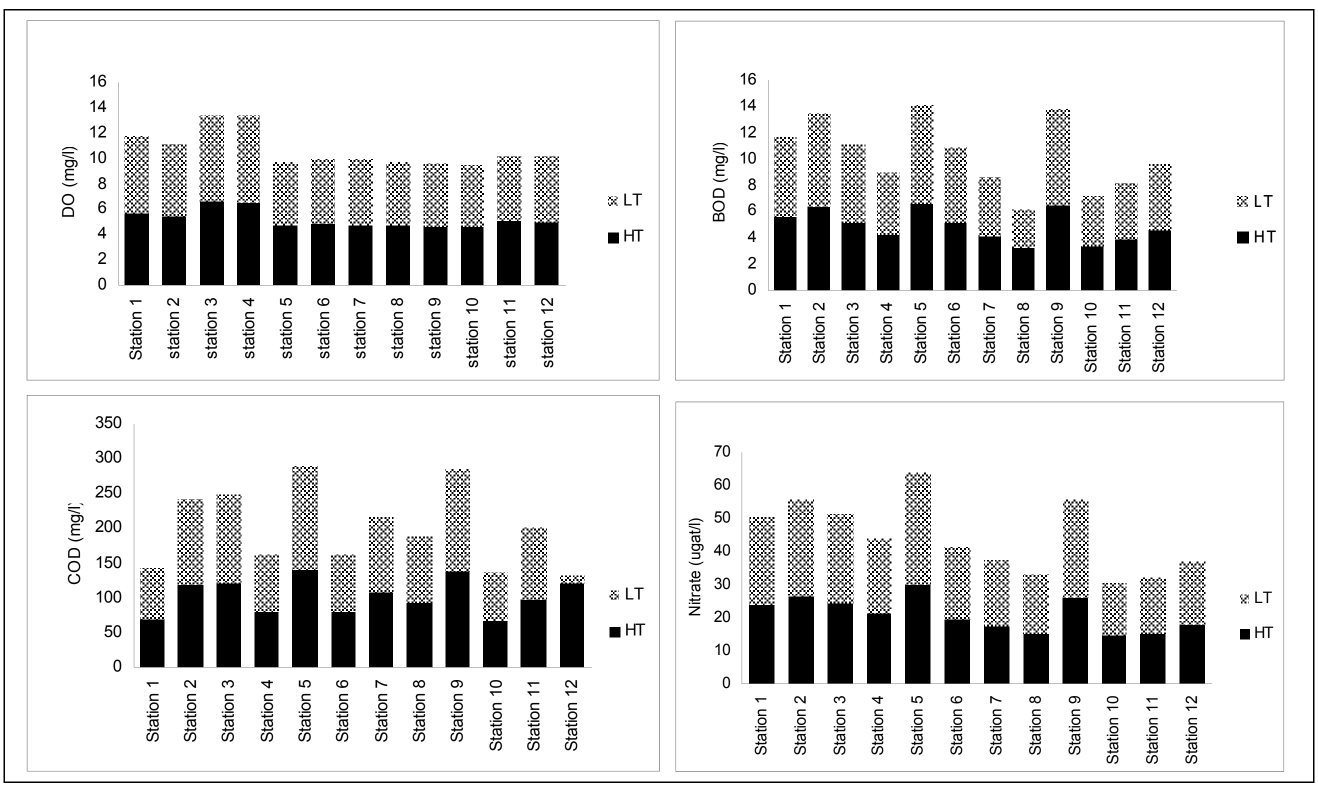
The extinction coefficient (K) which is a measure of the reduction of light intensity in a vertical column of sea water ranged from 4.80 to 6.05 m^{-1} during high tide (Table 1) and 5.29 to 6.89 m^{-1} during low tide (Table 2). The high value of extinction coefficient around station 5 may be related to the location of the station near Haldia port and industrial complex that discharge considerable amount of domestic sewage and industrial effluents. Station 9 is a busy market place with fish landing units and passenger vessel jetties, which generate considerable amount of sewage. The domestic sewage contains colloidal and finely divided suspended matter that impact turbidity in the water column thereby raising the value of extinction coefficient. Similar lowering of water transparency was confirmed by Satyanarayana, et al. (1990) while working in the other Indian estuaries. Extinction coefficient was also higher around station 8, which is an erosion prone zone contributing appreciable load of silt particles to ambient water (Hazra, et al., 2002). The high value of extinction coefficient at stations 1 and 2 is mainly attributed to its location to the highly urbanized city of Kolkata that release enormous load of municipal waste almost without any treatment (Mukherjee et al., 1993; Mitra, 1998 and Mitra et al., 2009). Significant higher extinction coefficient values during low tide compared to high tide (Table 3) indicate more riverine contribution of suspended particulate matter from the populated cities and towns of the upstream zone (Figure 2).

