CHAPTER 4

NUTRIENT DYNAMICS IN THE HOOGHLY ESTUARY
AND THE SUNDARBANS MANGROVE

Meteorological induced variations in nutrient dynamics are evident in complex dynamic estuarine and coastal waters (Jayaraman et al 2007). The physico-chemical characteristics of coastal waters are related to riverine flow, upwelling, atmospheric deposition, vertical mixing and other anthropogenic sources. The study of water - atmosphere interaction, needs a combined knowledge on temperature, wind speed, water current and several other micrometeorological parameters. The present study areas situated at coastal Bay of Bengal, exhibit significant seasonal and spatial variations. The Hooghly estuary is a freshwater dominated system, whereas the adjacent Sundarbans mangrove has both freshwater and marine influences. Understanding the varied physico-chemical characteristics due to the difference in anthropogenic input and mangrove density, the Sundarbans mangrove can be differentiated into two sectors, i) The western sector, which has profound influence of the adjacent Hooghly estuary and undergoes various anthropogenic stresses, ii) The eastern sector falls under core mangrove areas with tidally fed rivers, hence has more marine influence.

4.1 SPATIAL AND SEASONAL VARIATION OF MICRO-METEOROLOGICAL PARAMETERS

The climatic condition of Indian subcontinent is dominated primarily by south-west monsoon and north-east monsoon that cause regular
changes in the atmospheric and water temperatures, wind speed, water current, rainfall and other micro meteorological parameters. The observed micro-meteorological data from the Hooghly estuary, and the Sundarbans mangrove showed significant seasonal and spatial variations.

4.1.1 Air and Water Temperatures

In the Hooghly estuary, highest air temperature was obtained during pre monsoon with a mean value of 33.19 ± 1.5°C where as the lowest values were obtained during post monsoon with a mean value of 21.9 ± 2.07°C (Table 4.1). Same seasonal trend was observed in the Sundarbans mangrove, with comparatively higher air temperatures in the eastern sector (Table 4.2).

Generally, water temperature is directly related the air temperature. Surface water temperature is also influenced by the intensity of solar radiation, evaporation, freshwater influx and cooling and mix up with ebb and flow from adjoining neritic waters. Similar seasonal trends of water temperatures were observed in both the study areas Figure 4.1. There was not much variation (<8%) of temperatures between water and air.

The Hooghly estuary and the Sundarbans mangrove surrounding waters did not exhibit significant spatial variation of water temperature in a particular season (Table 4.1 and 4.2). This consistency in surface water temperature values is due to high specific heat of the aquatic phase, which permits water to resist much fluctuation of temperature than the adjacent landmasses. The aquatic ecosystem 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 (Mitra et al 2011).
Table 4.1  Seasonal variation of micro meteorological parameters of the Hooghly estuary

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pre monsoon</th>
<th>Monsoon</th>
<th>Post monsoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature (°C)</td>
<td>33.19 ± 1.50 (30.50 - 36)</td>
<td>30.47 ± 1.15 (28.5 - 33)</td>
<td>21.9 ± 2.07 (18.8 - 24.5)</td>
</tr>
<tr>
<td>Water Temperature (°C)</td>
<td>30.73 ± 0.40 (30.0 - 31.30)</td>
<td>29.72 ± 0.71 (28.6 - 30.9)</td>
<td>21.8 ± 0.42 (20.8 - 22.3)</td>
</tr>
<tr>
<td>Wind Speed (m s⁻¹)</td>
<td>4.99 ± 2.08 (0.80 - 8.70)</td>
<td>6.26 ± 0.67 (5.2 - 7.8)</td>
<td>4.44 ± 0.66 (3.4 - 6.2)</td>
</tr>
<tr>
<td>Water Current (m s⁻¹)</td>
<td>0.56 ± 0.06 (0.41 - 0.62)</td>
<td>0.63 ± 0.11 (0.46 - 0.97)</td>
<td>0.49 ± 0.11 (0.26 - 0.62)</td>
</tr>
</tbody>
</table>

Table 4.2  Seasonal variation of micro meteorological parameters in the western and eastern sectors of the Sundarbans mangrove

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pre monsoon</th>
<th>Monsoon</th>
<th>Post monsoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature (°C)</td>
<td>32.49 ± 0.51 (31.5 - 33.5)</td>
<td>33.46 ± 0.96 (32.0 - 35.0)</td>
<td>23.30 ± 2.18 (19.50 - 28.50)</td>
</tr>
<tr>
<td>Water Temperature (°C)</td>
<td>30.64 ± 1.06 (27.9 - 31.7)</td>
<td>31.14 ± 1.06 (28.4 - 32.2)</td>
<td>22.85 ± 0.49 (22.0 - 23.70)</td>
</tr>
<tr>
<td>Wind Speed (m s⁻¹)</td>
<td>4.90 ± 1.66 (2.2 - 7.9)</td>
<td>4.12 ± 1.96 (2.3 - 7.83)</td>
<td>4.49 ± 1.80 (2.10 - 7.30)</td>
</tr>
<tr>
<td>Water Current (m s⁻¹)</td>
<td>0.30 ± 0.09 (0.21 - 0.51)</td>
<td>0.25 ± 0.04 (0.19 - 0.31)</td>
<td>0.24 ± 0.09 (0.11 - 0.34)</td>
</tr>
</tbody>
</table>

In the following sections the Hooghly estuary and the western and the eastern sectors of the Sundarbans mangrove, will be mentioned as HG, SUN (W) and SUN (E), respectively.
Figure 4.1 Spatial and seasonal variation of air and water temperatures of the Hooghly estuary and the Sundarbans mangrove

4.1.2 Wind Speed

The wind in the lower atmosphere plays a major role in regulating various bio-physical processes both in terrestrial as well as aquatic ecosystems. It exerts a force on the surface over which it blows. It is effective in transporting heat and material from the surface, and it is highly variable in space and time. Wind forcing in the estuarine and mangrove systems showed seasonal variations (Table 4.1 and 4.2). Southwest monsoon is more intense with respect to its extreme character relative to the Northeast monsoon in this region. This is clearly reflected in the micro meteorological parameters like wind speed. The highest mean wind speed was recorded during monsoon in both the study areas [HG = 6.26 ± 0.67 m s$^{-1}$, SUN (W) = 6.77 ± 3.24 m s$^{-1}$ and SUN (E) = 5.29 ± 1.17 m s$^{-1}$], is a southerly or south-
westerly wind. South-westerly winds cross the Arabian Sea and bring humid maritime air (Mean humidity > 80%) to this area during monsoon resulting lowering of air temperature from pre monsoon maximum and initiation of monsoon season. Over the northern winter, during post monsoon northerly or north-easterly flow of wind was observed with mean lowest wind speed [HG = $4.44 \pm 0.66 \text{ m s}^{-1}$, SUN (W) = $4.49 \pm 1.80 \text{ m s}^{-1}$ and SUN (E) = $3.36 \pm 1.08 \text{ m s}^{-1}$]. This wind is relatively cool and brings calm condition with lesser humidity in the air in this climatic zone.

![Figure 4.2](image)

**Figure 4.2** Spatial and seasonal variation of wind speed and water current of the Hooghly estuary and the Sundarbans mangrove

Figure 4.2 shows that western sector of the Sundarbans mangrove experienced higher wind speed compare to the eastern sector. This could be due to the presence of dense mangroves in the eastern sector which obstructed the wind movement.
4.1.3 Water Current

The important factors that influence the hydrodynamics of any system are the wind and the currents resulting from the wind action. Wind plays an important role in the speed of the water currents and in defining the scenarios. Seasonal variation of water current followed the similar trend of wind speed patterns. Highest water current was observed during monsoon in both the areas \(\text{HG} = 0.63 \pm 0.11 \text{ m s}^{-1}, \text{SUN (W)} = 0.54 \pm 0.11 \text{ m s}^{-1}\) and \(\text{SUN (E)} = 0.38 \pm 0.06 \text{ m s}^{-1}\), which is mainly due to the stronger wind speed (Table 4.1 and 4.2). Another reason behind, is the highest freshwater discharge during monsoon, dominated the tidal current and made the flow almost unidirectional in the Hooghly estuary. In the Sundarbans, monsoonal freshwater inputs from upstream regions, increased the water current as well. Water current was found lowest during post monsoon \(\text{HG} = 0.49 \pm 0.11 \text{ m s}^{-1}, \text{SUN (W)} = 0.28 \pm 0.05 \text{ m s}^{-1}\) and \(\text{SUN (E)} = 0.24 \pm 0.09 \text{ m s}^{-1}\). These seasonal trends revealed that during post monsoon tidal force was the major factor in the water circulation whereas during monsoon non-tidal factors like wind speed and fresh water inflow from the rivers were the major driving forces. In the eastern sector of the Sundarbans mangrove, water current was comparatively lower than the western sector (Figure 4.2). This was due to the presence of dense mangrove vegetations and their complex root structures, which dissipated the water movement, in turn reduced the water current.

4.1.4 Rainfall

Rainfall is the most important cyclic phenomenon in tropical countries as it brings important changes in the hydrographical characteristics of the marine and estuarine environments. The Sundarbans mangrove ecosystem experiences a large amount of rainfall during monsoon starting
from June, and extends up to September (sometime up to October) of every year. This southwest monsoon carries a huge amount of humid air from the ocean to the terrestrial area causing substantial rainfall in this region. Figure 4.3 shows total annual rainfall records of last 5 yrs (2004 - 2008) of South 24 Parganas (West Bengal) (Indian Meteorological Department). The mean annual rainfall for the last 5 years was 1953 ± 250 mm of which 87% rainfall was recorded during monsoon.

![Rainfall Graph](image)

**Figure 4.3** Total annual rainfall (mm) of the study region during the period of 2004-2008

### 4.2 SPATIAL AND SEASONAL VARIATION OF PHYSICO-CHEMICAL PARAMETERS OF THE ESTUARINE AND THE MANGROVE WATERS

Estuaries occupy less than 10% of the ocean’s surface (Lisitsyn 1995), but play an important role in the global biogeochemical cycle of substances like organic matter, nutrients, metals, etc. (Gebhardt et al 2005). Mixing of riverine freshwater and marine saline water and the associated changes in physico-chemical properties lead to change in physical, chemical
and biochemical processes, which affects the dissolved and suspended load of the river (Mitra et al 2011). Changes in land use, vegetation cover and population density could result in major modification to the flux of carbon and nutrients from land and atmosphere to estuaries and the coastal oceans (Howarth and Marino 2006).

4.2.1 Salinity

Salinity of coastal waters, estuaries and bays depends on freshwater input from glaciers, precipitation and the subsequent runoff and seawater intrusion. Global warming phenomenon enhances glacial melting, brings more rain and in turn contributes more freshwater to the coastal waters (Mitra et al 2009).

Tables 4.3 and 4.4 shows the seasonal variation of salinity in the Hooghly and the Sundarbans, respectively. In both the study areas, lowest salinity level was noticed during monsoon \[HG = 3.10 \pm 4.14, \text{SUN (W)} = 16.97 \pm 1.37, \text{SUN (E)} = 18.05 \pm 1.50\], and it gradually increased from post monsoon to pre monsoon. The highest salinity was recorded during pre monsoon \[HG = 10.39 \pm 7.26, \text{SUN (W)} = 24.28 \pm 1.83, \text{and SUN (E)} = 26.07 \pm 3.32\]. In the Hooghly estuary, Mukhopadhyay et al (2006) reported that the freshwater discharged values were highest during monsoon (~3000 m$^3$ s$^{-1}$), lowest during pre monsoon (~1000 m$^3$ s$^{-1}$) and intermediate during post monsoon (~2100 m$^3$ s$^{-1}$). This seasonal trend is reflected in the salinity levels of the present study. Hence, it is to be concluded that seasonal variation of salinity was dependent on precipitation rate and amount of freshwater discharged from the Farakka barrage situated upstream.
Table 4.3  Seasonal variation of dissolved nutrients, physico-chemical and biological parameters of the Hooghly estuary