3.6 Dissolved Oxygen

Dissolved oxygen values ranged from 4.60 mg/l to 6.63 mg/l during high tide (Table 1) and 4.81 mg/l to 6.88 mg/l during low tide (Table 2). The higher values of DO in the upstream stations (stations 1, 2, 3 and 4) may be apparently due to DO rich freshwater conveyed through rivers and more dilution of the zone with Farakka barrage discharge (Figure 3). Significant tidal variation of DO (Table 5) with relatively higher value during low tide period is the result of more freshwater during this phase of the tidal cycle. The contributory role of fresh water to increase dissolved oxygen was confirmed by Nair (1985) while working in the Kalpakkam waters. Significant spatial variation of DO in the estuarine stretch (Table 5) may be attributed to dilution factor (high in the upstream stations) and anthropogenic pressure in and around selected stations *e.g.,* presence of Haldia port- cum-industrial complex (at station 4), passenger jetties, fish landing units and busy markets draining untreated sewage (at station 9) in to the estuary. Earlier workers in the present study area reported on low DO levels much below the optimum level of 3-4 ppm (Sharma, 1981; De, 1987). It has been documented that in addition to various industrial discharges (jute mills, textile mills, paper and pulp mills, tanneries, distilleries, etc.), about 360 outfalls on both sides of the river, continuously discharge community sewage into the water course, virtually without any treatment (Mukherjee et al., 1993). However, the present DO level is much above this optimum value, which speaks in favour of the stringent actions taken by the Central and the State Pollution Control Boards in recent time (WBPCB, 2003).

3.7 BOD and COD

In the present study the BOD values ranged from 3.2 to 6.6 mg/l during high tide condition (Table 1) and 3.0 to 7.5 mg/l during low tide condition (Table 2). The COD values ranged from 66 to 140 mg/l during high tide condition (Table 1) and 70 to 149 mg/l during low tide condition (Table 2). High BOD, COD and low DO levels observed at stations 2, 5 and 9 may be attributed to discharge of untreated municipal sewage and effluents from industries (Figure 3). The COD is used as a measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant. The mushroom growth of hotels, resorts and presence of fish landing centres in and around stations 2 and 9 may be another prominent cause of high BOD and COD values. Most pristine rivers have a 5-day BOD below 1 mg/l and moderately polluted rivers have a BOD value in the range of 2 to 8 mg/l (WBPCB, 2003). The present estuarine stretch is therefore not congenial in terms of organic load and nutrients. The anthropogenic activities of diverse nature have caused significant spatial variation of BOD and COD values (Table 3). The relatively higher dilution of the system during low tide brings more sewage from the upstream stations adjacent to the thickly populated city of Kolkata and increased BOD and COD values significantly (Table 3).



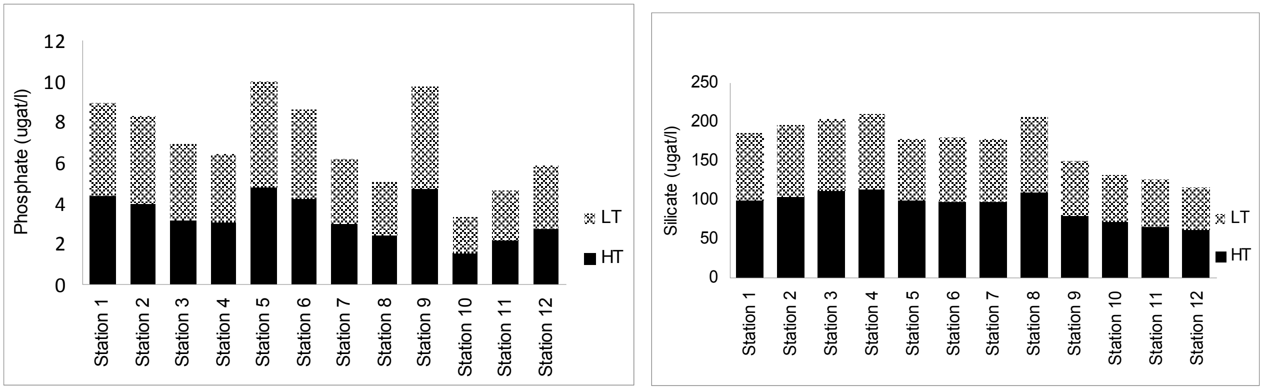


Figure 3. Tidal variation of surface water DO, BOD, COD, nitrate, phosphate and silicate in the sampling stations.

Table 1: Precision level and range of surface water physico-chemical variables at high tide condition during April 2008 (n = 3; Figures in bracket indicate range)

Parameter	Precision	Detection limit	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8	Station 9	Station 10	Station 11	Station 12
Water Temperature (ºC)	± 0.05 ºC	0-100 ºC	35.5 (35.2-35.6)	35.5 (35.3-35.6)	35.6 (35.3-35.7)	35.6 (35.2-35.8)	35.5 (35.1-35.6)	35.5 (35.2-35.8)	35.6 (35.3-35.8)	35.6 (35.4-35.7)	35.6 (35.2-35.7)	35.6 (35.3-35.8)	35.6 (35.3-35.9)	35.6 (35.4-35.8)
Salinity (‰)	± 0.5 ‰	0-100 ‰	2.48 (2.44-2.50)	3.97 (3.94-4.01)	5.65 (5.60-5.68)	12.14 (12.00-12.19)	11.24 (11.20-11.28)	12.80 (12.76-12.82)	14.41 (14.38-14.45)	14.70 (14.65-14.72)	16.02 (16.00-16.09)	18.34 (18.30-18.38)	19.55 (19.50-19.58)	22.08 (22.00-22.11)
pH	± 0.02	1-14	7.65 (7.61-7.66)	7.68 (7.64-7.70)	7.70 (7.68-7.72)	8.00 (7.88-8.01)	8.10 (8.09-8.12)	8.00 (7.99-8.04)	8.10 (8.08-8.11)	8.10 (8.09-8.12)	8.10 (8.09-8.13)	8.15 (8.12-8.18)	8.20 (8.18-8.24)	8.20 (8.17-8.22)
Alkalinity (mg/l)	± 5 mg/l	10-2000 mg/l	155 (152-157)	159 (156-161)	162 (160-164)	190 (188-193)	160 (158-162)	169 (165-172)	200 (198-204)	185 (182-187)	210 (205-212)	250 (245-253)	260 (258-264)	270 (268-274)
DO (mg/l)	0.3 mg/l	2-20 mg/l	5.71 (5.68-5.75)	5.43 (5.40-5.48)	6.63 (6.60-6.68)	6.55 (6.52-6.59)	4.8 (4.77-4.82)	4.91 (4.89-4.93)	4.80 (4.78-4.82)	4.75 (4.71-4.78)	4.60 (4.55-4.62)	4.68 (4.66-4.73)	5.05 (5.01-5.09)	5.02 (5.00-5.04)
BOD (mg/l)	± 0.2 mg/l	1-20 mg/l	5.6 (5.4-5.7)	6.4 (6.0-6.7)	5.2 (5.0-5.7)	4.3 (4.0-4.7)	6.6 (6.1-6.8)	5.2 (5.0-5.6)	4.1 (3.8-4.4)	3.2 (2.9-3.5)	6.5 (6.1-6.8)	3.4 (3.1-3.6)	3.9 (3.7-4.2)	4.6 (4.4-4.9)
COD (mg/l)	± 0.5 mg/l	10-300 mg/l	69 (65-72)	118 (115-120)	120 (118-124)	79 (75-82)	140 (138-145)	81 (79-85)	107 (105-110)	93 (91-98)	138 (135-142)	66 (65-71)	98 (96-102)	120 (117-125)
NO_3 (µgat/l)	± 0. 2 µgat/l (1µgat/l at 1.7 cm. Cell)	0.1-45 µgat/l	23.78 (23.75-23.82)	26.55 (26.50-26.59)	24.50 (24.45-24.52)	21.09 (21.07-21.12)	29.89 (29.82-29.93)	19.78 (19.72-19.81)	17.44 (17.41-17.49)	15.40 (15.35-15.47)	25.99 (25.92-26.01)	14.67 (14.62-14.71)	15.34 (15.30-15.39)	17.84 (17.81-17.90)
PO_4 (µgat/l)	± 0. 3 µgat/l (3 µgat/l at 1.7 cm. Cell)	0.05-5 µgat/l	4.34 (4.30-4.38)	3.98 (3.92-4.02)	3.20 (3.14-3.22)	3.09 (3.01-3.15)	4.77 (4.73-4.82)	4.18 (4.12-4.24	2.98 (2.93-3.05)	2.41 (2.38-2.47)	4.72 (4.69-4.77)	1.56 (1.50-1.64)	2.2 (2.15-2.25)	2.79 (2.74-2.82)
SiO_3 (µgat/l)	± 1.5 µgat/l	20-300 mgat/l	99.87 (98.85-99.90)	103.65 (103.62-103.70)	111.9 (111.85-111.92)	114.45 (114.39-114.47)	99.4 (99.32-99.46)	98.34 (98.32-98.40)	98.70 (98.66-98.74)	110.05 (110.00-110.09)	79.78 (79.75-79.86)	71.22 (71.18-71.26)	66.1 (66.07-66.13)	62.75 (62.71-62.80)
Extinction Coefficient (m^{-1})	± 0.2 m^{-1}	2-10 m^{-1}	5.5 (5.43-5.53)	5.61 (5.57-5.65)	4.98 (4.90-5.01)	4.80 (4.75-4.82)	5.30 (5.25-5.32)	4.80 (4.75-4.84)	4.99 (4.93-5.05)	6.05 (6.01-6.08)	5.52 (5.49-5.57)	50 (4.91-5.04)	5.13 (5.10-5.17)	5.05 (4.99-5.07)
SO_4 (mg/l)	± 3 mg/l	5-1500 mg/l	497 (495-500)	502 (498-504)	584 (580-589)	713 (710-719)	665 (661-670)	681 (674-686)	742 (739-749)	858 (854-862)	962 (956-969)	1041 (1038-1047)	1123 (1120-1129)	1200 (1198-1210)
Na (mg/l)	± 5 mg/l	10-15,000 mg/l	715 (710-719)	1189 (1183-1192)	1714 (1711-1720)	3685 (3680-3691)	3394 (3388-3396)	3870 (3867-3872)	4397 (4394-4400)	4231 (4227-4235)	4872 (4868-4876)	5605 (5601-5610)	5877 (5872-5880)	6619 (6614-6623)
K (mg/l)	± 3 mg/l	10-500 mg/l	27 (23-31)	44 (41-49)	62 (59-65)	134 (131-137)	124 (120-129)	142 (139-148)	159 (156-163)	163 (159-1670)	177 (173-182)	203 (200-208)	217 (214-227)	245 (240-251)
Cl (mg/l)	± 10 mg/l	100-20,000 mg/l	1305 (1301-1310)	2175 (2172-2180)	3099 (3094-3103)	6599 (6594-6604)	6054 (6051-6060)	6991 (6985-6994)	7861 (7858-7866)	8005 (8001-8010)	8575 (8571-8583)	9200 (9199-9209)	10079 (10072-10085)	11065 (11063-11072)
Total N (µgat/l)	± 0.5 µgat/l	5-75 mg/l	28 (21-30)	31 (28-33)	42 (39-48)	37 (34-42)	57 (53-63)	49 (44-52)	23 (21-29)	21 (18-25)	40 (37-45)	28 (23-36)	31 (28-37)	44 (41-50