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pre monsoon</th>
<th>Monsoon</th>
<th>Post monsoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity (mg L⁻¹)</td>
<td>10.39 ± 7.26 (1.30 - 21.70)</td>
<td>3.10 ± 4.14 (0 - 15.9)</td>
<td>4.74 ± 6.46 (0.10 - 18.20)</td>
</tr>
<tr>
<td>pH</td>
<td>8.0 ± 0.22 (7.43 - 8.45)</td>
<td>7.16 ± 0.29 (6.79 - 7.90)</td>
<td>7.79 ± 0.23 (7.36 - 8.08)</td>
</tr>
<tr>
<td>SPM (mg L⁻¹)</td>
<td>116 ± 63 (22 - 253)</td>
<td>133 ± 89 (27 - 350)</td>
<td>104 ± 45 (22 - 185)</td>
</tr>
<tr>
<td>Transparency (cm)</td>
<td>19.14 ± 4.17 (12.30 - 26.60)</td>
<td>12.92 ± 6.42 (4 - 26)</td>
<td>26.96 ± 13.92 (10.0 - 70.0)</td>
</tr>
<tr>
<td>DO (mg L⁻¹)</td>
<td>6.57 ± 0.20 (6.21 - 6.90)</td>
<td>6.46 ± 0.96 (4.6 - 7.8)</td>
<td>6.92 ± 0.44 (5.7 - 7.54)</td>
</tr>
<tr>
<td>DO Saturation (%)</td>
<td>77.98 ± 4.78 (72.20 - 86.61)</td>
<td>72.12 ± 10.93 (50.72 - 90.06)</td>
<td>77.67 ± 5.35 (65.53 - 88.39)</td>
</tr>
<tr>
<td>NO₃-N (µM L⁻¹)</td>
<td>20.72 ± 6.03 (10.81 - 32.71)</td>
<td>24.13 ± 4.38 (16.28 - 35.21)</td>
<td>22.45 ± 5.66 (12.59 - 32.42)</td>
</tr>
<tr>
<td>NO₂-N (µM L⁻¹)</td>
<td>0.13 ± 0.07 (0.05 - 0.36)</td>
<td>0.54 ± 0.45 (0.11 - 1.96)</td>
<td>0.36 ± 0.52 (0.04 - 2.51)</td>
</tr>
<tr>
<td>NH₄-N (µM L⁻¹)</td>
<td>1.25 ± 0.31 (0.81 - 2.16)</td>
<td>2.49 ± 1.37 (0.81 - 6.08)</td>
<td>1.23 ± 0.30 (0.81 - 2.16)</td>
</tr>
<tr>
<td>DIN (µM L⁻¹)</td>
<td>22.10 ± 6.34 (11.67 - 35.23)</td>
<td>27.16 ± 5.95 (17.20 - 43.25)</td>
<td>24.04 ± 6.29 (13.49 - 35.64)</td>
</tr>
<tr>
<td>DIP (µM L⁻¹)</td>
<td>0.83 ± 0.28 (0.43 - 1.41)</td>
<td>1.88 ± 1.04 (0.83 - 7.18)</td>
<td>0.81 ± 0.31 (0.27 - 1.44)</td>
</tr>
<tr>
<td>DIN / DIP</td>
<td>28.33 ± 9.92 (15.47 - 52.72)</td>
<td>16.03 ± 4.07 (6.03 - 25.14)</td>
<td>33.0 ± 11.93 (17.85 - 62.29)</td>
</tr>
<tr>
<td>DSi (µM L⁻¹)</td>
<td>83.85 ± 39.71 (35.80 - 169.68)</td>
<td>103.06 ± 34.9 (17.79 - 163.2)</td>
<td>95.73 ± 25.03 (53.03 - 144.9)</td>
</tr>
<tr>
<td>DIC (µM L⁻¹)</td>
<td>2129 ± 276 (1622 - 2603)</td>
<td>1867 ± 236 (1503 - 2372)</td>
<td>1549 ± 182 (1220 - 1863)</td>
</tr>
<tr>
<td>DOC (µM L⁻¹)</td>
<td>289.86 ± 55.75 (204.55 - 434.98)</td>
<td>282.13 ± 101.74 (174.97 - 714.20)</td>
<td>353.51 ± 135.51 (246.12 - 654.16)</td>
</tr>
<tr>
<td>Chl-a (mg m⁻³)</td>
<td>3.23 ± 1.66 (0.77 - 7.72)</td>
<td>1.87 ± 0.96 (0.65 - 4.26)</td>
<td>3.85 ± 2.28 (0.07 - 8.71)</td>
</tr>
</tbody>
</table>
Table 4.4  Seasonal variation of dissolved nutrients, physico-chemical and biological parameters of the western and eastern sectors of the Sundarbans mangrove

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pre monsoon</th>
<th>Monsoon</th>
<th>Post monsoon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Western Sector</td>
<td>Eastern Sector</td>
<td>Western Sector</td>
</tr>
<tr>
<td>Salinity (µM L⁻¹)</td>
<td>24.28 ± 1.83 (22.0-27.5)</td>
<td>26.07 ± 3.32 (22.32-31.7)</td>
<td>16.97 ± 1.37 (15.3-19.0)</td>
</tr>
<tr>
<td>pH</td>
<td>8.00 ± 0.09 (7.89-8.20)</td>
<td>8.02 ± 0.15 (7.86 - 8.27)</td>
<td>7.98 ± 0.02 (7.94 - 8.01)</td>
</tr>
<tr>
<td>DIN (mg L⁻¹)</td>
<td>80.40 ± 17.71 (56.95-105.92)</td>
<td>73.49 ± 24.31 (32.37-115.46)</td>
<td>141 ± 70 (46-266)</td>
</tr>
<tr>
<td>Transparency (cm)</td>
<td>35.12 ± 8.61 (22.58-48.10)</td>
<td>36.69 ± 1.78 (35.14-41.82)</td>
<td>21.53 ± 6.32 (11.03-32.20)</td>
</tr>
<tr>
<td>DO (mg L⁻¹)</td>
<td>6.79 ± 0.15 (6.47-6.98)</td>
<td>6.93 ± 0.15 (6.60-7.12)</td>
<td>6.19 ± 0.34 (5.49-6.73)</td>
</tr>
<tr>
<td>NO3-N (µM L⁻¹)</td>
<td>11.14 ± 1.03 (9.82-13.38)</td>
<td>9.97 ± 1.87 (6.34-13.85)</td>
<td>12.53 ± 2.34 (9.01-16.7)</td>
</tr>
<tr>
<td>NO2-N (µM L⁻¹)</td>
<td>0.20 ± 0.09 (0.02-0.53)</td>
<td>0.21 ± 0.20 (0.02-0.59)</td>
<td>1.13 ± 0.93 (0.50-3.40)</td>
</tr>
<tr>
<td>NH4-N (µM L⁻¹)</td>
<td>0.81 ± 0.21 (0.59-1.23)</td>
<td>0.74 ± 0.19 (0.53-1.10)</td>
<td>2.11 ± 1.28 (0.92-4.98)</td>
</tr>
<tr>
<td>DIN (µM L⁻¹)</td>
<td>12.15 ± 1.21 (10.55-14.63)</td>
<td>10.93 ± 2.05 (6.93-15.10)</td>
<td>15.76 ± 4.08 (10.81-25.08)</td>
</tr>
<tr>
<td>DIP (µM L⁻¹)</td>
<td>0.46 ± 0.14 (0.27-0.65)</td>
<td>0.53 ± 0.20 (0.30-0.91)</td>
<td>1.06 ± 0.28 (0.72-1.56)</td>
</tr>
<tr>
<td>DSI (µM L⁻¹)</td>
<td>33.77 ± 11.25 (11.96-51.31)</td>
<td>29.27 ± 11.13 (9.15-49.51)</td>
<td>65.81 ± 25.67 (34.0-117.60)</td>
</tr>
<tr>
<td>DIC (µM L⁻¹)</td>
<td>1806 ± 124 (1649-2078)</td>
<td>1785 ± 295 (1432-2598)</td>
<td>2183 ± 40 (2122-2554)</td>
</tr>
<tr>
<td>DOC (µM L⁻¹)</td>
<td>323.44 ± 71.16 (229.72-436.09)</td>
<td>288.68 ± 42.35 (196.45-343.87)</td>
<td>197.67 ± 38.56 (154.74-266)</td>
</tr>
<tr>
<td>Chl-a (mg m⁻³)</td>
<td>7.59 ± 3.72 (2.91-14.57)</td>
<td>7.63 ± 0.99 (5.45-9.11)</td>
<td>4.89 ± 0.30 (4.30-5.46)</td>
</tr>
</tbody>
</table>
Salinity shows a significant positive correlation with temperature. This is a generalized concept, but salinity of a specific region also depends on geographical settings. The Hooghly estuary is a freshwater dominated system due to Ganges, whereas the Sundarbans has different geographical settings. The western sector of the mangrove swamp has freshwater influence of the adjacent Hooghly, whereas the eastern part is devoid of direct freshwater source from mainstream rivers due to increase siltation. This is clearly observed as comparatively higher salinity levels (~5%) in the eastern sector of the Sundarbans than the western sector in all the seasons (Table 4.4). In case of spatial variation in the Hooghly estuary, the decline of salinity of the surface waters in the region of rivers mouths were observed, mainly due to the riverine contribution from the rivers like Roopnarayan and Haldi. In the Hooghly estuary, a steady increase in salinity was seen from the estuary upstream to mouth of the estuary towards Bay of Bengal (average salinity ~32) in all the sampling seasons.

4.2.2 pH

Generally, fluctuations in pH values during different seasons of the year is attributed to several factors like removal of CO$_2$ by photosynthesis through bicarbonate degradation, dilution of seawater by freshwater influx, low primary productivity, reduction of salinity and temperature and decomposition of organic materials. In the present study areas, the observed range of Hydrogen ion concentration (pH) in surface waters remained weakly alkaline (average 8) throughout the study period (Table 4.3 and 4.4). The range of pH in estuarine waters (7.16 - 8.00) was slightly lower than the global average (8.17). In the Hooghly, highest pH values were observed during pre monsoon, due to comparatively intense tidal action and lower rate of freshwater discharge during this particular season. In the Sundarbans, a slightly higher trend of pH in the eastern sector mainly owed to salinity effect
and also could be due to comparatively higher photosynthetic activity (Prabu et al 2008). Regions near to the sea showed higher pH level (8.05 - 8.15) because of the sea water intrusion from Bay of Bengal.

4.2.3 Suspended Particulate Matter (SPM)

Suspended Particulate Matter (SPM) or Total Suspended Matter (TSM) includes clay and silt (e.g. suspended sediment), and detritus and organisms (algae and zooplankton). Suspended sediment plays a major role in the hydro-geomorphological and ecological functioning of a river basin. Water currents have the capacity to mobilize fine sediments (including clays, silts and fine sands) in the coastal waters. SPM controls the transport, reactivity and biological impacts of substances in the marine environment, and are a crucial link in interactions between the seabed, water column and the food chain.

In the Hooghly estuary and the Sundarbans mangrove, the highest level of SPM was observed during monsoon [HG = 133 ± 89 mg L\(^{-1}\); SUN (W) = 141 ± 70 mg L\(^{-1}\); SUN (E) = 153 ± 67 mg L\(^{-1}\)] owing to high river discharge, which increased the rate of surface runoff (Table 4.3 and 4.4). Total suspended solids may naturally attain several hundred milligrams per litre in the meso- and macro-tidal coastal waterways (e.g. mean tidal range > 2m). In the Hooghly estuary in all the seasons, SPM levels were found to be >100 mg L\(^{-1}\) (Table 4.3). Whereas in the Sundarbans mangrove surrounding waters always showed SPM levels below 100 mg L\(^{-1}\) during pre and post monsoons (Table 4.4). Except monsoon, other seasons showed a distinct difference in SPM levels between the Hooghly estuary and the Sundarbans mangrove. This could be due to the presence of mangroves which decreased the water velocity (Leonard and Reed 2002), in turn reduced the turbulent
activity (Leonard et al. 2002) and directly trapped suspended sediments (Palmer et al. 2004). Hence, this can be concluded that the variation in SPM level between two systems was vegetation-induced and also depended on freshwater flow into the systems.

Figure 4.4 depicts that in the Hooghly and the Sundarbans (both eastern and western sectors), SPM levels gradually decreased towards the high salinity regime, i.e., regions in close proximity to Bay of Bengal, due to dilution with the sea water. This clearly showed that, the major source of suspended particles was from sediment laden river water.

Figure 4.4 Spatial and seasonal distribution of SPM (mg L$^{-1}$) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors)
4.2.4 Transparency

Water transparency or light penetration is a measure of the clarity of water, which indicates attenuation of light penetrating into water and is governed by its absorption and scattering properties. Scattering and absorption of light are dependent on the amount of particulate matter and dissolved substances in the water. The seasonal trend of transparency in both the systems followed just the opposite trend of SPM. The lowest transparency values [HG = 12.92 ± 6.42 cm; SUN (W) = 21.53 ± 6.32 cm; SUN (E) = 20.18 ± 6.53 cm] were observed during monsoon in both the areas (Table 4.3 and 4.4), due to increased riverine runoff along with physical churning of sediments, which decreased the light penetration in water. Northeast monsoon seasons, i.e., post monsoon period is comparatively calm w.r.t. discharge, physical mixing and hydrological activities. This was reflected as a highest transparency level in this season.

4.2.5 Dissolved Oxygen (DO)

Dissolved oxygen (DO) refer to the amount of oxygen contained in water, and define the living conditions for oxygen-requiring (aerobic) aquatic organisms. Oxygen has limited solubility in water, usually ranging from 6 to 14 mg L\(^{-1}\) in coastal waters. The seasonal distribution of DO in the Hooghly estuary showed that, highest DO levels during post monsoon (6.92 ± 0.44 mg L\(^{-1}\)), followed by pre monsoon (6.57 ± 0.20 mg L\(^{-1}\)) and least during a monsoon (6.46 ± 0.96 mg L\(^{-1}\)). There was not much variation in DO values were observed, and entire year DO remained under-saturated <80% (Table 4.3). In Figure 4.5, it was observed that DO varied positively with salinity, which did not support a classical trend. Usually the upper stream of the estuary should show higher concentration of DO, due to the increased
freshwater supply from the Ganges. The Hooghly estuary receives a copious amount of coastal discharges of wastes, rich in organic carbon (e.g. from domestic sewage, oil refineries and other surrounding industries) through Ganges. Biochemical degradation of anthropogenic organic matter brought to the estuary during monsoon could substantially reduced DO level in the upstream region of the estuary. The trend of SPM concentrations along the estuary also supported this occurrence. While comparatively higher DO concentrations in the lower part of the estuary, could be due to the increased tidal action, which aggravated the physical-mixing processes. Chla concentrations (Table 4.3) also showed a similar trend, which could be concluded that photosynthetic release of DO also played a role in determining the surface water DO.

The DO concentration in the eastern sector of the Sundarbans mangrove showed an increasing trend (maximum 2%) in contrast to the western part over the study period (Table 4.5). This increase of DO concentrations in the eastern sector was in contrast to the prevalent notion of increased salinity (Figure 4.5). As explained before, besides the, temperature and salinity, this trend could be attributed to the comparatively increased productivity in the eastern sector, which was also associated with lower values of SPM (Table 4.5) in all the seasons. In the Sundarbans, seasonal variation of DO showed highest concentrations during pre monsoon (6.79 ± 0.15 mg L⁻¹ and 6.93 ± 0.15 mg L⁻¹) and lowest during monsoon (6.19 ± 0.34 mg L⁻¹ and 6.24 ± 0.33 mg L⁻¹) in the western sector and in the eastern sector, respectively (Table 4.5).
Figure 4.5  Spatial and seasonal distribution of DO (mg L\(^{-1}\)) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors)

4.3  SPATIAL AND SEASONAL VARIATION OF DISSOLVED NUTRIENTS IN THE ESTUARINE AND THE MANGROVE WATERS

The study of the dynamics of biophilic elements (i.e. carbon, nitrogen, phosphorus and silicon) in coastal waters relate to the short-term variability of the water chemistry, which is strongly influenced by the effect of the seasonal and tidal cycle. Riverine transport is a principal pathway of particulates and dissolved elements from land to sea. Coastal ecosystems like
estuaries, mangroves, salt marshes modify riverine nutrient fluxes to the sea significantly through biogeochemical processes (Soetaert et al 2006; Liu et al 2011).

4.3.1 Dissolved Inorganic Nitrogen (DIN)

The spatial and seasonal distributions of dissolved inorganic nitrogen (DIN) in the Hooghly estuary and the Sundarbans mangrove showed a strong variability in terms of various nitrogen species (Nitrate-NO$_3^-$, Nitrite-NO$_2^-$, and Ammonium-NH$_4^+$), are given in the Tables 4.3 and 4.4, respectively. In general, in the total DIN pool, nitrogen was present in an oxidized form, i.e., NO$_3^-$, had dominance (average ~92% ) over both NH$_4^+$ and NO$_2^-$ species, in all the seasons. The NO$_2^-$, the intermediate oxidation state between NH$_4^+$ and NO$_3^-$, can appear as a transient species by the oxidation of NH$_4^+$ or by the reduction of NO$_3^-$. Thus, being the most unstable form of DIN species, its concentration level remained comparatively least among other nitrogen species, in both the systems. The most important source of NO$_3^-$ is biological oxidation of organic nitrogenous substances, which originates through sewage and industrial wastes.

The seasonal variation of DIN showed highest concentrations during monsoon [HG = 27.16 $\pm$ 5.95 $\mu$M L$^{-1}$, SUN (W) = 15.76 $\pm$ 4.08 $\mu$M L$^{-1}$, SUN (E) = 14.39 $\pm$ 4.15 $\mu$M L$^{-1}$], followed by post monsoon [HG = 24.04 $\pm$ 6.29 $\mu$M L$^{-1}$, SUN (W) = 13.25 $\pm$ 2.18 $\mu$M L$^{-1}$, SUN (E) = 11.96 $\pm$ 1.68 $\mu$M L$^{-1}$] and least during pre monsoon [HG = 22.10 $\pm$ 6.34 $\mu$M L$^{-1}$, SUN (W) = 12.15 $\pm$ 1.21 $\mu$M L$^{-1}$, SUN (E) = 10.93 $\pm$ 2.05 $\mu$M L$^{-1}$] in both the systems (Table 4.3 and 4.4). Especially NO$_3^-$ and NO$_2^-$ followed the similar seasonal trend with DIN. This trend is in accordance with the earlier work of Biswas et al (2009) in the same area. This seasonal trend clearly indicates the result of
monsoonal run off in the system, which increased the concentrations of nitrogenous nutrients in this particular season. While concentration of $\text{NH}_4^+$ could be ascribed to the concentration of DO, as it is a reduced form of nitrogen. This was reflected in the seasonal trend of $\text{NH}_4^+$.

It is observed from this study that DIN concentrations of the Hooghly estuary were almost twice of the Sundarbans sectors in all the seasons. This clearly indicates that the Hooghly estuary harbored more anthropogenic nutrients carried by the Ganges, while in the Sundarbans, presence of mangrove acting as a bio-filters and comparatively increased productivity attenuated the biological uptake of nutrients. In the Sundarbans mangrove, the western sector showed higher concentrations of nitrogenous nutrients, compared to the eastern sector. This could be attributed to the proximity of the western part of the Sundarbans to the Hooghly estuary, which supplied anthropogenic nutrient rich water to this region. Another probable reason could be the comparatively denser human inhabitants in the western sector than the eastern sector, contributed more domestic wastes.

In several time series surveys, plots of nutrients as a function of salinity have been used as a valuable tool to assess the different sources of nutrient's species, whether from inland, outside the estuary or within it (Clark et al 1992; Magni et al 2002). The spatial distribution of $\text{NO}_3^-$, $\text{NO}_2^-$ and $\text{NH}_4^+$ exhibited higher values towards the upstream stations from both the study areas. The mixing plots of $\text{NO}_3^-$, $\text{NO}_2^-$ and $\text{NH}_4^+$ (Figures 4.6, 4.7 and 4.8, respectively) clearly explained the non-conservative behavior of $\text{NO}_3^-$, $\text{NO}_2^-$ and $\text{NH}_4^+$ (comprehensively DIN) with respect to salinity, in both the systems. The occasional rise in $\text{NO}_3^-$ concentration in both the sectors of Sundarbans (Figure 4.6 could be attributed to their temporal variations, according to
Loder and Reichard (1981), or else it could be due to regeneration of the nutrients from organic materials, as suggested by Gupta et al (2006).

Figure 4.6 Spatial and seasonal distribution of Nitrate (µM L⁻¹) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors)
Figure 4.7  Spatial and seasonal distribution of Nitrite (µM L⁻¹) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors)
4.3.2 Dissolved Inorganic Phosphate (DIP)

The seasonal variation of Dissolved inorganic phosphate (DIP) showed highest concentrations during monsoon [HG = 1.88 ± 1.04 μM L⁻¹, SUN (W) = 1.06 ± 0.28 μM L⁻¹, and SUN (E) = 0.87 ± 0.13 μM L⁻¹]. In the Hooghly, DIP concentration did not reveal any significant variation between pre and post monsoons. Overall DIP concentrations remained at a similar level, with slightly higher concentrations during pre monsoon (HG = 0.83 ± 0.28 μM L⁻¹), than in post monsoon (HG = 0.81 ± 0.31 μM L⁻¹). While in the case of Sundarbans, monsoonal highest concentration followed
by post monsoon \[\text{SUN (W)} = 0.62 \pm 0.29 \mu\text{M L}^{-1}, \text{SUN (E)} = 0.70 \pm 0.28 \mu\text{M L}^{-1}\] and the lowest during pre monsoon \[\text{SUN (W)} = 0.46 \pm 0.14 \mu\text{M L}^{-1}, \text{SUN (E)} = 0.53 \pm 0.20 \mu\text{M L}^{-1}\] (Table 4.3 and 4.4). Monsoonal runoff is the main source of both natural (weathering of rocks soluble alkali metal phosphates) and anthropogenically derived DIP (phosphates based fertilizers applied in the agricultural fields, detergents used in households, sewage discharges from local and upstream regions) in both the systems. Gradual decrease in the DIP concentrations in following seasons (pre and post monsoons) could be attributed to the limited flow of freshwater, high salinity gradient and utilization of phosphate by phytoplankton (Prabu et al 2008). It was observed that DIP concentrations of the eastern sector the Sundarbans was comparatively higher than the western sector, in both pre and post monsoons. This could be attributed to the natural phosphate buffer mechanism. Comparatively higher salinity gradient in the eastern sector facilitated the desorption process of phosphate from the sediment (Sylaios 2003); in turn it enhanced the DIP concentration in the surrounding waters.

In the Hooghly estuary, spatial distribution of DIP showed distinct non-conservative behavior with salinity gradient, in all the seasons (Figure 4.8). In the Sundarbans, during monsoon similar trend has been observed, in both the sectors. This indicated that, in all the seasons, the Hooghly estuary and the Sundarbans (only during monsoon) received DIP from upstream riverine sources. However, during pre and post monsoons, both the western and eastern sectors of the Sundarbans DIP was seen to behave like conservative nutrient with salinity. The conservative plot (Figure 4.9) against salinity suggested an occasional source in the high saline waters (Table 4.4), this could be the natural effect of the phosphate buffer mechanism, which can cause the release of DIP to the water column from mangrove sediments (Froelich 1988). This phenomenon was prominently
observed in the Sundarbans, during pre and post monsoons due to comparatively higher salinity gradients than monsoon (Table 4.4).

![Diagram showing spatial and seasonal distribution of Dissolved Inorganic Phosphate (µM L⁻¹) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors).]

**Figure 4.9 Spatial and seasonal distribution of Dissolved Inorganic Phosphate (µM L⁻¹) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors)**

**4.3.3 N:P Stoichiometric Ratio**

Variability in Nitrogen (N) to Phosphorus (P) atomic ratios (N:P) can have an important biogeochemical implication. P is commonly the "limiting" nutrient for photosynthesis in terrestrial aquatic systems because of its low solubility, and N is limiting in coastal and marine surface waters. N, P
and O content of natural waters often co-vary in manners that are predicted by
the Redfield ratio (Redfield et al 1963).

In the present study, N:P atomic ratios were observed to be
significantly variable on a spatial and seasonal scale, in both the systems. In
the Hooghly estuary, N:P ratio was found to be the highest (33 ± 11.93)
during post monsoon, followed by pre monsoon (28.33 ± 9.92) and least
during monsoon (16.03 ± 4.07) (Table 4.3). In the Sundarbans mangrove, N:P
seasonal trend gradually decreased from pre monsoon [SUN (W) =
29.50 ± 10.55 and SUN (E) = 24.48 ± 11.88], to post monsoon [SUN (W) =
25.03 ± 10.61 and SUN (E) = 19.75 ± 8.10], ultimately to monsoon
[SUN (W) = 15.13 ± 2.25 and SUN (E) = 16.37 ± 2.33] (Table 4.4).

Overall, the lowest N:P ratios during monsoon indicated that the
nitrogen as the limiting factor to the trophic level, as similarly observed by
Biswas et al (2009) in the present study area and some other ecosystems in
India (Tripathy et al 2005 and the references there in). The seasonal trend of
N:P molar ratio in the Hooghly estuary indicated that during monsoon,
increased concentration of both DIN and DIP entered the system along with a
copious amount of suspended matter. In spite of the nutrient availability, due
to inadequate transparency, photosynthesis process got restricted, this
hindered the phytoplankton growth. While, during post monsoon,
comparatively the calm seasonal condition, helped in settling down of the
particulate matter and water transparency gradually increased (Table 4.3).
This condition favored primary productivity, as phytoplankton is more
efficient of uptaking P over N, the biological consumption during the post
monsoon period lowered the DIP concentration and led to increase nitrate
content in the medium. Thus, the N:P ratio gradually increased, and the
system became P limiting w.r.t. Refield ratio (N:P = 16:1). During pre
monsoon, N:P ratio further increased, this could be due to inorganic removal of phosphate through adsorption during sedimentation of SPM, as suggested by Biswas et al (2009).

In the Sundarbans mangrove, the difference in N:P ratios between pre and post monsoons were observed to be meager (Table 4.4). Hence, similar biogeochemical processes were expected to have happened.

4.3.4 Dissolved Inorganic Silicate (DSi)

The seasonal variation of dissolved inorganic silicate (DSi) showed the highest concentrations during monsoon [HG = 103.06 ± 34.9 μM L⁻¹, SUN (W) = 65.81 ± 25.67 μM L⁻¹, SUN (E) = 51.03 ± 29.05 μM L⁻¹], followed by post monsoon [HG = 95.73 ± 25.03 μM L⁻¹, SUN (W) = 40.79 ± 9.85 μM L⁻¹, SUN (E) = 38.48 ± 13.99 μM L⁻¹] and lowest during pre monsoon [HG = 83.85 ± 39.71 μM L⁻¹, SUN (W) = 33.77 ± 11.25 μM L⁻¹, SUN (E) = 29.27 ± 11.13 μM L⁻¹]. Similar seasonal trend has been reported by Mukhopadhyay et al (2006) in the same study area. The silicate concentration was higher than that of the other nutrients (DIN, DIP) (Tables 4.3 and 4.4).