Table 2: Precision level and range of surface water physico-chemical variables at high tide condition during April, 2008
(n=3; Figures in bracket indicate range)

Parameter	Precision	Detection limit	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8	Station 9	Station 10	Station 11	Station 12
Water Temperature (ºC)	± 0.05 ºC	0-100 ºC	35.4 (35.3-35.6)	35.4 (35.2-35.5)	35.4 (35.1-35.5)	35.4 (35.3-35.6)	35.4 (35.1-35.7)	35.5 (35.2-35.8)	35.5 (35.4-35.9)	35.5 (35.1-35.6)	35.5 (35.4-35.7)	35.5 (35.3-35.9)	35.5 (35.1-35.8)	35.5 (35.0-35.7)
Salinity (‰)	± 0.5 ‰	0-100 ‰	1.39 (1.34-1.43)	2.66 (2.59-2.72)	3.98 (3.92-4.03)	10.96 (10.91-11.02)	10.05 (10.01-10.09)	11.50 (11.46-11.55)	12.85 (12.81-12.90)	13.02 (12.97-13.08)	14.50 (14.44-14.53)	15.98 (15.92-16.03)	17.49 (17.41-17.53)	20.43 (20.38-20.49)
pH	± 0.02	1-14	7.52 (7.49-7.54)	7.55 (7.51-7.59)	7.55 (7.52-7.58)	7.85 (7.82-7.87)	7.90 (7.88-7.93)	7.80 (7.77-7.82)	8.00 (7.99-8.03)	8.00 (7.78-8.01)	8.00 (7.99-8.04)	8.00 (7.96-8.01)	8.06 (8.02-8.08)	8.15 (7.12-8.18)
Alkalinity (mg/l)	± 5 mg/l	10-2000 mg/l	137 (131-142)	146 (142-153)	145 (140-149)	170 (167-174)	144 (141-149)	154 (149-157)	183 (179-188)	169 (164-173)	193 (188-197)	231 (229-236)	247 (243-252)	258 (254-263)
DO (mg/l)	0.3 mg/l	2-20 mg/l	6.01 (5.99-6.05)	5.72 (5.69-5.78)	6.79 (6.75-6.82)	6.88 (6.85-6.93)	4.91 (4.88-5.96)	5.06 (5.02-5.09)	5.19 (5.11-5.24)	5.02 (4.98-5.06)	4.97 (4.93-5.01)	4.81 (4.78-4.87)	5.15 (5.10-5.19)	5.19 (5.17-5.27)
BOD (mg/l)	± 0.2 mg/l	1-20 mg/l	6.0 (5.7-6.5)	7.0 (6.5-7.4)	5.9 (5.4-6.2)	4.6 (4.2-4.9)	7.5 (7.2-8.0)	5.6 (5.1-6.2)	4.5 (4.2-4.9)	3.0 (2.7-3.5)	7.3 (6.9-7.7)	3.8 (3.2-4.3)	4.3 (4.0-4.8)	5.0 (4.7-5.5)
COD (mg/l)	± 0.5 mg/l	10-300 mg/l	73 (69-76)	125 (121-129)	128 (123-132)	82 (78-89)	149 (144-153)	82 (77-86)	109 (105-114)	94 (89-97)	148 (145-153)	70 (66-73)	102 (97-107)	123 (119-128)
NO_3 (µgat/l)	± 0. 2 µgat/l (1µgat/l at 1.7 cm. Cell)	0.1-45 µgat/l	26.85 (26.81-26.90)	29.01 (28.99-29.03)	27.02 (26.98-27.07)	23.00 (22.92-23.03)	33.99 (33.92-34.01)	21.56 (21.52-21.60)	19.85 (19.80-19.91)	17.45 (17.41-17.49)	29.75 (29.71-29.80)	15.88 (15.83-15.94)	16.83 (16.78-16.85)	19.05 (19.01-19.07)
PO_4 (µgat/l)	± 0. 3 µgat/l (3 µgat/l at 1.7 cm. Cell)	0.05-5 µgat/l	4.59 (4.56-5.05)	4.28 (4.25-4.32)	3.67 (3.65-3.73)	3.28 (3.24-3.33)	5.22 (5.19-5.27)	4.38 (4.36-4.43)	3.22 (3.18-3.28)	2.61 (2.58-2.66)	5.04 (5.00-5.08)	1.76 (1.70-1.81)	2.44 (2.39-2.51)	3.05 (3.00-3.08)
SiO_3 (µgat/l)	± 1.5 µgat/l	20-300 mgat/l	85.6 (85.57-85.66)	92.00 (91.99-92.10)	92.87 (92.83-92.91)	94.98 (94.93-95.07)	79.2 (79.15-79.22)	80.87 (80.83-80.91)	78.66 (78.60-78.69)	96.4 (96.38-96.44)	69.54 (69.52-69.58)	61.22 (61.17-61.26)	60.64 (60.61-60.67)	53.75 (53.71-53.79)