The recorded highest monsoonal values were due to heavy inflow of monsoonal fresh water derived from land drainage carrying silicate leached out from rocks from the upstream regions. Moreover, due to the turbulent nature of water during monsoon, the silicate from the bottom sediment might have been exchanged with overlying water, as suggested by Rajasegar (2003). Gradual lowering of DSi concentrations in post and pre monsoons were attributed to uptake of the silicates by phytoplankton for their biological activity, especially by diatoms and silico-flagellates (Aston 1980) and also to comparatively lean freshwater flow from the upstream regions.
The spatial distribution of DSI in both the systems, showed a gradual decrease in concentration towards the high salinity regime (Figure 4.10) in all the seasons. Since freshwater is the main source of silicate (Lal 1978), the above distribution of DSI with salinity described that dilution of silicate rich water with the sea water, as the other possibilities like precipitation and land drainage to the coastal water were not there during pre and post monsoons. Table 4.3 shows that the western sector of the Sundarbans mangrove had comparatively higher DSI concentrations than the eastern sector. This could be explained as the proximity of the western sector with the Hooghly estuary, which receives freshwater from the Hooghly through channels. Another possible reason could be the comparatively higher productivity (concentration of Chl$\alpha$, Table 4.4) in the eastern sector enhanced the biological uptake of DSI from the surrounding waters.

![Figure 4.10 Spatial and seasonal distribution of Dissolved Inorganic Silicate (µM L$^{-1}$) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors)](image)
4.3.5 Dissolved Inorganic Carbon (DIC)

Riverine input of dissolved and particulate carbon into the ocean is an important link in biogeochemical carbon cycling between land and ocean (Wu et al 2007). Riverine dissolved inorganic carbon (DIC) is composed of bicarbonate (HCO$_3^-$), carbonate (CO$_3^{2-}$), and dissolved CO$_2$ (pCO$_2$). DIC concentration was strongly affected by the pH and partial pressure of dissolved CO$_2$ (pCO$_2$). The latter factor is discussed thoroughly in Chapter 5.

In general, the HCO$_3^-$ is the dominant component when pH value of the river water ranges from 6.4 - 10.3 (Dreybrodt 1988), hence most of the coastal waters are rich in HCO$_3^-$ (Sun et al 2011). The spatial and seasonal distribution of pH and DIC are given in Table 4.3 and 4.4, respectively for the Hooghly estuary and the Sundarbans mangrove. In the present study areas, pH ranged from 7.5 - 8. In the Hooghly, maximum DIC concentrations were observed during pre monsoon ($2129 \pm 276 \, \mu M \, L^{-1}$), followed by monsoon ($1867 \pm 236 \, \mu M \, L^{-1}$) and minimum during post monsoon ($1549 \pm 182 \, \mu M \, L^{-1}$).

In the Hooghly estuary, highest DIC concentration during pre monsoon could be imputed to increase water temperature, which accelerated the DIC regeneration processes within the system in a comparatively higher salinity period, as reported by other scientists (Abril et al 2003; Feely et al 2004). In the Sundarbans mangrove, DIC concentrations steadily decreased from monsoon [SUN (W) = 2183 ± 40 μM L$^{-1}$; SUN (E) = 2220 ± 33 μM L$^{-1}$] to pre monsoon [SUN (W) = 1806 ± 124 μM L$^{-1}$; SUN (E) = 1785 ± 295 μM L$^{-1}$], and least during post monsoon [SUN (W) = 1115 ± 96 μM L$^{-1}$; SUN (E) = 1129 ± 81 μM L$^{-1}$]. Monsoonal highest concentration of DIC could be related to high surface runoff with associated lowering of water transparency, which led to dominant respiration over productivity, ultimately fueled DIC production. However, in both the systems, lowest DIC concentration in post
monsoon could be attributed to lean freshwater flow, which increased the water transparency and facilitated photosynthetic activity (increased Chla concentration) by converting inorganic carbon to organic carbon compounds, as suggested by Kanduč et al (2007).

In Figure 4.11, spatial distribution of DIC shows that in both the systems, DIC acted as non-conservative nutrient w.r.t. salinity. This downstream decreasing trend could be affected by the processes, including (1) carbonate mineral precipitation, (2) CO$_2$ out gassing and (3) aquatic photosynthesis (Dreybrodt 1988), (4) seawater characteristics influenced through the tides (Gupta et al 2008), as suggested by Sun et al 2011.

Figure 4.11 Spatial and seasonal distribution of Dissolved Inorganic Carbon (µM L$^{-1}$) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors)
4.3.6 Dissolved Organic Carbon (DOC)

The fate of riverine dissolved organic carbon (DOC) in the coastal ocean is of interest from a number of perspectives. DOC is typically the dominant form of organic matter in estuaries and coastal waters, which originates from leaching of plant litter, soil humus, microbial biomass, or root exudates (Ford et al 2005). In the Hooghly estuary, DOC concentration was found to be the highest during post monsoon (353.51 ± 135.51 µM L⁻¹), followed by pre monsoon (289.86 ± 55.75 µM L⁻¹) and lowest during monsoon (282.13 ± 101.74 µM L⁻¹) (Table 4.3). In the Sundarbans mangrove, the seasonal trends of DOC gradually decreased from pre monsoon [SUN (W) = 323.44 ± 71.16 µM L⁻¹; SUN (E) = 288.68 ± 42.35 µM L⁻¹] to post monsoon [SUN (W) = 269.71 ± 35.54 µM L⁻¹; SUN (E) = 246.25 ± 17.98 µM L⁻¹] and ultimately to monsoon [SUN (W) = 197.67 ± 38.56 µM L⁻¹; SUN (E) = 232.50 ± 76.87 µM L⁻¹] (Table 4.4).

DOC concentration in the present study area is consistent with previous study (Spitzy and Leenher 1991) on Ganges and Brahmaputra (260 - 380 µM L⁻¹). DOC dynamics is ultimately related to the productivity of the system, thus Chlα concentration has been considered here. During pre and post monsoons, observed higher DOC concentrations could be attributed to higher Chlα levels, which was a result of increased productivity. This condition favored the photosynthetic extracellular release of DOC from the phytoplankton (phytoexudation) in the surrounding waters (Mauriac et al 2011). During monsoon, in both the systems heterotrophy dominated over productivity (lowest Chlα level). This condition supported the heterotrophic bacterial activities on DOC consumption from the system (Mauriac et al 2011). Hence, monsoonal DOC sink was observed, in both the systems.
The spatial variation of DOC (Figure 4.12) did not show a distinct distribution pattern, though general trend showed that comparatively higher concentrations in the upper stretches of the Hooghly estuary, explained riverine DOC input to the system. Particularly, during post monsoon, slight conservative behavior of DOC was observed, which is also reported in many estuaries (Moran et al 1999 and references there in). Lower stretch of the estuary acted as a source of DOC, could be due to the export of DOC from the adjoining Sundarbans mangrove, which experiences the highest rate of litter fall (280 g dry wt. m\(^{-2}\) month\(^{-1}\)) during post monsoon, according to a recent study made in the same area by Ray et al (2011).

Figure 4.12 Spatial and seasonal distribution of Dissolved Organic Carbon (µM L\(^{-1}\)) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors)
4.4 SPATIAL AND SEASONAL VARIATION OF BIOLOGICAL PARAMETER IN THE ESTUARINE AND THE MANGROVE WATERS

4.4.1 Chlorophyll (Chla)

Chlorophyll (Chla) concentrations are an indicator of phytoplankton abundance and biomass in coastal and estuarine waters, as they constitute the chief photosynthetic pigment of phytoplankters. In the Hooghly estuary, seasonal fluctuations of Chla levels were observed with highest during post monsoon (3.85 ± 2.28), followed by pre monsoon (3.23 ± 1.66), and least during monsoon (1.87 ± 0.96) (Table 4.3). In the Sundarbans mangrove, the seasonal trends gradually declined from the peak pre monsoon season [SUN (W) = 7.59 ± 3.72 and SUN (E) = 7.63 ± 0.99], to post monsoon [SUN (W) = 5.67 ± 3.89 and SUN (E) = 6.20 ± 4.03] and ultimately to monsoon [SUN (W) = 4.89 ± 0.30 and SUN (E) = 5.01 ± 1.87] (Table 4.4).

In the Hooghly, there was a marginal variation of Chla levels between pre and post monsoons, while monsoon concentration was around twice lower than the former mentioned seasons. Lowest concentration of Chla during monsoon is a common seasonal trend in Indian coastal waters (Sarma et al 2006; Satpathy et al 2010). In both the study areas, a sharp decline in Chla concentrations during monsoon could be attributed to monsoon runoff and land drainage, which made the systems unfavorable for phytoplankton growth by decreasing transparency (increased SPM concentration) (Figure 4.14) and decreasing salinity (Figure 4.13). This was clearly evident from the spatial and seasonal trend of the aforementioned parameters (Tables 4.3 and 4.4). Figure 4.13 distinctly shows the conservative behavior of Chla with salinity, as salinity increased towards Bay of Bengal, water transparency also increased with decreasing SPM levels, which facilitated the primary productivity process. This was again supported by the spatio-temporal trend...
of DO concentrations, which was likely to be the byproduct of the photosynthetic activity. The gradual increase in Chla levels during pre and post monsoons could be subjected to increasing transparency and comparatively higher salinity, made the systems more conducive for primary productivity.

The spatial variation of Chla levels revealed that the Sundarbans mangrove waters contained comparatively higher levels of Chla than the Hooghly estuary, which could be similarly explained by the lower SPM levels and higher transparency. Likewise, the eastern sector of the Sundarbans mangrove held more Chla than the western sector.

**Figure 4.13** Spatial and seasonal distribution of Chlorophylla (mg m$^{-3}$) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors)
Figure 4.14 Spatial and seasonal distribution of Chlorophyll\(a\) (mg m\(^{-3}\)) w.r.t. Suspended Particulate Matter (mg L\(^{-1}\)) in the Hooghly estuary and the Sundarbans mangrove (western and eastern sectors)

4.5 SUMMARY OF NUTRIENT DYNAMICS IN THE ESTUARINE AND THE MANGROVE WATERS

During monsoon, the highest concentration of nutrients (DIN, DIP, DSi) were observed due to high freshwater discharge. The strong negative correlations between salinity and nutrient levels, underlined the importance of terrestrial runoff with a significant contribution of nutrients of anthropogenic
origin from local and upstream agricultural field, industries and urban areas. Small seasonal variation of DIN compared to DIP seasonal variation, indicated all over the year constant input of allochthonous DIN. Elevated DIN/DIP ratio during pre and post monsoons showed a gradual increase of productivity. Increase in productivity related to more uptake of P over N, made the system P limiting. The present study depicted that phytoplankton growth and primary production in the Hooghly estuarine, and the Sundarbans mangrove environment was not exclusively dependent on nutrient availability; rather, it was majorly dependant upon a proper combination of physico-chemical parameters (transparency, salinity, SPM, temperature, etc.).

4.6 SEASONAL BUDGETING OF NUTRIENTS (C-N-P-Si) USING LOICZ BIOGEOCHEMICAL MODEL: A CASE STUDY OF THE HOOGHLY ESTUARY

River fluxes of carbon, and nutrients have an insignificant impact on the global open ocean, but can have an important effect on the coastal ocean. Anthropogenic inputs of all forms of C, N, and P from rivers have increased during the thirty-year period between 1970 and 2000 at a global scale (Smith et al 2003; Seitzinger et al 2010). These changes have resulted in a massive mobilization of bioactive nutrients such as carbon, nitrogen and phosphorus in watersheds, enter surface waters and are transported by rivers to coastal marine systems (Seitzinger et al 2005). Changes in the amount and form of nutrient inputs (dissolved inorganic, organic, particulate) to coastal ecosystems contribute to numerous negative human health and environmental impacts, such as general loss of habitat and biodiversity, increased frequency and severity of blooms of certain species of harmful algae, eutrophication, hypoxia and fish kills (Rabalais 2002; Turner et al 2003; Billen and Garnier 2007; Diaz and Rosenberg 2008; Seitzinger et al 2010). Several authors
predicted that N and P inputs to surface waters are projected to continue to increase over the next several decades, both globally and regionally (Kroeze and Seitzinger 1998; Galloway et al 2004; Seitzinger et al 2005).