Extinction Coefficient (m^{-1})	± 0.2 m^{-1}	2-10 m^{-1}	6.09 (6.01-6.11)	6.12 (6.07-6.18)	5.63 (5.58-5.69)	5.29 (5.22-5.34)	6.2 (6.14-6.23)	5.5 (5.43-5.52)	5.73 (5.69-5.78)	6.89 (6.83-6.93)	6.31 (6.26-6.35)	5.45 (5.40-5.47)	5.63 (5.58-5.66)	5.66 (5.62-5.69)
SO_4 (mg/l)	± 3 mg/l	5-1500 mg/l	349 (344-351)	418 (414-422)	496 (491-502)	645 (642-650)	578 (572-583)	590 (588-596)	600 (593-603)	759 (753-764)	830 (827-835)	922 (919-927)	916 (911-920)	1106 (1101-1111)
Na (mg/l)	± 5 mg/l	10-15,000 mg/l	436 (432-440)	802 (797-806)	1200 (1194-1202)	3259 (3256-3264)	2998 (2992-3002)	3469 (3464-3472)	3856 (3852-3860)	3870 (3863-3875)	4355 (4351-4358)	4894 (4890-4906)	5245 (5239-5252)	6100 (6098-6107s)
K (mg/l)	± 3 mg/l	10-500 mg/l	22 (19-26)	39 (32-43)	59 (52-61)	129 (124-133)	119 (116-123)	133 (129-140)	152 (148-157)	158 (155-163)	170 (168-176)	197 (193-201)	212 (209-217)	236 (231-243)
Cl (mg/l)	± 10 mg/l	100-20,000 mg/l	809 (799-815)	1460 (1458-1465)	2150 (2146-2153)	5943 (5937-5948)	5507 (5502-5511)	6150 (6148-6153)	6991 (6989-6995)	7139 (7133-7145)	7875 (7871-7879)	8445 (8442-8450)	9263 (9257-9268)	10236 (10232-10241)
Total N (µgat/l)	± 0.5 µgat/l	5-75 mg/l	33 (29-39)	46 (42-51)	50 (46-53)	45 (42-50)	68 (62-71)	52 (47-54)	31 (28-36)	27 (23-32)	51 (44-56)	39 (36-44)	43 (37-46)	57 (53-61)

Table 3: Duncan's Multiple Test Range to determine the spatial and tidal variation of hydrological parameters

Station	Water Temperature		Salinity (‰)		pH		Alkalinity (mg/l)		DO (mg/l)		BOD (mg/l)		COD (mg/l)		NO_3 (µgat/l)		PO_4 (µgat/l)		SiO_3 (µgat/l)		Extinction Coefficient (m^{-1})		SO_4 (mg/l)		Na (mg/l)		K (mg/l)		Cl (mg/l)		Total N (µgat/l)	
	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT
1	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
2	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
3	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
4	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
5	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
6	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
7	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
8	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
9	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
10	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
11	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d
12	a	a	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	a	a	b	a	b
	c	c	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	d	c	c	c	d	c	d

a-a combination = tidal similarity, a-b combination = tidal variation, c-c combination = spatial uniformity, c-d combination = spatial variation; the similarity and differences are at significant level of an alpha 0.05, HT = High Tide, LT = Low Tide