To quantify the impact of these nutrients on the estuaries, a number of models have been proposed to calculate the net budgets of carbon, nitrogen and phosphorus in the estuaries, which apply simple mass-balance calculations to available data (McKee et al 1997; Yanagi 1999; Gupta et al 2006). One such model is that of the Land Ocean Interaction in the Coastal Zone (LOICZ) that determines the capacity of estuaries to transform and store dissolved C, N, P and Si (Gordon et al 1996; Sylaios 2003). This model has been widely tested and used for C-N-P budget of about 250 tropical and temporal estuaries worldwide, due to its simple structure and applicability with minimal data (Hung and Kuo 2002; Sylaios 2003; Gazeau et al 2004; Smith and Hollibaugh 2006; Sylaios and Tsihrintzis 2009; Padedda et al 2010).

This case study aims to illustrate the seasonal nutrient budgets (C-N-P-Si) in the Hooghly estuarine system by using LOICZ biogeochemical model, which may be associated with variations of external inputs and nutrient processing within the system and nutrient exchange with the Bay of Bengal. This study also addresses the effect of mud in the budgeting.

4.7 THE LOICZ BIOGEOCHEMICAL MODEL FOR TURBID ESTUARIES

The previous version of the LOICZ model (Smith et al 1991; Gordon et al 1996) commonly neglected the nutrients in particulate form and budgeting was made under the assumption that they are locked away and do
not contribute to the nutrient budget of estuaries. This assumption is reasonable for estuaries with clear water but may be unreasonable in turbid estuaries in view of the field finding that the relative fraction of carbon in particulate form, i.e., the fractioning coefficient, increases with increasing suspended particulate matter (SPM) (Middelburg and Herman 2007). That fraction is typically zero in clear water, 20% at SPM of 10 mg L\(^{-1}\), 60% at SPM of 100 mg L\(^{-1}\), and 80% at SPM of 1000 mg L\(^{-1}\). Turbid estuaries commonly have SPM in the range 100-1000 mg L\(^{-1}\), hence the neglect of suspended fine sediment in estuarine nutrient budgets may yield incorrect results. The problem is due to the fine sediment which absorbs dissolved nutrients in the turbidity maximum zone (thus behaving like a sponge inhibiting eutrophication) or desorbs nutrients closer to the estuary mouth, and past the turbidity maximum zone where the turbidity decreases (thus facilitating eutrophication). Thus, a revised version of LOICZ model formulated for turbid systems (Wolanski 2009) has been employed in the present study.

The Hooghly estuary is an ideal study area for the application of new muddy LOICZ model. The Hooghly estuary is one of the world’s major estuaries, fed by one of the world’s largest rivers, the Ganges (0.9 x 10\(^6\) km\(^2\)) with a flow of 15,646 m\(^3\) s\(^{-1}\) (1.6% of the worlds combined river flow). The Ganges is one out of 9 major rivers of Asia. The Ganges - Brahmaputra riverine system is the largest supplier of suspended matter to the oceans, accounting for 1.7 x 10\(^{15}\) g sediment dispersed in 1 x 10\(^{15}\) l of water (Milliman and Meade 1983). Because the Hooghly is a well mixed estuary with no appreciable stratification of temperatures and salinities throughout its entire length, a steady-state single box model was constructed to obtain the net fluxes of water, salt and nutrients. The funnel shape of the estuary helps to maintain a near constancy of nutrient ranges over its length. The entire
estuarine reach of about 55 km length was divided into three topographical zones: 1. Upper or freshwater zone, 2. Estuarine or gradient zone and 3. Coastal waters. To accomplish the objectives of the present study, three compartments are considered (Box 1-River, Box 2-System and Box 3-Ocean) based on the salinity gradient of the estuary. The study area map delineating the three boxes is shown in Figure 4.15.

Figure 4.15  Map of the Hooghly estuary showing limits of River, System and Ocean boxes

This region experiences pre-monsoon, monsoon and post-monsoon seasons, though there is not much significant variation of freshwater
discharge and rainfall between pre and post monsoons. Hence, the budgeting of C-N-P-Si has been done for monsoon (June 2008) and pre-monsoon (May 2009) seasons, which are denoted as wet and dry seasons respectively. The fluxes of phosphate and dissolved silicate are assumed to be an approximation of net metabolism, because phosphorus and silica are not involved in gas-phase reactions. Nitrogen and carbon both have other major pathways such as denitrification, nitrogen fixation, and gas exchange across the air-sea interface, and calcification. However, the biogeochemical pathways of carbon and nitrogen can be approximated from phosphate and silicate flux and C-N-P-Si stoichiometric ratios of reactive particles coupled with measured flux for carbon and nitrogen (Liu et al 2009). A comparison of the model considering the effect of mud (recent LOICZ model) was also made with a model that did not consider the effect of mud (previous LOICZ model).

Conservation of mass is one of the most fundamental concepts of ecology and geochemistry, and the LOICZ budget procedure assumes that materials are conserved. The difference (Σ[sources - sinks]) of imported (Σ Inputs) and exported (ΣOutputs) materials may be explained by the processes within the system (Gordon et al 1996) (Figure 4.16).

![Generalized diagram indicating the components of the LOICZ budget procedure](image)

**Figure 4.16** Generalized diagram indicating the components of the LOICZ budget procedure (adapted from Wepener 2007)
In general terms, the sequence of budgets for use in stoichiometrically linked C-N-P-Si follows four steps: water budgets, salt budgets, non-conservative materials and stoichiometric linkages among non-conservative budgets. The different methods and formulae used to derive the salt, water and nutrient budgets, as well as the stoichiometric linkages are summarized below.

Considering salt as a conservative tracer, the water budget of the estuary can be derived from the balance of salt transported through the estuary. Under steady-state condition, the water mass balance can be estimated by using Equation (4.1),

\[ V_q + (V_p - V_e) + V_g + V_w + V_{in} - V_{out} = 0 \] (water mass) \hspace{1em} (4.1)

Where \( V_q \), \( V_p \), \( V_e \), \( V_g \), \( V_w \), \( V_{in} \), and \( V_{out} \) are the mean flow rates of river water, precipitation, evaporation, groundwater, waste water advective inflow and advective outflow of water from the estuary. The compensating outflow or inflow that balances the water volume in the system called residual flow (\( V_r \)) can be expressed by the following Equation (4.2),

\[ V_r = V_{in} - V_{out} = V_q + (V_p - V_e) + V_g + V_w \] \hspace{1em} (4.2)

In the Hooghly estuary, the contribution of ground water (\( V_g \)) has not been considered as it is difficult to measure and its influence on the vast estuarine system is assumed to be insignificant. The waste water term (\( V_w \)) is not considered in this study due to lack of data.

Taking salinity as 0 for freshwater (\( V_q \), \( V_p \) and \( V_e \)), the salt balance in the estuary can be obtained from the salt mass balance in Equation (4.3),
\[ S_r V_r = (S_{ocn} - S_{sys}) V_x \]  

(4.3)

Where \( S_r \) is the salinity of the residual flow at the ocean - system boundary, often taken to be \( (S_{syst} + S_{ocn}) / 2 \) and \( S_{syst} \) and \( S_{ocn} \) are mean salinity of system (estuarine) and ocean boxes; \( V_x \) is the water exchange flow or mixing flow from the seawater end-member (Wolanski 2009). This can be rearranged to solve for \( V_x \) in Equation (4.4),

\[ V_x = S_r V_r / (S_{ocn} - S_{sys}). \]  

(4.4)

Residual outflow \( (V_r) \) is equal to the net input of freshwater, i.e., \( V_r = V_q + V_p - V_e \) (from equation 4.2). The total water exchange time (\( \lambda \)) can be estimated from the ratio of \( V_{sys} / (V_r + V_x) \), where \( V_{sys} \) is the volume of the estuary (secondary data collected from Mukhopadhyay et al 2006).

Dissolved nutrient budgets are estimated from water budgets and measured nutrient concentrations in each box (river, system and ocean). The nutrient budgets are derived from dissolved inorganic \( (\Delta\text{DIN}, \Delta\text{DIP}, \Delta\text{DSi} \text{ and } \Delta\text{DIC}) \) and dissolved organic \( (\Delta\text{DOC}) \) concentrations. At steady state, non-conservative fluxes of DIN \( (\Delta\text{DIN}), \Delta\text{DIP}, \Delta\text{DSi}, \Delta\text{DIC} \) and DOC \( (\Delta\text{DOC}) \) can be derived from the following Equation 4.5 (Wolanski 2009).

\[ \Delta\text{DIN} = - (\Sigma\text{DIN}_{\text{outflux}} - \Sigma\text{DIN}_{\text{influx}}) \]

\[ = - [(1 - \Delta K_d) V_r \text{DIN}_r + V_x \{(1 - \Delta K_d) (\text{DIN}_{ocn} - \text{DIN}_{sys})\} + V_q \text{DIN}_q] \]

\[ \Delta\text{DIP} = - (\Sigma\text{DIP}_{\text{outflux}} - \Sigma\text{DIP}_{\text{influx}}) \]

\[ = - [(1 - \Delta K_d) V_r \text{DIP}_r + V_x \{(1 - \Delta K_d) (\text{DIP}_{ocn} - \text{DIP}_{sys})\} + V_q \text{DIP}_q] \]

\[ \Delta\text{DSi} = - (\Sigma\text{DSi}_{\text{outflux}} - \Sigma\text{DSi}_{\text{influx}}) \]

\[ = - [(1 - \Delta K_d) V_r \text{DSi}_r + V_x \{(1 - \Delta K_d) (\text{DSi}_{ocn} - \text{DSi}_{sys})\} + V_q \text{DSi}_q] \]
\[ \Delta \text{DIC} = -(\Sigma \text{DIC}_{\text{outflux}} - \Sigma \text{DIC}_{\text{influx}}) \]
\[ = -[(1-\Delta K_d) \, V_r \text{DIC}_r + V_x \{(1-\Delta K_d) (\text{DIC}_{\text{ocn}}-\text{DIC}_{\text{sys}})\} + V_q \text{DIC}_q] \]

\[ \Delta \text{DOC} = -(\Sigma \text{DOC}_{\text{outflux}} - \Sigma \text{DOC}_{\text{influx}}) \]
\[ = -[(1-\Delta K_d) \, V_r \text{DOC}_r + V_x \{(1-\Delta K_d) (\text{DOC}_{\text{ocn}}-\text{DOC}_{\text{sys}})\} + V_q \text{DOC}_q] \]

\[ (4.5) \]

In the current version of LOICZ model, \( K_d \) factor is introduced, which is a partition coefficient due to turbidity in water. The \( K_d \) values are assumed to be the same for C, N and P and follow the model of Middelburg and Herman (2007), where SPM is expressed in mg L\(^{-1}\)

\[ K_d = \frac{\text{SPM}}{(\text{SPM} + 72)} \]  \[ (4.6) \]

\( \text{DIN}_q, \text{DIN}_{\text{sys}}, \text{DIN}_{\text{ocn}} \) and \( \text{DIN}_r \) denote the mean DIN concentration in the river, estuary, oceanic water and the residual-flow boundary respectively. According to Gordon et al (1996), \( \text{DIN}_r \) can be determined as \( (\text{DIN}_{\text{ocn}} + \text{DIN}_{\text{sys}}) / 2 \). DIP, DSi, DIC and DOC notations are similar to those of the DIN budget derivation.

Direct measurements of Net Ecosystem Metabolism or NEM are very sparse, thus it has been inferred indirectly via available data on nutrients in specific coastal ecosystems. NEM is the difference between primary production (p) and ecosystem respiration (r) can be estimated stoichiometrically from \( \Delta \text{DIP} \) and the C : P ratio of organic matter being produced or consumed in the estuary. Therefore,

\[ [p-r] = -\Delta \text{DIC} = -\Delta \text{DIP} \times (C: P)_{\text{particulate}} \]  \[ (4.7) \]

From Equation (4.7), it is noted that only DIP is used in the calculation of \([p-r]\) because production or consumption of DIP is regarded as one of the possible sinks or sources for \( \Delta \text{DIP} \), according to Wolanski (2009).
Net organic production removes DIP, while net organic consumption (respiration or oxidation of organic matter by bacteria or secondary producers) releases DIP (Liu et al 2009). The particulate organic C : P of 106:1 was assumed from stoichiometry. A positive NEM (p-r >0) indicates an autotrophic system which requires an input of inorganic nutrients supply from outside the system to support this positive net ecosystem production. While a negative NEM (p-r <0) denotes heterotrophy requires a source of organic matter supplied from outside the system to support this condition (Smith and Hollibaugh 1997). Ultimately, NEM values describe the role of organic metabolism in the specific system as a source or sink of CO$_2$.

Nitrogen metabolism in the estuary expressed as the net result of nitrogen fixation (i.e., conversion of N$_2$ gas to organic N) and denitrification (i.e., conversion of NO$_3$ to N$_2$ and N$_2$O gases) (N$_{fix}$-D$_{enit}$) can be derived from the difference between non-conservative nitrogen flux and expected nitrogen removal through biological uptake. This stoichiometric calculation involves both nitrogen and phosphorus.

$$\text{[N$_{fix}$-D$_{enit}$]} = \Delta N_{\text{observed}} - \Delta N_{\text{expected}}$$
$$= \Delta N_{\text{observed}} - \Delta P*(N: P)_{\text{particulate}}$$

(4.8)

In the Equation (4.8), the Redfield N:P ratio was also applied for the calculation.

### 4.8 WATER AND SALT BUDGET IN THE HOOGHLY ESTUARY

Assessment of water quality of a system is established to the extent of natural variation and the fate of substances entering the system. However, this is not possible unless the hydrodynamic characteristics of the estuary are understood (Allanson 2001; Wepener 2007).
4.8.1 Water Budget

The Hooghly is a well mixed estuary with no appreciable stratification of salinity throughout its entire length; a steady-state single box model was constructed to obtain the net fluxes of water, salt and nutrients. The fresh water source from northern part of the estuary and tidal influence from sea water from the mouth of the estuary makes the system dynamic. The fresh water inflow in the Bhagirathy-Hooghly River constitutes mainly of two components - 1. Western tributaries of the river Bhagirathy-Hooghly, 2. Discharge from the Farakka Barrage. Box1 (River box) has taken into account all the sources of freshwater inflows into the estuarine system (Figure 4.15). The detailed water budget and its seasonal variation in the estuary are given in Table 4.5 and schematically shown in Figure 4.17.

Secondary data were used for surface area (A), volume (V_{sys}), freshwater discharge (V_q) (Mukhopadhyay et al 2006), precipitation (V_p) and evaporation (V_e) (www.indiawaterportal.org). The fresh water discharge (V_q) into the estuary was ~3 times higher during wet season 259.20 \times 10^6 \text{ m}^3 \text{ d}^{-1} than during dry season 86.40 \times 10^6 \text{ m}^3 \text{ d}^{-1}. The watershed area of Bhagirathi-Hooghly is about 60,000 sq. km. This area receives 70 - 80% of the total precipitation during wet season due to south-west monsoon. Total precipitation (V_p) over the area in the wet and dry seasons were 18.4 \times 10^6 \text{ m}^3 \text{ d}^{-1} and 3.81 \times 10^6 \text{ m}^3 \text{ d}^{-1}, respectively. The higher (59%) volume of evaporated water (V_e) loss was detected in dry season (4.16 \times 10^6 \text{ m}^3 \text{ d}^{-1}) than the wet season (1.7 \times 10^6 \text{ m}^3 \text{ d}^{-1}). In both wet and dry seasons, freshwater runoff (V_q) plus precipitation (V_p) exceeded evaporation (V_e) (Table 4.5). Loss of water due to evaporation (V_e) varied between 0.6% - 4.6% of the cumulative fresh water input (V_q + V_p). The estimated residual fluxes (V_r) of the water were 276 \times 10^6 \text{ m}^3 \text{ d}^{-1} and 86 \times 10^6 \text{ m}^3 \text{ d}^{-1} during wet and dry seasons, respectively, which indicated that the system was approximately three times more freshwater dominated during wet season than dry. The
estimated mixing fluxes were $V_x = 168 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ during wet and $112 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ during dry season. During the wet season, residual flux was 64% more than the mixing flux, this indicated that the estuary had a net positive water balance. During dry season, mixing flux exceeded residual flux by 30% due to considerable reduction of freshwater discharge, this indicated that net sea water intrusion into the system (Table 4.5).

The water exchange time ($\lambda$) of the estuary was calculated to be ~41 days during dry season to ~18 days during the wet season (Figure 4.17). Lower residual flux in dry season was related to higher water residence time (Table 4.5). Longer water-residence time played a key role in nutrient metabolism, as it allowed the retention of anthropogenic phosphorus and nitrogen loadings in the sediment (Souza et al 2003; Padedda et al 2010). Considering the total inflows and outflows, the water budget of the estuary displayed a seasonal dominance of fresh water during wet to sea water in dry seasons.

**Table 4.5** The water budget and residence time of the estuary during wet and dry seasons

<table>
<thead>
<tr>
<th>Sampling season</th>
<th>Total fresh water input ($\times 10^6$ m$^3$ d$^{-1}$)</th>
<th>Residual flow ($\times 10^6$ m$^3$ d$^{-1}$)</th>
<th>Mixing flux ($\times 10^6$ m$^3$ d$^{-1}$)</th>
<th>Estuary volume ($\times 10^6$ m$^3$)</th>
<th>Residence time ($\lambda$) in days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet</td>
<td>259</td>
<td>18.4</td>
<td>1.7</td>
<td>276</td>
<td>168</td>
</tr>
<tr>
<td>Dry</td>
<td>86.4</td>
<td>3.81</td>
<td>4.16</td>
<td>86</td>
<td>112</td>
</tr>
</tbody>
</table>
Vq(w) = 259.2
Vq(d) = 86.4

Vr(w) = 276
Vr(d) = 86

Vx(Socn – Ssys)(w) = 3393
Vx(Socn – Ssys)(d) = 2010

Vx(w) = 168
Vx(d) = 112

Vp(w) = 18.40
Vp(d) = 3.81

Vsys = 8205*10^6
Ssys(w) = 2.11
Ssys(d) = 11.6
λ(w) = 18.5 days
λ(d) = 41.3 days

Salt and Water budget for Wet & Dry Seasons

Figure 4.17  Water and Salt budgets for the Hooghly Estuary for wet and dry seasons. Water flux is given in 10^6 m^3 d^{-1} and Salt flux in 10^6 m^3 d^{-1}

4.8.2 Salt Budget

The spatial and seasonal salinity variations in different boxes of the estuary and their mixing salt flux \( V_r S_r \) are given in Table 4.6 and also presented schematically in Figure 4.17. The compartmental boundaries were established based on significant differences of salinity between the riverine and oceanic compartments. Table 4.6 shows distinct seasonal variation of salinity in different boxes. During the wet season, the salinity in river box was near 0.1 whereas in the dry season, it was 2.8, due to reduced freshwater discharge and precipitation. The salinity of the ocean box \( S_{ocn} \) was 22.3 in wet and 29.5 in dry seasons. Based on the seasonal variation of salinity in the system and ocean, mixing salt flux \( V_r S_r = V_x(S_{ocn} - S_{sys}) \) of the estuary was estimated to be 3393 x 10^6 m^3 d^{-1} during wet and 2010 x 10^6 m^3 d^{-1} during dry season, which denoted an overall positive salt balance in both the seasons from the system. The salt flux during the wet season was around 1.6 times higher than dry season due to high river discharge \( V_x \) in wet season.
Table 4.6  Salinity variations in different systems of the estuary and the salt mixing flux during wet and dry seasons

<table>
<thead>
<tr>
<th>Sampling period</th>
<th>Different systems salinity</th>
<th>Salt flux (x 10^6 m^3 d^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>River</td>
<td>System</td>
</tr>
<tr>
<td>Wet season</td>
<td>0.1</td>
<td>2.11</td>
</tr>
<tr>
<td>Dry season</td>
<td>2.8</td>
<td>11.6</td>
</tr>
</tbody>
</table>

4.9 NUTRIENTS BUDGET

Spatial patterns of nutrients reflect the influence of riverine flux and tidal mixing. Dissolved nutrients move with the water and salt from land to the coastal systems and between the coastal systems and the ocean; these nutrients undergo transformations within all of these systems. Hence, in most cases, dissolved nutrient budgets are based on water and salt budgets to establish the advection and mixing of water in the particular system. Thus, the dissolved nutrient budgets are said to ‘behave non-conservatively’ with respect to water and salt flux. The factors controlling the loading rates of N, P and Si into large rivers are dissimilar. N and P loadings are dependent on land use, fertilizer application, and population density (Howarth et al 1996; Caraco and Cole 1999) whereas DSi appears in surface waters as a result of the weathering of sedimentary and crystalline rocks.

4.9.1 Dissolved Inorganic Nitrogen (DIN) Budget

Anthropogenic nitrogen input is the main source of inorganic nitrogen in coastal waters. The distribution of DIN (NO_3^- + NO_2^- + NH_4^+) in the estuary varied both spatially and seasonally. The seasonal and spatial variations of DIN concentrations of the Hooghly estuary are given in
The spatial distribution of non-conservative behavior of DIN in the system showed a non-linear relationship with respect to salinity. In the riverine box, DIN concentrations varied from 30.74 µM L\(^{-1}\) in dry to 33.28 µM L\(^{-1}\) in wet seasons, indicated that slightly higher concentrations of DIN could be related to major freshwater inputs of nitrogen into the system. In the system and oceanic boxes, DIN concentrations gradually decreased in both the seasons (Table 4.7). The global average river water concentration of NO\(_3^-\) is 16.1 µM L\(^{-1}\) (Meybeck 1982). In general, in the total DIN pool, nitrogen was present in an oxidized form, i.e., NO\(_3^-\), and was dominant over both NH\(_4^+\) and NO\(_2^-\) species. In wet season, NO\(_3^-\) comprised 73% of the total DIN concentration, followed by 22% as NH\(_4^+\) and rest as NO\(_2^-\). NO\(_3^-\) was the dominant form during the dry season (average concentration was 95% of the total DIN concentration). Both the seasons showed substantially low concentration of NO\(_2^-\) in all three boxes.

The detailed nitrogen budgets are shown schematically in Figure 4.18. Riverine flux (VqDINq) of DIN decreased from 8746 x 10\(^3\) moles d\(^{-1}\) in the wet season to 2714 x 10\(^3\) moles d\(^{-1}\) in the dry season (Table 4.8). Both seasons showed negative mixing flux values indicated that DIN entered into the sea from the estuary. The non-conservative flux of DIN\(\Delta\)DIN = Outflux – Influx was derived from the difference between the residual flux and sum of the river and mixing flux. It was observed from this study, that the seasonal variations in the riverine DIN fluxes were large and so also the residual flux owing to large variation in the seasonal river inflow, though the concentration of DIN in the system remained almost at a similar level. As a result, the non-conservative fluxes of DIN (\(\Delta\)DIN) varied remarkably on a seasonal scale. A positive \(\Delta\)DIN indicates that DIN is supplied from PON and/ or DON due to mineralization and from air due to nitrogen fixation, making the system as a source for DIN.
and a negative $\Delta$DIN indicates that DIN is transformed to PON and/or DON in the system, or it is lost from the system by denitrification. Considering the effects of mud, during the wet season $\Delta$DIN was negative, which indicated that system acted as a sink for DIN by various biogeochemical processes like denitrification, which is a process of removal of nitrogen from the system to the atmosphere as gaseous phase ($N_2$ and $N_2O$) (Smith and Hollibaugh 2006) whereas in the dry season positive $\Delta$DIN indicated *in-situ* mineralization of DIN from both dissolved and particulate organic matter in the water column of the system due to high residence time (Gupta et al 2006). The wet season was characterized by higher riverine DIN load ($Vq_{DINq}$) suggested that at high loads, the system did not fix DIN, instead lost nitrogen. This response has also been observed in other estuarine systems (Giordani et al 2008; Padedda et al 2010) and appears to be a general trend.

If the SPM is neglected, $\Delta$DIN in both wet and dry seasons showed negative flux, $-750 \times 10^3$ moles d$^{-1}$ and $-330 \times 10^3$ moles d$^{-1}$, respectively indicated the system was a sink for DIN (Table 4.8). This could be due to the biological conversion of DIN to PON, which was ignored in non-mud approach.