3.8 Nutrients

Nitrate represents the highest oxidized state of nitrogen. The most important source of nitrate is biological oxidation of organic nitrogenous substances, which originates through sewage and industrial wastes. Nitrate, phosphate and silicate usually exhibited higher values towards the upstream stations. This trend is in accordance with the earlier work of Mukhopadhyay et al. (2006). The nitrate values ranged from 14.67 to 29.89 µgat/l during high tide (Table 1) and 15.88 to 33.99 µgat/l during low tide (Table 2). Phosphate values ranged from 1.56 to 4.77 µgat/l during high tide (Table 1) and 1.76 to 5.22 µgat/l during low tide (Table 2). The silicate values showed an increasing trend while proceeding from the coastal zone to riverine zone with significantly low values at stations 9, 10, 11 and 12 near the bay (Figure 3). This is because silica is associated with the silt particles that dominate in the upstream region. Another possible cause of the low silicate value in the downstream region is the abundance of siliceous diatom which incorporates silica from the ambient sea water as source of nutrient (Banerjee, 2004). The values ranged from 62.75 to 114.45 µgat/l during high tide (Table 1) and 53.75 to 96.40 µgat/l during low tide (Table 2). Observations of increase in nutrients with decrease in salinity have been reported in the Indian estuaries by various studies (*e.g.*, Sankaranarayanan and Qasim, 1969; Solarzano and Ehrilich, 1975). The considerable nutrient load in the present study area may be attributed to: (i) increased industrialization and urbanization, (ii) unplanned expansion of shrimp culture units, (iii) large-scale use of fertilizers (urea, super-phosphate etc.) for boosting crop production in mono-cropping areas of the islands of Sundarbans, (iv) mushrooming of tourism units (v) considerable number of unorganized fish landing sites with no provision for proper sewage and garbage disposal, (vi) increased number of fishing vessels and trawlers (Mukherjee, et al., 2007), (vii) erosion of embankments and mudflats due to wave action and (ix) contribution of litters and mangrove detritus from the adjacent landmasses. The significant tidal variations of nutrients (Table 3) is the net effect of freshwater flow from upstream regions that bring contributions from the industries, shrimp farms, tourism units, fish landing stations and agricultural lands.

The variations of nutrients were significant between two tidal conditions and also with space (Table 3). The higher nitrate and phosphate levels in and around stations 2, 5 and 9 are the results of anthropogenic activities. The considerable nutrient load around station 8 is the result of erosion activities due to sea level rise (Hazra, et al., 2002). The spatial oscillation of nutrients (nitrate, phosphate and silicate) is therefore the resultant of several causes and it is extremely difficult to isolate the exclusive contribution of each factor in the nutrient budget of the estuary.

3.9 Sulphate

Sulphate is a major constituent of seawater and is used as an electron acceptor for the oxidation of organic matter in the absence of oxygen. The site of sulphate reduction is more often on the surface of sediments than the water column. The reaction kinetics of sulphate reduction and associated sulphur cycling depend on the interplay between sulphate concentration and availability of organic matter (Goldhaber and Kaplan, 1974). In coastal sediments, reduction of sulphate through respiratory metabolism of sulphate by the sulphate reducing bacteria is reported to be a common phenomenon (Jorgensen, 1977). A principal controlling factor of sulphate reduction is the abundance and type of organic matter present (Berner, 1972).

In the present study the sulphate values ranged from 497 to 1200 mg/l during high tide condition (Table 1) and 349 to 1106 mg/l during low tide condition (Table 2). Significant spatial and tidal variations of sulphate were observed in the estuarine stretch of the delta complex (Table 3). Sulphate exhibited a higher concentration in the downstream stations under the influence of seawater mixing (Figure 4). The relatively lower concentration of sulphate in the upper estuarine stretch may be due to consumption of the anion by paddy fields along the upstream stations, whereas removal is compensated in the lower part of the estuary by the contribution of seawater and decay of organic matter from mangroves. Similar observations were reported by several researchers. According to Ramanathan et al. (1993) seawater input along with resuspension mixing (turbidity and mixing) of decayed organic matter and oxidation of buried biogenic materials result in enhanced sulphate levels in mangrove waters. The sulphate value is generally higher during high tide due to the intrusion of seawater from Bay of Bengal which has high concentration of sulphate ions than river water.