Table 4.7  Distribution of SPM, DIN, DIP and DSi in different compartments of the Hooghly estuary during wet and dry season

<table>
<thead>
<tr>
<th></th>
<th>SPM mg L$^{-1}$</th>
<th>DIN µM L$^{-1}$</th>
<th>DIP µM L$^{-1}$</th>
<th>DSi µM L$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet</td>
<td>Dry</td>
<td>Wet</td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td>River</td>
<td>136</td>
<td>126.8</td>
<td>33.28</td>
<td>30.74</td>
</tr>
<tr>
<td>System</td>
<td>128.5</td>
<td>115.4</td>
<td>28.00</td>
<td>24.16</td>
</tr>
<tr>
<td>Ocean</td>
<td>78.8</td>
<td>31.2</td>
<td>23.00</td>
<td>20.60</td>
</tr>
</tbody>
</table>
Table 4.8 Summary of seasonal variation of DIN budget in the Hooghly

<table>
<thead>
<tr>
<th>Sampling period</th>
<th>River flux ((V_r\text{DIN}_q)) ((10^3 \text{ mol d}^{-1}))</th>
<th>Residual flux ((V_r\text{DIN}_r)) ((10^3 \text{ mol d}^{-1}))</th>
<th>Mixing flux ([V_r(\text{DIN}<em>{\text{sys}} - \text{DIN}</em>{\text{mix}})]) ((10^3 \text{ mol d}^{-1}))</th>
<th>(\Delta\text{DIN}) ((10^3 \text{ mol d}^{-1}))</th>
<th>% Additional / Removal</th>
<th>Residence Time ((\lambda)) days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet season (with mud)</td>
<td>8746</td>
<td>7035</td>
<td>-1294</td>
<td>-416</td>
<td>-5</td>
<td>40</td>
</tr>
<tr>
<td>Wet season (without mud)</td>
<td>8626</td>
<td>7035</td>
<td>-840</td>
<td>-750</td>
<td>-8</td>
<td>37</td>
</tr>
<tr>
<td>Dry season (with mud)</td>
<td>2714</td>
<td>1926</td>
<td>-1125</td>
<td>336</td>
<td>12</td>
<td>248</td>
</tr>
<tr>
<td>Dry season (without mud)</td>
<td>2656</td>
<td>1926</td>
<td>-400</td>
<td>-330</td>
<td>-12</td>
<td>130</td>
</tr>
</tbody>
</table>

Seasonal variation in the residence time of nutrients varied with the water exchange time, since the nutrient residence time is a function of the nutrient inventories and their residual and mixing fluxes in the system. The residence time of DIN in the estuary was six times higher (248 days) during the dry compared to wet seasons (40 days) (Table 4.8). DIN residence time was 2 - 6 times longer than that of estuarine water (Table 4.5). The longer residence time might allowed more effective biological utilization of nutrients for productivity (Hung and Kuo 2002). However, the presence of high level of suspended particulate matter (SPM) (>100 mg L\(^{-1}\)) hindered the primary productivity in the system (Hung and Kuo 2002; Gupta et al 2006; Mukhopadhyay et al 2006).
Figure 4.18 DIN budgets for the Hooghly Estuary for wet and dry seasons. Concentrations are expressed in µM L⁻¹, fluxes in 10^3 mol d⁻¹ and Nfix – Denit in mmol m⁻² d⁻¹

### 4.9.2 Dissolved Inorganic Phosphorus (DIP) Budget

All phosphorus (P) in the system can be considered to be in either the dissolved or the particulate phase, and P reactions involve transfers between these phases; there is no gas phase (Wepener 2007). The seasonal variations of dissolved inorganic phosphorus (DIP) in different boxes are given in Table 4.7 together with their fluxes in Table 4.9 considering the cases with and without effects of mud. It was observed that in both the seasons, mean values for DIP were higher than average values reported for rivers by Meybeck (1982), i.e., 0.65 µM L⁻¹ for inorganic reactive phosphate. Higher concentrations of DIP can be attributed to anthropogenic sources such as use of phosphorus fertilizers, detergents, industrial wastes and sewage discharge (Ramesh et al 1995). In the Hooghly estuary, all these sources are pronounced. During the wet season, monsoonal runoff increased the concentration of DIP in the estuarine water, and the increase was about two times with respect to its concentrations in the dry season (Table 4.7). Increased concentration of DIP in the wet season suggested external sources
of DIP entering into the system. In both seasons concentration of DIP gradually decreased towards the oceanic boundary. The seasonal non-conservative DIP budget is shown in Figure 4.19. Mixing flux of DIP was negative during both the seasons which indicated a flux from the estuary to the ocean. Considering mud, wet and dry seasons showed net positive $\Delta$DIP of the order of $19 \times 10^3$ mol d$^{-1}$ and $20 \times 10^3$ mol d$^{-1}$ respectively, indicating a net flux of DIP to the sea from the system (Table 4.5).

According to Hung and Kuo (2002), a system with positive $\Delta$DIP, acts as a net producer of CO$_2$ (p<r), which was evident with high pCO$_2$ levels (> 1500 $\mu$atm) in the Hooghly estuary, in both the seasons. High residence time of DIP (Table 4.9) in the system could also assisted in the regeneration of DIP from organic matter (Mukhopadhyay et al 2006). In addition, the natural effect of the phosphate buffer mechanism could cause the release of DIP to the water column from estuarine sediments (Froelich 1988; Sylaios 2003) and made the system a source of DIP. During the wet season when mud was not taken into account, $\Delta$DIP showed negative flux, which could be possible if the system exhibited a net CO$_2$ consumption via net production of organic matter (p>r) (Hung and Kuo 2002). This was evident by the positive NEM value (0.52 mmol m$^{-2}$ d$^{-1}$) in wet season without considering mud (Table 4.10).

The ratio of DIN to DIP in the water attained a maximum value of 17.6:1 during wet season at the river box. This ratio gradually decreased to a minimum value of 14:1 at the ocean box (Table 4.7) which was lower than the ratio of utilization by phytoplankton, i.e., the Redfield ratio, 16:1 (Redfield et al 1963). The ratios of availability to utilization were found to be 0.87 - 1 for DIN and DIP, respectively. This indicated that nitrogen could be limiting before P. Decreasing trend of DIN: DIP ratio towards the sea end was evident. During dry season, the DIN: DIP ratio increased around two fold, 33.41:1 at
the river box indicating that the system received very high anthropogenic N loading, which remained undiluted as in wet season, resulting in seasonal phosphorus limitation of phytoplankton growth, which is a common trend in tropical systems (Fisher et al 1999; Yin et al 2001; Murrell et al 2002).

Table 4.9  Summary of seasonal variation of DIP budget in the Hooghly estuary obtained from LOICZ model considering mud and without mud effect

<table>
<thead>
<tr>
<th>Sampling period</th>
<th>River flux  ( V_qDIP_q ) (10^3 mol d^{-1})</th>
<th>Residual flux ( V_rDIP_r ) (10^3 mol d^{-1})</th>
<th>Mixing flux ( [V_q(DIP_{sca} - DIP_{sys})] ) (10^3 mol d^{-1})</th>
<th>( \Delta DIP ) (10^3 mol d^{-1})</th>
<th>% Additional / Removal</th>
<th>Residence Time (( \lambda )) days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet season (with mud)</td>
<td>497</td>
<td>466</td>
<td>-49</td>
<td>19</td>
<td>4</td>
<td>34</td>
</tr>
<tr>
<td>Wet season (without mud)</td>
<td>490</td>
<td>466</td>
<td>-17</td>
<td>-7</td>
<td>-1.5</td>
<td>32</td>
</tr>
<tr>
<td>Dry season (with mud)</td>
<td>81</td>
<td>57</td>
<td>-44</td>
<td>20</td>
<td>25</td>
<td>497</td>
</tr>
<tr>
<td>Dry season (without mud)</td>
<td>79</td>
<td>57</td>
<td>-25</td>
<td>2</td>
<td>2.5</td>
<td>197</td>
</tr>
</tbody>
</table>

DIP budget in the estuary for Wet & Dry Seasons

Figure 4.19  DIP budgets for the Hooghly Estuary for wet and dry seasons. Concentrations are expressed in \( \mu \text{M L}^{-1} \), fluxes in 10^3 mol d^{-1} and p-r in mmol m^{-2} d^{-1}
4.9.3 Net Ecosystem Metabolism (NEM)

Dominance of heterotrophy or autotrophy in coastal aquatic ecosystems depends upon the accumulated organic matter budget (Nixon 1995) and C: N: P stoichiometry (Smith 1993; Giordani et al 2008). The detailed seasonal NEM (p-r) and Nfix-Denit rates in the estuary with and without considering mud are given in Table 4.10 and shown in the Figures 4.18 and 4.17. In the Hooghly estuary, estimated NEM was found to be negative with community respiration exceeding phytoplankton production during wet season (p-r = -1.44 mmol m⁻² d⁻¹) and dry season (p-r = -1.51 mmol m⁻² d⁻¹) with considering the effect of mud (Table 4.10). This estimation of fluvial net heterotrophy supports the global trend. Battin and his colleagues (2008), estimated global fluvial respiration from headwaters through estuaries equals 1.55 Pg C y⁻¹ and represents a global net heterotrophy of 0.32 Pg C y⁻¹.

According to Wang et al (1999) temperature and light intensity are the major factors in primary productivity rather than nutrients. As the Hooghly is a turbid estuary (SPM > 100 mg L⁻¹) (Table 4.7), euphotic depth is always less than 1m. Hence, in spite of the occurrence of high nutrient concentrations in the water column, community respiration dominated primary productivity, and this turned the estuary heterotrophic (Young and Huryn 1996). Mukhopadhyay et al (2006) mentioned another factor, that the dynamic nature (with respect to hydrodynamics) of this estuary could cause phytoplankton damage and restrict production by supressing plankton growth. The increased rate of heterotrophy during dry season could be attributed to augmented DOC concentration which fueled microbial respiration (Howarth et al 1996) (Table 4.12).
Table 4.10 Net Ecosystem Metabolism (NEM) and Nfix-Denit in the Hooghly estuary during wet and dry seasons in both conditions (with mud and without mud)

<table>
<thead>
<tr>
<th>Season</th>
<th>With Mud</th>
<th>Without Mud</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NEM (p-r) (mmol m$^{-2}$ d$^{-1}$)</td>
<td>Nfix - Denit (mmol m$^{-2}$ d$^{-1}$)</td>
</tr>
<tr>
<td>Wet</td>
<td>-1.44</td>
<td>-0.52</td>
</tr>
<tr>
<td>Dry</td>
<td>-1.51</td>
<td>0.02</td>
</tr>
</tbody>
</table>

NEM results obtained from the LOICZ (CABARET) model without considering mud are shown in Table 4.10. Without considering the effects of mud, the wet season showed positive NEM (0.52 mmol m$^{-2}$ d$^{-1}$) indicated an autotrophic system. The slightly negative NEM (-0.15 mmol m$^{-2}$ d$^{-1}$) in the dry season indicated a shift to heterotrophy. According to Hung and Kuo (2002), a combination of negative $\Delta$DIP and positive (p-r) indicated a CO$_2$ consuming system via a net production of organic matter. In this model (without mud), POC was not taken into account, which was the major contributing factor for heterotrophy. Anesio et al (2003) showed that respiration of bacteria attached to particulate carbon have a significant role in heterotrophy. During the dry season, both the models of (considering mud and omitting mud) have shown a positive $\Delta$DIP with negative NEM. When the interaction of SPM with the water column was considered (i.e., effects of nutrient sorption in muddy systems), the rate of heterotrophy was ten times higher.

Net nitrogen fixation or denitrification (Nfix - Denit) was calculated from the difference between observed and expected $\Delta$DIN. This is indicative of the nitrogen metabolism in the estuary. The system was denitrified in excess of N fixation, at an average rate of 0.52 mmol m$^{-2}$ d$^{-1}$ during the wet season which was correlated with negative $\Delta$DIN when considering mud (Table 4.10). During the dry season Nfix-Denit was positive, indicating that
the system produced more N through fixation than was lost to denitrification, at an average of 0.02 mmol N m$^{-2}$ d$^{-1}$ while considering mud. Distinct seasonal variation was recorded when effects of mud were included, which could be attributed to the differential interaction between particulate matter and the water column during wet and dry seasons. Seasonal shifting of ΔDIN from a sink to source was evident with shifting of the system from denitrification to nitrification in wet to dry seasons. Denitrification rates did not show major seasonal variations when mud is not taken into account (Table 4.10).

4.9.4 Dissolved Inorganic Silicate (DSi) Budget

Silicon is the second most abundant element in the Earth’s crust, but only a minor portion takes part in biogeochemical cycles. Dissolved silicate is mainly delivered via weathering, which is restrained by the interaction of tectonic conditions, rock/soil and climate (Conley 2002). The seasonal and spatial variations of DSi concentrations of the Hooghly estuary are given in Table 4.7. Mean silicate concentrations were lower than the world average, i.e., 147.8 μM L$^{-1}$ (GEMS database 2002). Dissolved Silicate concentration (DSi) in both seasons, gradually decreased from the river to ocean box as salinity increased. DSi was observed to be higher in the wet season due to high freshwater discharge. In general, higher trend of dissolved silica in the riverine water can be related to the effect of climate on weathering, which resulted in an extensive leaching of silica from drainage areas, followed by higher riverine concentrations in the subtropical zone relative to temperate zones (Liu et al 2009).

The seasonal DSi fluxes were determined with and without considering mud effect, and results are given in Table 4.11. The detailed silicate budgets are shown schematically in Figure 4.20. Mixing fluxes for both the seasons and under both conditions (with mud and without mud) were
found to be negative indicating unidirectional flow of DSi from estuary to ocean. Taking mud into account, the wet season showed negative $\Delta$DSi indicates that the system acted as a sink for DSi while the dry season showed positive net flux of DSi (Table 4.11). The regeneration of silicate was not organic degradation, but other chemical processes of DSi could be the reason of positive flux. These processes are much slower than those of nitrogen and phosphorus regeneration processes (Dugdale and Wilkerson 2001). Hence, it was assumed that shifting of a sink to source of DSi could be attributed to the interplay between varied rate of biological uptake (absorb significant amounts of dissolved silicate) by Diatoms (Turner et al 2003; Laruelle et al 2009) and slow mineralization processes along with surface runoff.

The DSi: DIN ratio was a sensitive indicator of aquatic food web health. DSi: DIN ratio and the nitrate concentration, when used together, could be applied as a comparative indicator of eutrophication that is robust across the broad landscapes represented by the large river systems. In this study, DSi : DIN ratio ranged between 3 - 4 : 1, which was higher than the minimal DSi : DIN proportion of 1:1 for diatoms, indicated estuarine waters were suitable for diatom growth (Elser et al 1996; Turner et al 2003).