3.10 Chloride

Chloride is the major ion in seawater, which regulates the estuarine salinity. Chloride level exerts considerable influence on the biotic community of marine and estuarine system. It has got biological effects at different levels such as at cellular level, in animal tissues and is also responsible for mortality of organisms. Fishes in saline water with considerable chloride concentrations must maintain proper concentration of salts in the body fluid and prevent excessive loss of water (Parry, 1966; Conte, 1969) for basic physiology of osmoregulation. This requires various adaptive mechanisms and the expenditure of energy since osmotic concentration in fishes is less than that of seawater. Osmoregulatory mechanism includes drinking water and excretion or secretion of accumulating salts. These mechanisms are aided by limited skin permeability of marine adapted fish. Studies on marine fish have shown that the first detectable damage occurs in the blood cells. Osmoregulatory dysfunction and disturbance to calcium and magnesium levels precede haemolysis. These effects have been observed in number of species (Hose, et al., 1983; Cohen and Valenzuela, 1977; Middaugh, et al., 1977; Buckley, et al., 1976). The degree of damage by chloride ions has been reported to occur at a concentration of 0.1 mg/l in 30 minutes (Hose et al., 1983). Kidney damage has been observed in a chlorine concentration as low as 0.06 to 0.3 mg/l (Bass and Heath, 1977). Other than fishes, several marine invertebrate species (*Amphiporeia virginiana and Eohaustorius washingtonianus*) are also affected by lethal concentration of chlorine in ambient waters. In the present study the chloride values ranged from 1305 to 11065 mg/l during high tide condition (Table 1) and 809 to 10236 mg/l during low tide condition (Table 2). The higher values of chloride in the downstream stations are due to proximity of the stations to Bay of Bengal (Figure 4). Significant spatial and tidal variations of chloride ion in the estuarine stretch (Table 3) confirm the influence of seawater intrusion in the upstream zone of the Gangetic delta region. The discharge from Farakka barrage, however, acts as a shield against seawater penetration in the upper estuarine stretch due to which the values were lower around stations 1, 2 and 3. The saline soil (range 2.5 to 5 psu) and saline ground water in Sundarbans region is another plausible reason for high chloride level in the downstream stations as reported by Das and Singh (1996) while working in the Vellar estuary (south India).

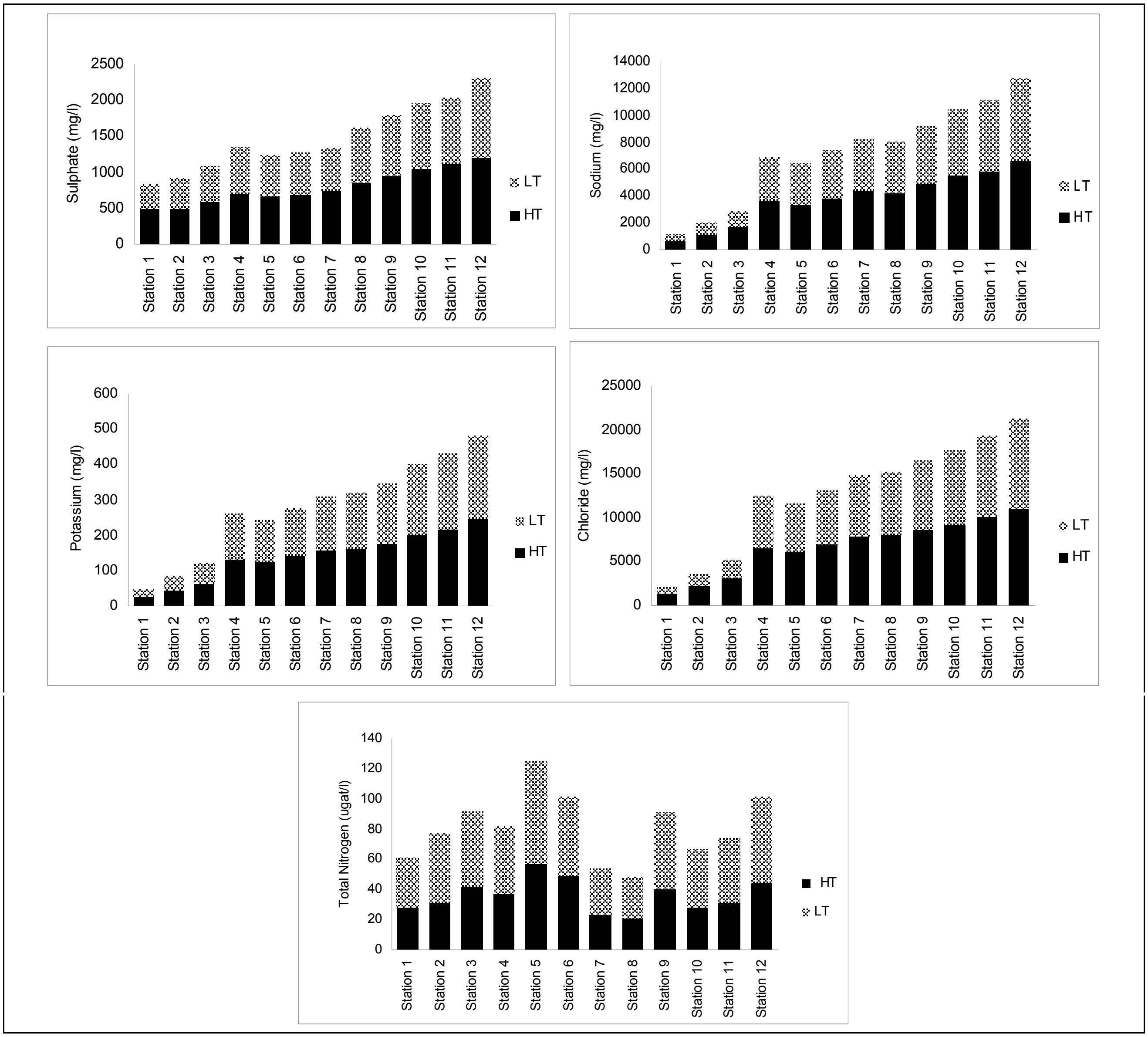


Figure 4. Tidal variation of surface water sulphate, sodium, potassium, chloride and total nitrogen in the sampling stations.

3.11 Sodium

The sodium values ranged from 715 to 6619 mg/l during high tide (Table 1) and 436 to 6100 mg/l during low tide condition (Table 2), and represent the dominant cation in the system contributing to 28% of surface water salinity. These values are comparable to sodium level in the water of Pichavaram mangrove, Vellar estuary, and Coleroon estuary in the southeast coast of India (Ramanathan *et al*., 1999). The progressive increase of sodium from stations 1 to 12 is due to proximity of the downstream stations to Bay of Bengal, and the higher values during high tide are the result of intrusion of seawater from the bay (Figure 4). Significant tidal and spatial variations of the cation are confirmed by the Duncan Multiple Range Test (Table 3).

3.12 Potassium

Seawater contains about 400 ppm potassium. It tends to settle, and consequently ends up in sediment mostly. Rivers generally contains about 2-3 ppm potassium. This difference is mainly caused by a large potassium concentration in oceanic basalts. Calcium rich granite contains up to 2.5% potassium. In water this element is mainly present as K^+ (aq) ions. Potassium is a naturally abundant radioactive potassium isotope. Seawater contains a natural concentration of about 4.5×10^{-5} mg/l. Potassium occurs in various minerals, from which it may be dissolved through weathering processes. Some clay minerals also contain potassium, which ends up in seawater through natural processes and settles in sediments.

In the present study the potassium values ranged from 27 to 245 mg/l during high tide condition (Table 1) and 22 to 236 mg/l during low tide condition (Table 2). Unlike other variables, the tidal difference of potassium is not as significant (Figure 4). The spatial variation of the cation is highly significant (Table 3). The higher values of potassium in the lower estuarine stretch are due to deposition of clay particles in the high saline downstream stations at the apex of Bay of Bengal. The extreme erosion in the lower estuarine stretch is another prominent cause of origin of clay particles enriched with potassium. Earlier study in this estuarine system recorded lower potassium level in the upper estuary in comparison to downstream zone (Chaudhuri and Choudhury, 1994).

3.13 Total Nitrogen

Water samples from the study area were significantly enriched with nitrogen (NH_4^+, NO_2^- and NO_3^-) indicating that inputs from sewage, shrimp farms, agricultural run-off and benthic fluxes are not fully assimilated within the system. In the present study the total nitrogen values ranged from 21 to 57µgat/l during high tide condition (Table 1) and 27 to 68 µgat/l during low tide condition (Table 2). The significant tidal (Figure 4) and spatial variations of total nitrogen (Table 3) reflect anthropogenic sources. The present study stretch acts as sink of sewage and other wastes from the highly urbanized city of Kolkata, which is one of the major mega-cities in India where the population has increased from 9,194,018 (in 1981) to 11,021,918 (in 1991) and to 13,216,546 (in 2001). This means an exponential growth rate of 1.72 during 1981-1991 and 1.82 during 1991-2001. The wastes generated from such quantum of population load reaches the Hooghly estuarine stretch. Apart from these, the area supports large numbers of shrimp (*Penaeus monodon*) culture farms often co-existing with brick manufacturing units that are potential sources of nitrogen in the Gangetic delta complex.

4. Conclusions

In this study, sixteen environmentally important physico-chemical parameters were measured in two tidal phases during the pre-monsoon period (April 2008) at 12 sampling stations in the Hooghly estuary flowing through the lower stretch of the Gangetic delta. The oscillation of different variables (except surface water temperature and potassium) with the semi-diurnal tide of the estuary proves the dynamic nature of the system, on which the marine and estuarine life of the region is sustained. The high nutrient load in the upstream zone is an indication of rising population density and subsequent anthropogenic pressure around the area. Here it can also be stressed that such research is a need of the present time when global warming and sea level changes are predominant in certain regions of the world that has considerable impact on physico-chemical parameters of the aquatic ecosystem. Sundarbans, a hotspot of biodiversity, (sustaining 34 true mangrove species and the only mangrove base of Royal Bengal Tiger) situated at the lower stretch of this Gangetic delta needs regular monitoring as sea level is rising at a relatively faster rate (3.14 mm/yr) in comparison to average global value (~2.50 mm/yr). It is also an erosion-prone system that can cause substantial effect on extinction coefficient and nutrient load. Development of a data bank of such a dynamic system is not only ecologically important but also it can reflect the trend of system in terms of water quality.

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