Table 4.11  Summary of seasonal variation of DSi budget in the Hooghly estuary obtained from LOICZ model considering mud and without mud effect

<table>
<thead>
<tr>
<th>Sampling period</th>
<th>River flux ( (V_{q,DSi}) ) ( \times 10^3 ) mol d(^{-1})</th>
<th>Residual flux ( (V_{r,DSi}) ) ( \times 10^3 ) mol d(^{-1})</th>
<th>Mixing flux ( [V_{r,DSi} - (DSi_{sys})] ) ( \times 10^3 ) mol d(^{-1})</th>
<th>$\Delta$DSi ( \times 10^3 ) mol d(^{-1})</th>
<th>% Additional / Removal</th>
<th>Residence Time ( (\lambda) ) days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet season (with mud)</td>
<td>36265</td>
<td>24969</td>
<td>-7007</td>
<td>-4289</td>
<td>-12</td>
<td>49</td>
</tr>
<tr>
<td>Wet season (without mud)</td>
<td>35770</td>
<td>24969</td>
<td>-5546</td>
<td>-5256</td>
<td>-14.6</td>
<td>45</td>
</tr>
<tr>
<td>Dry season (with mud)</td>
<td>9537</td>
<td>6497</td>
<td>-5026</td>
<td>1986</td>
<td>21</td>
<td>491</td>
</tr>
<tr>
<td>Dry season (without mud)</td>
<td>9331</td>
<td>6497</td>
<td>-2808</td>
<td>-27</td>
<td>-0.28</td>
<td>196</td>
</tr>
</tbody>
</table>
Figure 4.20  DSi budgets for the Hooghly Estuary during wet and dry seasons. Concentrations are expressed in µM L⁻¹ and fluxes in 10³ mol d⁻¹

4.10  CARBON BUDGET

Main sources for the organic matters are the fluvial and anthropogenic inputs. Each year streams and rivers of the world transport, transform or store nearly 2 Pg of terrestrial organic carbon (Battin et al 2008), this suggests that land-derived organic carbon is an important integrator of terrestrial and aquatic ecosystem processes that fuel the net heterotrophy of fluvial ecosystems (Mayorga et al 2005).

4.10.1  Dissolved Inorganic Carbon (DIC) Budget

In the Hooghly estuary, spatial and seasonal distribution of DIC is given in Table 4.12. The DIC concentrations were found to be increased from the sea end to river end, with maximum values in dry and minimum values in wet season. This trend corresponds with finding of Mukhopadhyay et al (2006) in the same system. Riverine DIC was higher by 49% in dry season
than wet season. Higher concentration of DIC could be attributed to allochthonous C input, which was less diluted during dry season than wet. The detailed DIC budget is shown in Figure 4.21.

According to the DIC budget in the Hooghly estuary considering mud (Figure 4.21), riverine inflow ($V_{q\text{DIC}}$) delivered twice as much DIC ($435178 \times 10^3$ mol DIC d$^{-1}$) during the wet season than the dry season ($217403 \times 10^3$ mol DIC d$^{-1}$). Residual outflow ($V_{r\text{DIC}}$) removed $490824 \times 10^3$ mol DIC d$^{-1}$ and $166253 \times 10^3$ mol DIC d$^{-1}$, while mixing flux transported $-55050 \times 10^3$ mol DIC d$^{-1}$ and $-89229 \times 10^3$ mol DIC d$^{-1}$ into the system during wet and dry seasons respectively (Table 4.13). In order to support this net import, there was a net positive value for $\Delta$DIC, indicated system served as a source of DIC during both the seasons. DIC of the estuary was ~3 times higher during wet than dry seasons. DIC budget model thus suggested that the estuarine system may be generating excess DIC, which can be substantiated due to mineralization of the riverine and/or in-situ produced organic carbon either in the form of DOC or POC. Another reason could be the presence of Sundarbans mangrove adjacent to the estuary. Autochthonous carbon import to the estuary could have a significant role on the overall carbon budget. When mud is not taken into consideration, only dry season showed negative $\Delta$DIC (Table 4.13).

| Table 4.12 Distribution of DIC and DOC in different boxes during wet and dry seasons |
|---------------------------------|---------------------------------|
| **DIC µM L$^{-1}$** | **DOC µM L$^{-1}$** |
| **Wet** | **Dry** | **Wet** | **Dry** |
| River | 1656 | 2462 | 261.67 | 360.83 |
| System | 1842 | 2044 | 290.00 | 311.67 |
| Ocean | 1716 | 1820 | 245.00 | 269.17 |
Table 4.13 Summary of seasonal variation of DIC budget in the Hooghly estuary obtained from LOICZ model considering mud and without mud effect

<table>
<thead>
<tr>
<th>Sampling period</th>
<th>River flux ($V_q$DIC$_q$) ($10^3$ mol d$^{-1}$)</th>
<th>Residual flux ($V_r$DIC$_r$) ($10^3$ mol d$^{-1}$)</th>
<th>Mixing flux [$V_x$DIC$<em>{ocn}$ – DIC$</em>{sys}$] ($10^3$ mol d$^{-1}$)</th>
<th>$\Delta$DIC ($10^3$ mol d$^{-1}$)</th>
<th>% Additional / Removal</th>
<th>Residence Time ($\lambda$) days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet season (with mud)</td>
<td>435178</td>
<td>490824</td>
<td>-55050</td>
<td>110695</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>Wet season (without mud)</td>
<td>429235</td>
<td>490824</td>
<td>-21176</td>
<td>82765</td>
<td>19</td>
<td>32</td>
</tr>
<tr>
<td>Dry season (with mud)</td>
<td>217403</td>
<td>166253</td>
<td>-89229</td>
<td>38079</td>
<td>17.5</td>
<td>218</td>
</tr>
<tr>
<td>Dry season (without mud)</td>
<td>212717</td>
<td>166253</td>
<td>-25157</td>
<td>-21307</td>
<td>-10</td>
<td>119</td>
</tr>
</tbody>
</table>

DICsys(w) = 1842
DICsys(d) = 2044
$\Delta$DIC(w) = 110695
$\Delta$DIC(d) = 38079
$\lambda$(w) = 35 days
$\lambda$(d) = 218 days

Figure 4.21 DIC budgets for the Hooghly Estuary during wet and dry seasons. Concentrations are expressed in µM L$^{-1}$ and fluxes in $10^3$ mol d$^{-1}$

The residence time of DIC in the estuary was approximately twice longer (35 days) than the water residence time during wet. Similarly, during dry the residence time of DIC was more than five times longer (218 days) than the water exchange time of the estuary.
4.10.2 Dissolved Organic Carbon (DOC) Budget

DOC is the most important intermediate in global carbon cycling. In fact, only low-molecular-weight compounds (500-1,000 daltons) are transported through the microbial cell membrane and subsequently subject to metabolism (Battin et al 2008). Carbon fluxes of the major world rivers identify the flux of terrestrial DOC (0.25 Pg C y\(^{-1}\)) as the largest transfer of reduced carbon from the land to the ocean with POC export estimated at 0.18 Pg C y\(^{-1}\) (Cauwet 2002).

In the Hooghly estuary, dissolved organic carbon (DOC) concentrations varied considerably both spatially and seasonally. The concentration level of DOC in the water of river, estuary and oceanic boxes during both seasons are displayed in Table 4.12. During wet season, DOC concentrations showed higher values in the system than the ocean and river boxes, this could be attributed to the allochthonous DOC input from Haldia industrial complex and Haldia Petrochem adjoining to lower stretch of the system box. Mukhopadhyay et al (2006) reported that input from adjacent Sundarbans mangrove could act as an additional source of organic matter apart from the riverine source. During the dry season, DOC concentration decreased gradually towards the ocean box. High DOC was found in the dry season; this could be from phytoplankton exudation (Lalli and Parsons 1993) in the system. Another reason of higher DOC attributed to less dilution of raw sewage and industrial effluent released from surrounding industries, and fishing harbors.

The seasonal DOC influx and out fluxes with net budget in the estuary with and without considering mud are given in Table 4.14. Detailed seasonal DOC budget is shown in Figure 4.22. In the muddy LOICZ model, river influx of DOC during the wet and dry seasons were 68764 x 10\(^3\) mol d\(^{-1}\)
and $3.1863 \times 10^3$ mol d$^{-1}$ respectively. The wet season residual flux was around three times higher ($7.3803 \times 10^3$ mol d$^{-1}$) than the dry season ($2.4991 \times 10^3$ mol d$^{-1}$). Both wet and dry seasons showed negative mixing fluxes of $-1.2399 \times 10^3$ mol d$^{-1}$ and $-1.4249 \times 10^3$ mol d$^{-1}$ respectively, indicated flow from the estuarine system to oceanic compartment. Net fluxes of DOC for both seasons were positive when considering mud indicated that the system was a net source of DOC (Table 4.14) which turned the system heterotrophic. Excess supply of DOC from the mangrove surrounding waters enhanced the DIC: DIN and DIC: DIP ratios compared to Redfield Ratio (Koertzinger et al 2001; Mukhopadhyay et al 2006). While the effect of mud was not considered, $\Delta$DOC during the wet season was positive, and during the dry season was negative (Table 4.14). This anomaly in the result between mud and non-mud approach could be due to the role of POC supplied by the mangrove litter, which was very significant in this aspect (Marcelo et al 2009).

Table 4.14 Summary of seasonal variation of DOC budget in the Hooghly estuary obtained from LOICZ model considering mud and without mud effect

<table>
<thead>
<tr>
<th>Sampling period</th>
<th>River flux ($V_{Q_{DOC_{r}}} (10^3 \text{ mol d}^{-1})$)</th>
<th>Residual flux ($V_{r_{DOC_{h}}} (10^3 \text{ mol d}^{-1})$)</th>
<th>Mixing flux $[V_{x_{DOC_{ocn}} - DOC_{sys}}] (10^3 \text{ mol d}^{-1})$</th>
<th>$\Delta$DOC $(10^3 \text{ mol d}^{-1})$</th>
<th>% Additional / Removal</th>
<th>Residence Time ($\lambda$) days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet season (with mud)</td>
<td>6.8764</td>
<td>7.3803</td>
<td>-1.2399</td>
<td>1.7438</td>
<td>25</td>
<td>39</td>
</tr>
<tr>
<td>Wet season (without mud)</td>
<td>6.7825</td>
<td>7.3803</td>
<td>-0.7563</td>
<td>1.3541</td>
<td>20</td>
<td>36</td>
</tr>
<tr>
<td>Dry season (with mud)</td>
<td>3.1863</td>
<td>2.4991</td>
<td>-1.4249</td>
<td>0.7378</td>
<td>23</td>
<td>238</td>
</tr>
<tr>
<td>Dry season (without mud)</td>
<td>3.1176</td>
<td>2.4991</td>
<td>-0.4773</td>
<td>-0.1411</td>
<td>-4.5</td>
<td>126</td>
</tr>
</tbody>
</table>
**Figure 4.22** DOC budgets for the Hooghly Estuary during wet and dry seasons. Concentrations are expressed in µM L$^{-1}$ and fluxes in 10$^3$ mol d$^{-1}$

### 4.11 CONCLUSION

According to the LOICZ model for muddy systems, the Hooghly estuary acted as a source for all nutrients in both the seasons except for DIN where it acted as a sink in the wet season. During the wet season, overall runoff increased the concentration of nutrients in the estuarine system. The non-conservative fluxes of DIN and DIP observed were likely the results of a combination of abiotic processes (P adsorption), primary production, and heterotrophy (denitrification). In the export of dissolved nutrients, either in inorganic or organic forms, mangrove’s role was distinct.

The Hooghly estuary is situated adjacent to Sundarbans mangrove, which produces copious amounts of organic carbon (DOC, POC) due to litter decomposition and exports it to the estuary. High organic carbon from exogenous sources in the estuarine system enhances microbial metabolic activities (Duarte and Cebrian 1996) at a cost of lower levels of dissolved
oxygen. This led to emission of trace gases (like CO$_2$ and CH$_4$) to the atmosphere from this system. In the Hooghly estuarine system, even though the nutrient concentrations were high and their longer residence times in the system were sufficient to trigger primary production, but high levels of SPM (> 100 mg L$^{-1}$) inhibited the light availability for photosynthesis and in turn their growth, made the system net heterotrophic in both the seasons. Omitting the effect of SPM, would lead to the incorrect conclusion that the Hooghly estuary is an autotrophic system during wet season. This indicated that the presence of SPM controls the NEM of the system.

In the present study, the budgets of inorganic nutrients can result in unaccounted nutrient inputs due to the re-mineralization of more labile organic compounds, especially in the presence of high N fixation rates and inputs of untreated waste loads. It was reported that C, N, P cycles are strongly influenced by sediment fluxes and consequently, by climate variability in this region. However, high interannual unpredictability and rapid change on the larger and delayed time scale of the monsoon in this region would need to be understood with further research, to establish the climate link conclusively. The roles of the microbial community also need to be studied in details to understand the biotransformation processes of nutrients in the system.